Open Access

*Journal of Energy and Power Technology*

Research Article

# Physical Characterization of Solar Thermal Energy Storage (TES) Materials for Solar Dryers: Case of Volcanic Stone (Pozzolan) in Chad

Michel Boukar [1], Etienne Tchoffo Houdji [1, 2, ‡, *], Dimitri Valdes Tchuindjang Kwatchie [3], Guy Bertrand Tchaya [1, 3], Danwe Raidandi [1]

1. National Advanced School of Engineering, the University of Maroua, Maroua, Cameroon; E-Mails: boukarmichel910@gmail.com; tchoffohoudji@gmail.com; tchayaguy@gmail.com; rdanwe@yahoo.fr
2. Advanced School of Mines Processing and Energy Resources, the University of Bertoua, Bertoua, Cameroon
3. Faculty of Sciences, the University of Dschang, Dschang, Cameroon; E-Mail: tchuindjangdimitrivaldes@gmail.com

‡ Current Affiliation: Advanced School of Mines Processing and Energy Resources, the University of Bertoua, Cameroon

* **Correspondence:** Etienne Tchoffo Houdji; E-Mail: tchoffohoudji@gmail.com

**Academic Editor:** Xiaolin Wang

**Special Issue**: Thermal Energy Storage and Energy Engineering

*Journal of Energy and Power Technology*
2024, volume 6, issue 3
doi:10.21926/jept.2403014

**Received:** March 25, 2024
**Accepted:** July 22, 2024
**Published:** August 01, 2024

**Abstract**

Many sensible heat storage materials are regularly used as thermal energy storage (TES) systems to improve the efficiency of solar dryers. The present work focuses on the effects of the volume and particle sizes of a volcanic stone (pozzolan) for the same purpose. Samples soaked in matt black and without soaking were also considered. Heat charge and discharge tests were carried out by exposing the pozzolan contained in a solar collector of the direct solar dryer (DSD) and indirect solar dryer (ISD) to the sun. Charge and discharge heat transfer models of the pozzolan enable determining the time constant $\tau(s)$. The results show that during the charge phase, the non-soaked sample for volumes of 25 l and 20 l in the ISD and the DSD stores heat more than the soaked sample. The half-filled solar collector for ISD with a pozzolan bed depth of 5 cm gives high time-constant values compared to other studied samples. Thus, the pozzolan charges for a longer time for this volume. Soaked samples discharge more slowly than non-soaked samples for particle sizes of 8 to 12 mm and 12 to 16 mm in the ISD and 4 to 8 mm and 8 to 12 mm in the DSD.

**Keywords**
Solar dryer; thermal energy storage; sensible heat thermal system; pozzolan

## 1. Introduction

The 2030 Agenda, established in 2015 by the United Nations, is based on the 17 Sustainable Development Goals (SDGs). Achieving these SDGs will not be possible without the contribution of the agriculture and agro-food sector. The United Nations states through the Food and Agriculture Organization (FAO) that these sectors are crucial to achieving the Sustainable Development Goals, specifically SDG 1 (ending poverty) and SDG 2 (ending hunger) [1]. Many primarily consumed agricultural products are not always available seasonally. As a result, harvesting, preservation, processing, and distribution operations are not sufficiently addressed to meet the SDGs. To overcome this handicap, several solutions have been proposed: preservation by drying, greenhouse cultivation, freezing, etc. Drying is a safe, simple, and appropriate solution for many products. Usually, the drying process decreases the moisture content of food and agricultural products, making their preservation easier and increasing their shelf life. To appropriately control the nutritional properties of food products and ensure their good quality, the humidity level and operating temperature (usually 40–60°C) are regulated during drying [2-5].

According to his geographical position, Chad has good sunshine. It has one of the best sunny hours throughout the year in Africa. Chad receives more than 3030.91 hours of sunshine each year [6]. In addition, Chad's daily solar irradiance ranges from 5.5 kWh/m$^2$ to 7 kWh/m$^2$ [7, 8]. Most of Chad's provinces have experienced rapid agrarian development. Therefore, Chad highly produces agricultural products such as tomatoes, potatoes, mangos, maize (corn), wheat, rice, sesame seeds, recession sorghum, and sorghum [9, 10]. Hence, the potential of solar drying can be considered an appropriate technology for the country's domestic and industrial sectors.

Solar drying is attractive for many agricultural and food products in the industrial and domestic sectors. The quality of the final products will be preserved if the products are dried in an enclosed space and a clean environment [11]. Solar drying also contributes to increasing product storage capacity, transforming some products into a much more usable form, and reducing transportation costs [4, 5]. Products can be dried continuously during intermittent cloud cover, bad weather conditions, and at night if the dryer is coupled with a TES unit or a backup heater [11, 12]. Since solar dryers can be built with local resources, they improve the farming community's economy. Based on the air circulation mode in the solar collector, solar dryers are broadly divided into natural convection and forced convection dryers. These two categories of dryers are also classified as direct, indirect, and mixed types based on the exposure of the product to the sun [11, 13]. Beyond this general classification based on the airflow movement and product heating in the dryer, there are other types of solar dryers. They are the following: hybrid solar dryers [14]; desiccant bed solar dryers [15]; heat pump operated solar dryers [16, 17]; conductive type solar dryers [18]; dual-purpose solar dryers [19]. Among all these solar dryers, indirect forced convection dryers are the most widely used because they are cheap, avoid contamination, are cost-effective, allow thermal control of drying, do not expose drying products to direct sunlight, and are highly recommended for photosensitive agro-products [20].

Many factors limit the use of solar drying. These include the intermittency of solar energy, fluctuation of ambient conditions, and partial rehydration of the product at night [5, 21]. Thus, the real challenge is developing a solar drying technique with efficient energy consumption for a desired product. TES systems are integrated into solar dryers to store excess thermal energy during the sunshine. The dryers use this stored energy during off-sunshine periods. [4, 5]. This aims to mitigate fluctuations in climate parameters and enable continuous dryer operation [22]. Therefore, TES is essential in improving solar dryers' overall drying efficiency [23]. TES can be used in various solar thermal systems for short- or long-term energy storage [24]. Therefore, a TES can help develop energy-efficient thermal systems, decreasing energy consumption and capital cost. This leads to the development of a cost-efficient solar system [25]. For example, Vásquez et al. have demonstrated a potential energy savings of about 80% compared to conventional drying using a proper TES control system [26]. Krishnan and Sivaraman have shown that the solar dryer with TES's thermal efficiency improved by 50% compared to the conventional dryer [27]. The effect of thermal storage was observed to stabilize the temperature in the dryer for 3 h after sunset and then gradually decrease. Other benefits of using TES are reduced fossil fuel, better system reliability, environment friendly, improved energy security [28], and reduced time between energy supply and demand [29].

Thermal solar energy can be stored in well-insulated fluids or solids in three forms: sensible heat, latent heat, or thermochemical. It can also be stored in any combination mentioned above [5]. In sensible heat storage (SHS) material, the change in temperature of a solid or liquid results in a shift in heat stored as sensible heat. The amount of energy in SHS depends on the storage medium's specific heat capacity, the increase in storage medium temperature, and the storage material mass. In latent heat storage (LHS), the heat is absorbed or released when the thermal storage material undergoes a phase change from the gaseous to the liquid state or from the liquid state to the solid state or vice versa at a constant temperature. LHS through phase change materials (PCM) is a promising technology for TES due to its isothermal nature during the phase transition from gas to liquid or liquid to solid (or vice versa) and its high-thermal energy storage density [30]. PCMs can reduce the heat losses in solar dryers and significantly increase their efficiency [2]. Nevertheless, the higher volume changes in phase transition are their difficulties [31]. In addition, PCM is an option to rationalize TES's high cost and power utilization. On the other hand, the major disadvantage of PCMs is their high cost, which restricts their use in TES systems [24]. The thermochemical energy storage system depends on the energy absorbed at the breaking of molecular bonds and the release of energy during reformation of the molecular bonds in an entirely reversible chemical reaction [5].

Each method of energy storage has some essential advantages and drawbacks over others. Storing energy as latent heat or sensible heat is cheaper and simpler [32, 33]; however, it is stored for short periods in these forms [32, 34]. It is lost to the ambient once the energy supply source is removed. Thus, it must be used within a certain period after storage. Hence, they are used chiefly for heating applications at night or intermittent cloudy hours. The efficiency of PCMs in solar energy systems is also limited by irregular sunlight [35]. Thermo-chemical storage systems, in which thermal energy is stored in chemical reactions, overcome this drawback. These chemical reactions usually consist of removing the water of hydration from the hydrated salts. With the thermo-chemical storage systems, the energy can be stored for months. The energy is later recovered by mixing the separated chemical species to get the original product and releasing stored heat. There is heat loss during storage in sensible and latent modes of heat storage. However, in thermochemical storage, there is no loss of heat since salt and water are stored separately [32, 36]. Also, thermochemical storage systems have much higher storage density than latent and sensible heat storage systems. However, the practical application of this technology is limited because it is not yet well developed [32]. Ultimately, SHS requires more volume than LHS and thermo-chemical storage respectively [37, 38].

Depending on the type of application, TES materials are divided into three temperature categories: low-temperature heating (up to 90°C), medium-temperature heating (90°C to 300°C), or high-temperature heating (300°C to 1250°C) [28]. Solar dryers with TES systems are efficient for continuous drying in a steady state at temperatures ranging from 40°C to 60°C [3, 28]. Thus, solar dryers belong to low-temperature applications, and latent heat and sensible heat energy storage systems are adapted for them [32]. SHS materials have been divided into solid and liquid materials for convenience. A solid or liquid material is used because gas has too low specific heat [28]. The following liquids have been widely used as thermal storage materials: water, Water–ethylene glycol, Draw salt, Ethylene glycol, Molten salts, some alcohol (Butanol, Ethanol, Isopentanol), Octane, Therminol 66, Mineral oil, etc. Water is a free and abundant natural resource with a high heat capacity. These make it a popular thermal energy storage system among several applications [32]. The significant advantage of using solids for SHS is that they do not need any particular mechanism for heat exchange between the material and the charging/discharging medium (heat transfer fluid).

On the other hand, the liquid needs better-sealed heat exchangers to avoid leakage. Also, most solids are stable and do not sustain any significant changes under repeated charging and discharging cycles. The use of solids as SHS materials has several advantages, including low cost, absence of leakage, wider range of temperature application, easy to handle, no requirement of freeze protection, and no material loss over time (except corrosion, which is usually slow) and the ability to use locally available materials for energy storage [32, 39]. Globally, it is found in the literature that various naturally available solid materials, such as rock, pebbles, sand, soil, cast iron, cast steel, NaCl, concrete, brick, and volcanic black stones, can store energy by increasing their sensible temperatures [11, 40-42]. The dryer performance showed a satisfactory overall performance improvement compared to the conventional solar air heater without the integrated volcanic black stone storage and collection system [43-46]. However, this storage material has not yet been characterized in terms of its physical properties (volume and particle sizes). Thus, in the present study, the volcanic black stone, known as the pozzolan, is selected and characterized as the thermal storage material for solar dryers. The volcanic black stone used comes from Chad. They have been chosen because of their ease of availability and low cost in many areas of the country.

## 2. Materials and Methods

### *2.1 Materials*

2.1.1 Pouzzolan

Pouzzolan is a natural rock formed from slag (basaltic volcanic projections) or a similar composition. It has a honeycomb structure. Figure 1 shows pozzolan, generally red or black, with all shades in between and exceptionally grey. With a trachytic composition, this porous volcanic rock is used in construction for its thermal and sound insulation qualities. The absorption coefficient of the pozzolan is $\alpha_{stone} = 0.50$, the thermal conductivity: $\lambda_{stone} = 1.65\ W/m^2$ [47].

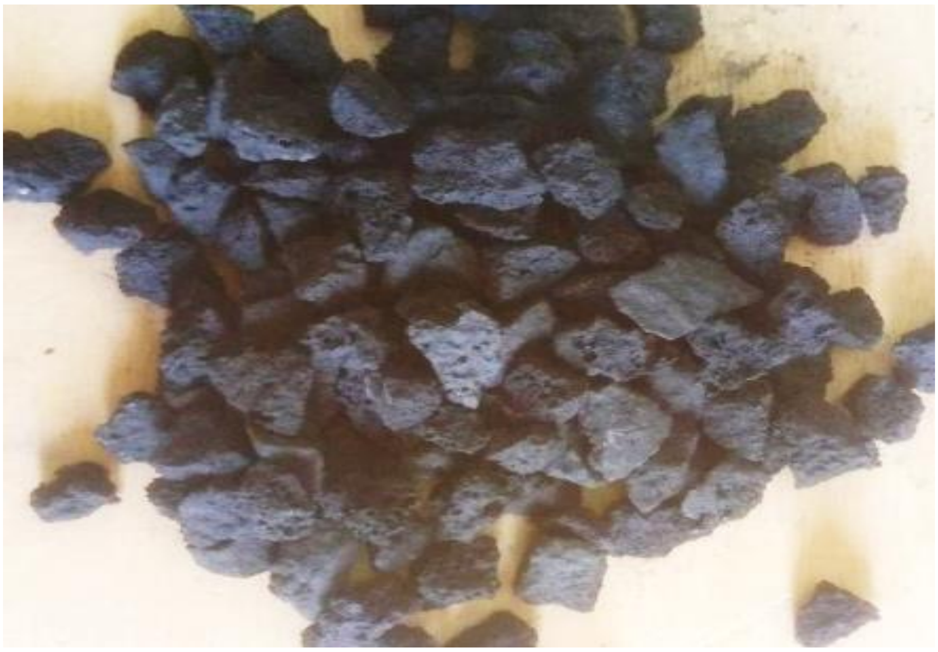


**Figure 1** Pouzzolan.

2.1.2 Measuring Equipment

The devices used to sample and characterize the volcanic stone are listed in Table 1.

**Table 1** Test equipment.

| N° | Designation | Photos | Description |
|---|---|---|---|
| **1** | Pyranometer GSM 0.7 having a measuring range of 0 to 1300 W/m² with an absolute error of ±10% |  | Used to measure irradiance. |
| **2** | Digital scale balance measuring masses from 0 to 600 g with an accuracy of 0.01 g |  | Sensitive scale balance used to measure the mass of different samples |
| **3** | Digital Vernier calliper measuring diameter from 0 to 150 mm with an accuracy of 0.03 mm |  | Digital Vernier to differentiate sample sizes |

| | | | |
|---|---|---|---|
| **4** | ALMEMO® 2690-8, having a precision class AA, a measuring rate of 500 mops, an integrated atmospheric pressure sensor with a measuring range from 700 to 1100 mbar, and an accuracy of ±2.5 mbar (at 23°C ± 5°C) |  | Precision measuring instrument with data acquisition function |

2.1.3 Dryers

The direct solar dryer (DSD) (Figure 2a) and the indirect solar dryer (ISD) (Figure 2b) used in this work are shown in Figure 2. The absorber sensor is placed on the pozzolan under the glass, and the ambient sensor is placed under the dryer. The ISD has two main parts: the drying chamber and the solar collector. The absorber in both cases is the pozzolan. In the DSD, the drying chamber is directly exposed to the sun, and the sun's rays reach the crop and the pozzolan. In the case of ISD, the solar collector containing the pozzolan is essential to convert sunlight into heat, and then the convection mode drives the heated air into the drying room where the crops are sprayed. In both cases, the measuring device (temperature sensor) is on the bed of the pozzolan. The pozzolan was placed in the DSD chamber and the ISD solar thermal collector. The ISD solar collector has a volume of 50 liters and a depth of 10 cm, and the space for the pozzolan in the DSD has a volume of 20 liters and a depth of 8 cm.

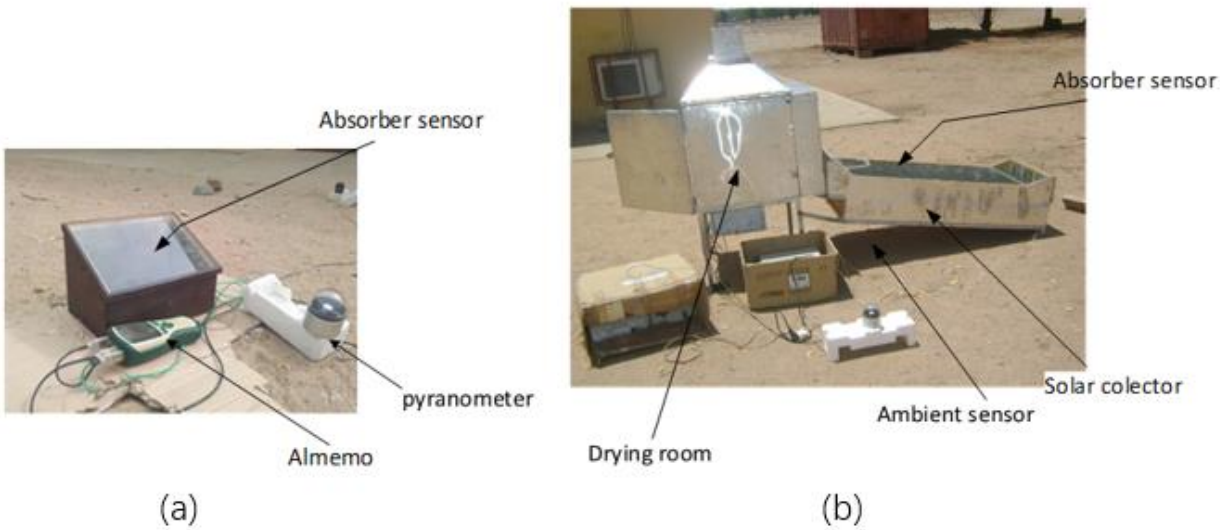



**Figure 2** (a) Direct solar dryer, (b) Indirect solar dryer.

### *2.2 Description of the Method Used*

The method used to sample the black stones is described in Figure 3. The test was carried out from 1st June to 15 August at the Renewable Energies Laboratory of the University of Maroua, Cameroon, situated at 10°35′ North, 14°19′ East. After collection, the stones were crushed and sorted using the Vernier. Three particle sizes were considered: 4 to 8 mm, 8 to 12 mm, and 12 to 16 mm. Dryers containing stones samples were exposed to the sun for three days per sample. Different volumes of stones were used for each particle size and each dryer. This means six sunny days for each sample in the two dryers. The stone volumes for the indirect solar dryer were 12.5 l, 25 l, and

50 l. The stone volumes for the direct solar dryer were 10 l and 20 l. All studied samples ($E_i$) are given in Table 2 for different volumes and sizes of pozzolan particles. Volumes were chosen according to the type of dryer and its capacity. The non-soaked sample represents natural pouzzolan used directly in the dryer, while the soaked sample represents pouzzolan impregnated in matt black before use. During each test, the ambient, outlet, solar collector temperatures, and irradiance were measured every 5 minutes.

**Table 2** Pouzzolan sampling.

| | **Non-soaked sample (mm)** | | | **Soaked sample (mm)** | | |
|---|---|---|---|---|---|---|
| | $4<E_1<8$ | $8<E_2<12$ | $12<E_3<16$ | $4<E_1<8$ | $8<E_2<12$ | $12<E_3<16$ |
| **Sample volume for ISD (*l*)** | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| | 25 | 25 | 25 | 25 | 25 | 25 |
| | 50 | 50 | 50 | 50 | 50 | 50 |
| **Sample volume for DSD (*l*)** | 10 | 10 | 10 | 10 | 10 | 10 |
| | 20 | 20 | 20 | 20 | 20 | 20 |

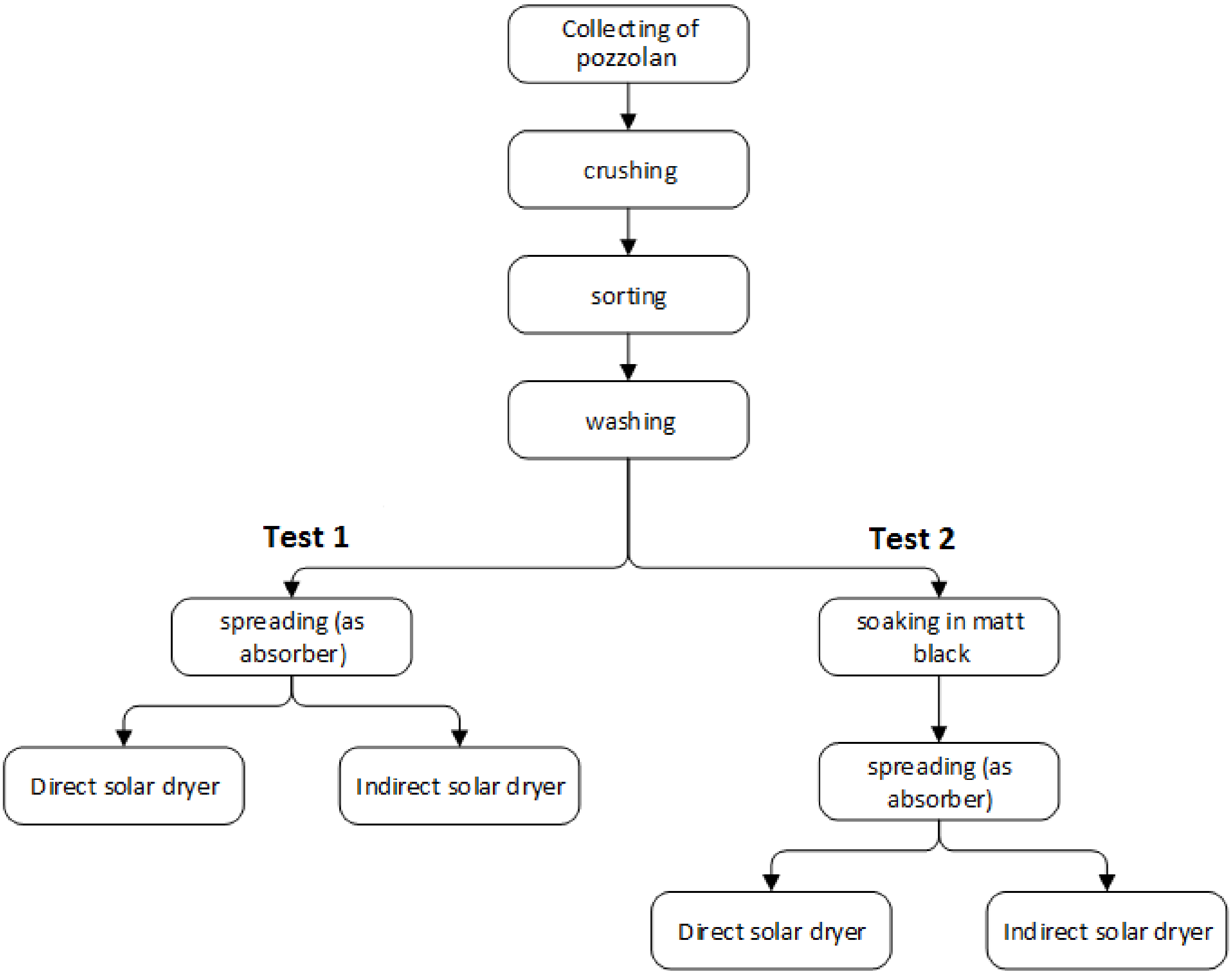



**Figure 3** Sampling Method.

### 2.2.1 Modeling of the Solar Collector

The modeling of the system assumes that the ISD has a solar collector that captures the sun's rays and converts them into heat, whereas the DSD enclosure has its collector built in. Thus, volcanic rock is used as an absorber in the solar collector of both dryers. Figure 4a shows the energy flows, and Figure 4b presents the heat transfer coefficient and temperature, which determines energy exchange in different components. The study evaluates heat absorber behavior. Based on the equations for various heat transfer modes in each system (conduction, convection, and radiation), an energy balance is established considering the accumulation and removal of energy in the thermal collector. In both cases, ISD and DSD have the same model of collector, and equations are written to express the temperature of the absorber, which here is Pouzzolan. Figure 4 shows how the irradiance *I* passes through the glass in both cases and exchanges with the absorber by conduction, convection, and radiation. When performing a heat balance on air, the equation of air temperature at the outlet of the collector $T_n(t)$ can be expressed as a function of time [42], with some simplifying assumptions.

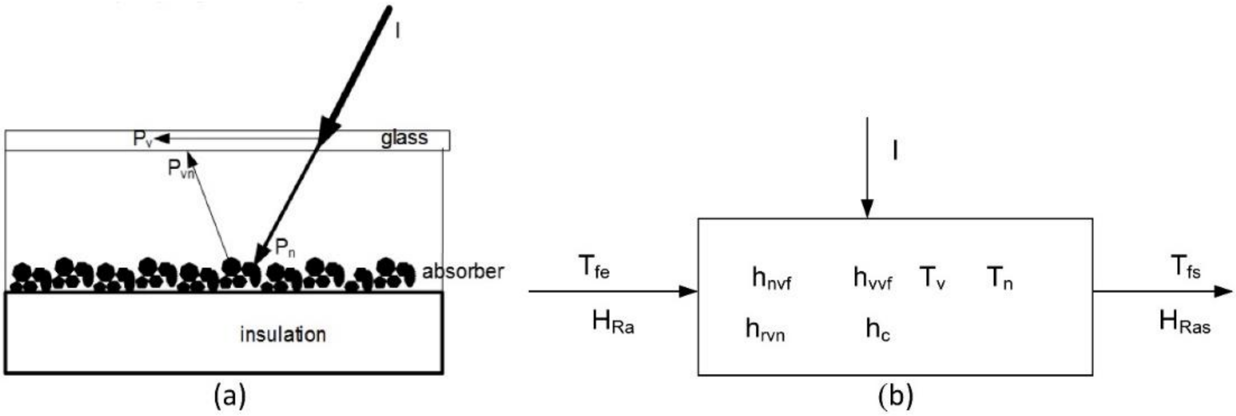



**Figure 4** (a) energy flows and (b) heat transfer diagram in the solar collector.

**Charge equation:**

$$\frac{M_n C_n}{S_n}\frac{dT_n}{dt} = \frac{P_n}{S_n} + h_{rnv}(T_v - T_n) + h_{vnf}\left(T_f - T_n\right) + h_c(T_\mathrm{a} - T_n) \tag{1}$$

**Discharge equation:**

$$\frac{M_n C_n}{S_n}\frac{dT_n}{dt} = h_{rnv}(T_\mathrm{v} - T_n) + h_{vnf}\left(T_f - T_n\right) + h_c(T_\mathrm{a} - T_n) \tag{2}$$

By solving the differential equations (1) and (2), the temperature at the outlet of the solar collector can be determined.

**Charge equation:**

$$T_n(\mathrm{t}) - T_a = \frac{\mathrm{B}}{\mathrm{A}}\left(1 - \mathrm{e}^{\frac{-\mathrm{At}}{\mathrm{M_n C_n}}}\right) \tag{3}$$

**Discharge equation:**

$$T_n(\mathrm{t}) = \frac{\mathrm{B}'}{\mathrm{A}} + \frac{\mathrm{P_n}}{\mathrm{A}}\mathrm{e}^{\frac{-\mathrm{At}}{\mathrm{M_nC_n}}} \tag{4}$$

Constants A, B, $\mathrm{B}'$ and $\tau$ are expressed as:

$$\mathrm{A} = (\mathrm{h_{vvf}} + \mathrm{h_{rnv}} + h_c)\mathrm{S_n} \tag{5}$$

$$\mathrm{B} = (\mathrm{h_{vvf}T_f} + \mathrm{h_{rnv}T_v} + h_c\mathrm{T_a})\mathrm{S_n} + \mathrm{P_n} \tag{6}$$

$$\mathrm{B}' = B - \mathrm{P_n} \tag{7}$$

$$\tau = \frac{\mathrm{M_n}C_\mathrm{n}}{\mathrm{A}} \tag{8}$$

Below are listed the meanings of all parameters contained in equations (1) to (8):
$C_n$: Mass heat capacity of the absorber (J/kg °C);
$h_{rnv}$: Coefficient of heat exchange between the radiation absorber and the glass (W/m$^2$ °C);
$h_{vnf}$: Heat transfer coefficient between the convection absorber and the air (W/m$^2$ °C);
$\mathrm{h_{vvf}}$: Heat transfer coefficient between the convection glass and the air (W/m$^2$ °C);
$h_c$: Heat transfer coefficient by conduction (W/m$^2$ °C);
$H_{Ra}$: Inlet air humidity (%);
$H_{Ras}$: Outlet air humidity (%);
$T_{fe}$: Inlet air temperature (°C);
*I*: Irradiance (W/m$^2$);
$M_n$: Mass of the absorber (kg);
$P_n$: Power absorbed by the absorber (W);
$S_n$: Surface area of the absorber (m$^2$);
t: Time (s);
$T_{fs}$: Outlet air temperature (°C);
$T_\mathrm{a}$: Ambient temperature (°C);
$T_f$: Heat transfer fluid temperature (°C);
$T_{max}$: Maximum temperature reached in the dryer during each charging test (°C);
$T_n$: Absorber temperature (°C);
$T_\mathrm{v}$: Temperature of the glass (°C).

The time constant ($\tau$) is a function of various exchanges and the intrinsic properties of the absorber (pozzolan). It influences how quickly the maximum temperature is reached. Thus, it characterizes the charge and discharge times of the absorber. It describes the capacity of the pozzolan to manage the energy received and dissipated over a given period. For the Pouzzolan, $\mathrm{M_nC_n} = 36950\ W/°C$ [47]. A, B, and B' depend on various exchanges (convection, radiation, and loss in the wood, considered as insulation) and the input irradiance *I* reaching the absorber. To simplify the study of the energy transfer at the collector, the following assumptions were made. The thickness of the glass (3 mm) is negligible, so conduction through the glass can't be considered, and the volcanic rocks form a homogeneous bed.

### 2.2.2 Determination of Storage Parameters

Curves of the air temperature $T(t)$ at the outlet of the thermal collector are plotted from experimental data recorded every 5 minutes during charging and discharging tests on samples. The discharge tests on the samples were carried out during the day and at night. By fitting the curves of the theoretical equations of charge and discharge given above (Equations (3) and (4)) with the experimental one, parameters A, B, and B' of the temperature model in the thermal collector are evaluated. Then, the time constant ($\tau$) is calculated using Equations (8). This fitting was done using the sigmaplot 12 software.

## 3. Results and Discussion

### *3.1 Variation of the Experimental Parameters over Time*

The profiles of the temperature (ambient and internal) of the solar collector and the irradiance as a function of time are shown in Figure 5 for a sunny day. This figure is plotted only to show the almost identical profiles in all the tests. In the case of this day, the irradiance reached 1141 W/m² while the absorber temperature reached 82.7°C. The profile observed on the temperature curve between 1.2 and 6.6 hours shows a slight variation, with the temperature still higher for 5.4 hours despite the increase and decrease in irradiance. This variation at 5.4 h in the absorber temperature can be linked to other meteorological parameters around this period. The absorber temperature depends mainly on the irradiance and other meteorological parameters such as wind speed, ambient humidity, etc. This variation, which is not repeated on other testing days, is not enough to modify the global profile of this temperature depending on the irradiance. Therefore, it can be considered stable, given that the pozzolan is adapted to store thermal energy at low temperatures, as required for solar dryers [31]. These curves fit in two parts according to the charge and discharge areas, as shown in Figure 6. The fitting equation of the absorber temperature during the charging of the pozzolan is:

$$T_c = 14.92 + 64.19(1 - e^{-1.73t}) \tag{9}$$

With: $R^2 = 0.9761$ *and* RMSE: 1.728

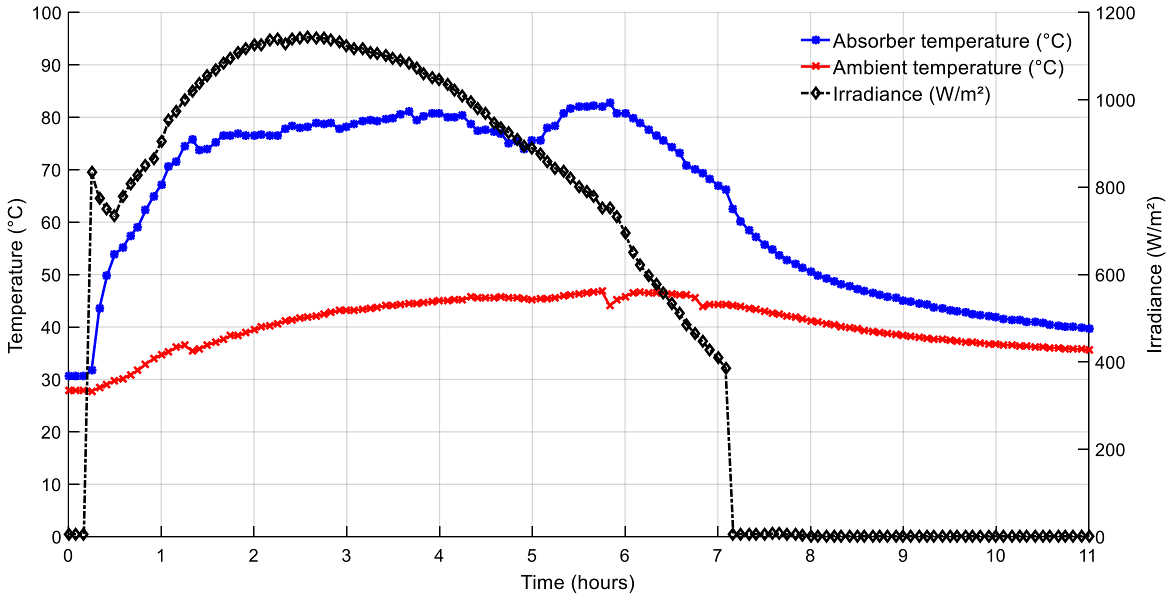
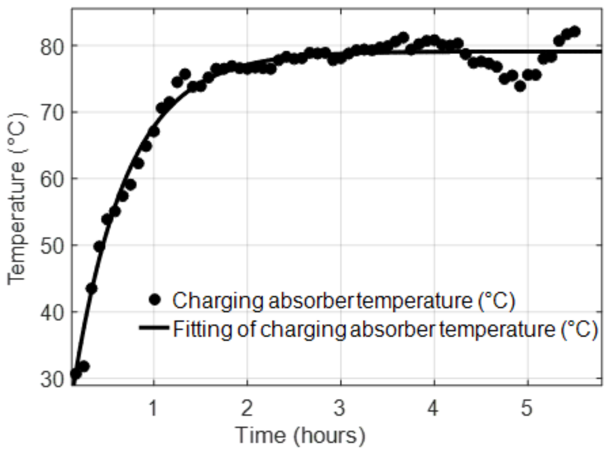
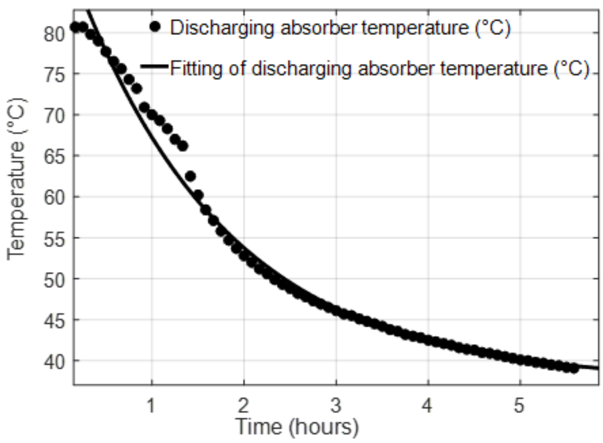



**Figure 5** Profile of internal and ambient temperatures and irradiance for non-soaking sample $E_2$ during a sunny day.




(a) Thermal charging of Pouzzolan




(b) Thermal discharging of Pouzzolan

**Figure 6** Examples of fitting curves of the absorber temperature during charging (a) and discharging (b) of the pozzolan.

The fitting equation of the absorber temperature during the discharging of the pozzolan is:

$$T_d = 37.51 + 54.36e^{-0.60t} \tag{10}$$

With: $R^2 = 0.9985$ *and* RMSE: 0.5157

The equation $T_c$ is compared to equation (3) and $T_d$ is compared to equation (4), and the parameters A, B, and B' of the temperature model in the thermal collector are derived, and finally, the time constant ($\tau$) (equation (8)).

### *3.2 Influence of the Volume of the Samples on the Heat Charging Phase*

3.2.1 Heat Charging Tests of Samples in an Indirect Solar Dryer

For soaked and non-soaked samples in ISD, the time constants $\tau(s)$ calculated for each volume during the heat charge tests of ISD are given in Table 3. *R* is the regression coefficient that fits the curves of the calculated and measured temperatures. $T_{max}$ is the maximum temperature reached in the dryer during each charging test. *R* is greater than 0.90 and 0.95, respectively, for all considered unsoaked and soaked samples. For the two types of samples, the highest τ is obtained for a volume of 25 l corresponding to the sample $E_2$ for non-soaked samples and $E_1$ for soaked ones. It can be concluded that for the best storage of thermal energy, the absorber of the ISD containing non-soaked and soaked samples should not be full and the size of the pozzolans particles should be between 8 and 12 mm for non-soaked samples and between 4 and 8 mm for soaked samples. On the other hand, soaked samples seem more efficient than the non-soaked ones since their best time constant is higher than those of the non-soaked samples. A non-soaked sample with a volume of 12.5 l gives the smallest values of τ. This means that the heat discharge of this sample is too rapid. This volume will no longer be used for soaking samples. Thus, a volume of pozzolan in the dryer collector of less than one-fourth of its total volume is not recommended.

**Table 3** Parameters during charge tests on non-soaked and soaked samples in an indirect solar dryer.

| Sample | Volume (l) | Non-soaked samples | | | Soaked samples | | |
|---|---|---|---|---|---|---|---|
| | | $T_{max}(°C)$ | $\tau(s)$ | *R* | $T_{max}(°C)$ | $\tau(s)$ | *R* |
| $E_1$ | 12.5 | 50.23 | 35.97 | 0.97 | / | / | / |
| | 25 | 78.42 | 123.46 | 0.98 | 71.22 | 713.28 | 0.95 |
| | 50 | 59.46 | 103.09 | 0.90 | 69.24 | 109.00 | 0.99 |
| $E_2$ | 12.5 | 62.93 | 81.97 | 0.99 | / | / | / |
| | 25 | 78.12 | 370.37 | 0.99 | 71.56 | 107.00 | 0.98 |
| | 50 | 76.39 | 111.05 | 0.92 | 78.57 | 48.00 | 0.99 |
| $E_3$ | 12.5 | 75.58 | 31.85 | 0.99 | / | / | / |
| | 25 | 74.95 | 256.41 | 0.99 | 48.60 | 196.00 | 0.98 |
| | 50 | 78.78 | 40.16 | 0.96 | 60.10 | 49.00 | 0.99 |

Non-soaked samples of particle sizes $E_2$ (8 to 12 mm) and $E_3$ (12 to 16 mm) for the volume of 25 l with time constants greater than those for soaked samples, charge longer in the indirect solar dryer. The short charging time of the soaked samples corresponds to the low time constants for particle sizes $E_2$ and $E_3$, maybe because the pores of the pozzolan grains are blocked during a soak in matt black.

3.2.2 Heat Charging Tests of Samples in a Direct Solar Dryer

For non-soaked and soaked samples in DSD, the time constants $\tau(s)$ calculated for each volume during the heat charging tests are given in Table 4. The regression coefficient *R* is greater than or equal to 0.95 for samples without soaking and 0.96 for soaked samples. For all samples, the time constants τ are higher for volumes of 20 l and correspond to the sample $E_1$ for non-soaked samples and $E_3$ for soaked ones. Thus, for the best storage of thermal energy, the particle size of the pozzolans in the collector of the direct solar dryer should be between 4 and 8 mm for non-soaked samples and between 12 and 16 mm for soaked samples. On the other hand, non-soaked samples with particle sizes between 4 and 8 mm are more efficient than the best-soaked samples. For the 20 l volume of pozzolan, non-soaked samples have more significant time constants than soaked samples. Thus, non-soaked samples with a volume of 20 l charge longer than soaked samples in the case of the direct solar dryer.

**Table 4** Parameters during charge tests on non-soaked and soaked samples in a direct solar dryer.

| Sample | Volume (l) | Non-soaked samples | | | Soaked samples | | |
|---|---|---|---|---|---|---|---|
| | | $T_{max}(°C)$ | $\tau(s)$ | *R* | $T_{max}(°C)$ | $\tau(s)$ | *R* |
| $E_1$ | 10 | 59.46 | 49.02 | 0.96 | 48.79 | 89.00 | 0.96 |
| | 20 | 78.42 | 769.23 | 0.99 | 53.28 | 158.00 | 0.99 |
| $E_2$ | 10 | 62.93 | 55.25 | 0.95 | 78.57 | 75.00 | 0.99 |
| | 20 | 81.35 | 250.00 | 0.98 | 44.83 | 116.00 | 0.98 |
| $E_3$ | 10 | 74.95 | 24.39 | 0.99 | 50.71 | 64.00 | 0.98 |
| | 20 | 78.78 | 192.31 | 0.97 | 48.60 | 192.01 | 0.97 |

### *3.3 Influence of the Volume of the Samples on the Heat Discharging Phase*

#### 3.3.1 Heat Discharging Tests of Samples in an Indirect Solar Dryer

The time constants $\tau(s)$ calculated for each volume during heat discharging are given in Table 5 for non-soaked and soaked samples in ISD. The regression coefficient *R* is greater than or equal to 0.95 for samples without soaking and 0.98 for soaked samples. The best storage of thermal energy is obtained during the discharge of the two types of samples for a volume of 25 l corresponding to the sample $E_1$ for non-soaked samples and $E_3$ for soaked ones. The time constant is the highest for that volume and is higher for soaked sample $E_3$ compare to the non-soaked sample $E_1$. The time constants of soaked samples of particle size $E_2$ (8 to 12 mm) and $E_3$ (12 to 16 mm) are higher than those of their non-soaked correspondents. Therefore, it will take more time for these soaked samples to discharge the stored heat in the ISD.

**Table 5** Parameters during discharge tests on non-soaked and soaked samples in an indirect solar dryer.

| Sample | Volume (l) | Non-soaked samples | | | Soaked samples | | |
|---|---|---|---|---|---|---|---|
| | | $T_{am}(°C)$ | $\tau(s)$ | *R* | $T_{am}(°C)$ | $\tau(s)$ | *R* |
| $E_1$ | 12.5 | 27.02 | 49.02 | 0.97 | / | / | / |
| | 25 | 29.29 | 256.41 | 0.97 | 28.87 | 125.00 | 0.997 |
| | 50 | 29.87 | 116.28 | 0.97 | 28.93 | 98.00 | 0.990 |
| $E_2$ | 12.5 | 29.49 | 90.09 | 0.97 | / | / | / |
| | 25 | 29.139 | 142.86 | 0.98 | 29.33 | 200.00 | 0.985 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 30.73 | 114.94 | 0.98 | 30.02 | 188.00 | 0.988 |
| $E_3$ | 12.5 | 31.05 | 121.95 | 0.99 | / | / | / |
| | 25 | 30.38 | 250.00 | 0.95 | 30.59 | 285.00 | 0.999 |
| | 50 | 29.91 | 178.57 | 0.95 | 29.07 | 116.00 | 0.990 |

3.3.2 Samples Heat Discharging Tests in a Direct Solar Dryer

The time constants $\tau(s)$ calculated for each volume during the heat discharging of non-soaked and soaked samples in DSD are given in Table 6. The regression coefficient *R* is greater than or equal to 0.94 for non-soaked samples and 0.97 for soaked samples. For all samples, the time constants τ are higher for volumes of 20 l and correspond to the sample $E_3$ for non-soaked samples and $E_2$ for soaked ones. Increased volume improves the energy dissipation of the solar collector. Thus, for the best storage of thermal energy, the particle size of the pozzolans in the collector of the direct solar dryer should be between 12 and 16 mm for non-soaked samples and between 8 and 12 mm for soaked samples. Soaked samples with particle sizes between 8 and 12 mm are more efficient than the best non-soaked samples. The volume of 10 l in DSD has the lowest value of the time constant in soaking and non-soaking samples compared to the volume of 20 l, resulting from the fact that the depth bed influences the charge and discharge of heat by pozzolan. Soaked samples for volume 20 l and particle size $E_1$ (4 to 8 mm) and $E_2$ (8 to 12 mm) have higher time constants than the non-soaked ones and thus discharge more slowly in the direct solar dryer. This conclusion, which is similar to soaked samples of particle sizes $E_2$and $E_3$ in the indirect solar dryer, shows that soaking pouzzolan grains increases the discharge time of thermal storage material.

**Table 6** Parameters during discharge tests on non-soaked and soaked samples in a direct solar dryer.

| Sample | Volume (l) | Non-soaked samples | | | Soaked samples | | |
|---|---|---|---|---|---|---|---|
| | | $T_{am}(°C)$ | $\tau(s)$ | *R* | $T_{am}(°C)$ | $\tau(s)$ | *R* |
| $E_1$ | 10 | 27.02 | 57.14 | 0.97 | 28.93 | 125.00 | 0.995 |
| | 20 | 29.87 | 133.33 | 0.98 | 28.87 | 166.00 | 0.998 |
| $E_2$ | 10 | 29.29 | 82.64 | 0.96 | 30.02 | 178.00 | 0.988 |
| | 20 | 29.49 | 188.68 | 0.98 | 29.33 | 217.00 | 0.999 |
| $E_3$ | 10 | 31.05 | 54.95 | 0.94 | 30.59 | 109.00 | 0.980 |
| | 20 | 30.38 | 200.00 | 0.97 | 29.07 | 185.52 | 0.970 |

On the other hand, the particle size of the pozzolan influences the time constant value in the indirect solar dryer more than in the direct solar one. This is due to the difference in the heat transfer mode present in the two types of dryers.

## 4. Conclusions

This work aimed to characterize the volcanic black stone (pozzolan) used as thermal storage material based on their physical properties (volume and particle sizes). The pozzolan used comes from Chad. The experiments were carried out on two sample types: soaked in matt black paint and natural (i.e., non-soaked). The main parameters used for that characterization were the time constants of heat charge and discharge of the pozzolan. The results show that the time constant is strongly related to the volume of pozzolan in the collector or to the thickness of the stone bed. Thus, samples with a volume of 25 l, corresponding to half the total volume of the absorber container in the ISD, give the best time constant during heat charge and discharge of the thermal storage material, whether the sample is soaked or not. The same result is observed for the volume of 20 l for the sample in the DSD. This explains the best performance of these solar dryers during heat charge and discharge of the pozzolan. Samples with a volume of 12.5 l (a quarter of the total volume of the absorber container) give bad results for all considered nonsoaking samples during heat charge and discharge in the ISD. Therefore, this volume is not suitable for the required thermal storage material. During the heat charge phase of the pozzolan, with a sample volume of 25 l in the ISD and 20 l in the DSD, the time constant is higher for non-soaked samples than for soaked samples. It means that a non-soaked sample of pozzolan stores heat more than the soaked one for these volumes in the considered solar dryers. Thus, soaking does not increase the value of the time constant in the considered solar dryers during the charging of pozzolan. This can be explained by the fact that the pores of pozzolan, responsible for the easy heat exchange, are blocked by the matt black paint in the soaked samples. During the heat discharge phase, the time constants are greater for soaked samples with particle sizes of 8 to 12 mm and 12 to 16 mm in the ISD and 4 to 8 mm and 8 to 12 mm in the DSD than for non-soaked samples of the same particle size. As a result, these soaked samples discharge more slowly than non-soaked samples for these particle sizes in the considered solar dryers.

## Abbreviations

| | |
|---|---|
| DSD | Direct solar dryer |
| FAO | Food and Agriculture Organization |
| ISD | Indirect solar dryer |
| LHS | Latent heat storage |
| PCM | Phase change materials |
| RMSE | Root Mean Square Error |
| SDG | Sustainable Development Goals |
| SHS | Sensible heat storage |
| TES | Thermal energy storage |

## Author Contributions

All people who met the authorship criteria are listed as authors, and all authors have certified that they have participated sufficiently in the work to assume public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certified that this material or similar material has not been and will not be submitted or published in any other publication prior to its appearance in the special issue of the Journal of Energy and Power Technology (JEPT): Thermal Energy Storage and Energy Engineering. Specifically, E. Tchoffo Houdji, G. B. Tchaya, and Danwe Raidandi conceived the present idea. M. Boukar, E. Tchoffo Houdji, and D.V. Tchuindjang Kwatchie developed the theory and performed the experimentations. E. Tchoffo Houdji, G. B. Tchaya, and Danwe Raidandi verified the analytical methods and supervised the findings of this work. M. Boukar, E. Tchoffo Houdji, and D.V.

Tchuindjang Kwatchie wrote the manuscript under the supervision of G. B. Tchaya and Danwe Raidandi. All authors discussed the results and contributed to the final manuscript.

**Funding**

This research did not receive external funding.

**Competing Interests**

The authors have declared that no competing interests exist.

**Data Availability Statement**

The data used in this article come from experiments and the solution of the mathematical equations of the models of the systems under consideration. They are available in the article, and the corresponding author can give more clarifications if necessary upon request.

**References**

1. Katila P, Colfer CJ, De Jong W, Galloway G, Pacheco P, Winkel G. Sustainable development goals. Cambridge, UK: Cambridge University Press; 2019.
2. Das S, Biswas A, Das B. A review on solar drying applications using latent heat as energy storage media. In: Recent advances in mechanical engineering. Singapore: Springer Nature; 2021. pp. 305-317.
3. Kant K, Shukla A, Sharma A, Kumar A, Jain A. Thermal energy storage based solar drying systems: A review. Innov Food Sci Emerg Technol. 2016; 34: 86-99.
4. Sharma VK, Colangelo A, Spagna G. Experimental investigation of different solar dryers suitable for fruit and vegetable drying. Renew Energy. 1995; 6: 413-424.
5. Kaviti AK, Deep H. Thermal energy storage in solar dryer. In: Solar drying technology: Concept, design, testing, modeling, economics, and environment. Singapore: Springer; 2017. pp. 603-617.
6. Goni S, Adannou HA, Diop D, Drame MS, Tikri B, Barka M, et al. Long-term variation of sunshine duration and their inter-action with meteorogical parameters over Chad, Central Africa. Nat Resour. 2019; 10: 47-58.
7. Soulouknga MH, Coulibaly O, Doka SY, Kofane TC. Evaluation of global solar radiation from meteorological data in the Sahelian zone of Chad. Renew Wind Water Solar. 2017; 4: 4.
8. Hamda Soulouknga M, Pishkar I, Kaoga Kidmo D, Jahangiri M. Estimation and mapping of the global component of solar radiation and wind power density over Chad. J Simul Anal Novel Technol Mech Eng. 2023; 15: 39-49.
9. Bank W. Chad growth and diversification leveraging export diversification to foster growth: Leveraging export diversification to foster growth. Washington, DC: World Bank; 2019; No: AUS0000826.
10. Nilsson E, Uvo C. Nonlinear dynamics in agricultural systems in Chad. Afr Geogr Rev. 2020; 39: 1-27.
11. Srinivasan G, Rabha DK, Muthukumar PJ. A review on solar dryers integrated with thermal energy storage units for drying agricultural and food products. Sol Energy. 2021; 229: 22-38.

12. Ramirez C, Palacio M, Carmona M. Reduced model and comparative analysis of the thermal performance of indirect solar dryer with and without PCM. Energies. 2020; 13: 5508.
13. Fernandes L, Tavares PB. A review on solar drying devices: Heat transfer, air movement and type of chambers. Solar. 2024; 4: 15-42.
14. Reyes A, Mahn A, Vásquez F. Mushrooms dehydration in a hybrid-solar dryer, using a phase change material. Energy Convers Manag. 2014; 83: 241-248.
15. Dorouzi M, Mortezapour H, Akhavan HR, Moghaddam AG. Tomato slices drying in a liquid desiccant-assisted solar dryer coupled with a photovoltaic-thermal regeneration system. Sol Energy. 2018; 162: 364-371.
16. Aktaş M, Ceylan İ, Yilmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. Desalination. 2009; 239: 266-275.
17. Daghigh R, Ruslan MH, Sulaiman MY, Sopian K. Review of solar assisted heat pump drying systems for agricultural and marine products. Renew Sustain Energy Rev. 2010; 14: 2564-2579.
18. Borah A, Hazarika K, Khayer SM. Drying kinetics of whole and sliced turmeric rhizomes (Curcuma longa L.) in a solar conduction dryer. Inf Process Agric. 2015; 2: 85-92.
19. Mohajer A, Nematollahi O, Joybari MM, Hashemi SA, Assari MR. Experimental investigation of a hybrid solar drier and water heater system. Energy Convers Manag. 2013; 76: 935-944.
20. Boateng ID. A review of solar and solar-assisted drying of fresh produce: State of the art, drying kinetics, and product qualities. J Sci Food Agric. 2023; 103: 6137-6149.
21. Chua KJ, Chou SK. Low-cost drying methods for developing countries. Trends Food Sci Technol. 2003; 14: 519-528.
22. Babalis S, Papanicolaou E, Belessiotis V. Fundamental mathematical relations of solar drying systems. In: Solar drying technology: Concept, design, testing, modeling, economics, and environment. Singapore: Springer; 2017. pp. 89-175.
23. Senthil R, Vijayan G, Phadtare G, Gupta B. Performance enhancements of solar dryers using integrated thermal energy storage: A review. In: International Conference on Recent Advancements in Mechanical Engineering. Singapore: Springer Nature; 2020. pp. 355-362.
24. Jain A, Kumar A, Shukla A, Sharma A. Development of Phase Change Materials (PCMs) for solar drying systems. In: Solar drying technology: Concept, design, testing, modeling, economics, and environment. Singapore: Springer; 2017. pp. 619-633.
25. Hamdan M, Abdelhafez E, Ajib S, Sukkariyh M. Improving thermal energy storage in solar collectors: A study of aluminum oxide nanoparticles and flow rate optimization. Energies. 2024; 17: 276.
26. Vásquez J, Reyes A, Mahn A, Cubillos F. Experimental evaluation of fuzzy control solar drying with thermal energy storage system. Dry Technol. 2016; 34: 1558-1566.
27. Krishnan S, Sivaraman B. Experimental investigations on thermal storage in a solar dryer. Int Energy J. 2017; 17: 23-36.
28. Angula JP, Inambao FL. Optimization of solar dryers through thermal energy storage: Two concepts. Int J Eng Res Technol. 2020; 13: 2803-2813.
29. Bal LM, Satya S, Naik SN. Solar dryer with thermal energy storage systems for drying agricultural food products: A review. Renew Sustain Energy Rev. 2010; 14: 2298-2314.
30. Mofijur M, Mahlia TM, Silitonga AS, Ong HC, Silakhori M, Hasan MH, et al. Phase change materials (PCM) for solar energy usages and storage: An overview. Energies. 2019; 12: 3167.

31. Fikri MA, Suraparaju SK, Samykano M, Pandey AK, Rajamony RK, Kadirgama K, et al. Enhanced thermal properties of phase change materials through surfactant-functionalized graphene nanoplatelets for sustainable energy storage. Energies. 2023; 16: 7668.
32. Mishra L, Sinha A, Majumder P, Gupta R. Energy storage using sensible heat storage media: Thermal and economic considerations. In: Recent advances in mechanical engineering. Singapore: Springer; 2021. pp. 41-50.
33. Latifa EK, Asbik M, Zari N, Zeghmati B. Experimental study of the sensible heat storage in the water/$TiO_2$ nanofluid enclosed in an annular space. Appl Therm Eng. 2017; 122: 673-684.
34. Eslami M, Bahrami MA. Sensible and latent thermal energy storage with constructal fins. Int J Hydrog Energy. 2017; 42: 17681-17691.
35. Bal LM, Satya S, Naik SN, Meda V. Review of solar dryers with latent heat storage systems for agricultural products. Renew Sustain Energy Rev. 2011; 15: 876-880.
36. Prieto C, Blindu A, Cabeza LF, Valverde J, García G. Molten salts tanks thermal energy storage: Aspects to consider during design. Energies. 2023; 17: 22.
37. Prasant, Roy S, Das B, Debbarma S. Experimental evaluation of sand-based sensible energy storage system. In: Recent advances in mechanical engineering. Singapore: Springer; 2021. pp. 563-572.
38. Hadorn JC. Advanced storage concepts for active solar energy—IEA SHC Task 32 2003-2007. In: Eurosun 1st International Conference on Solar Heating, Cooling and Buildings. Lisbon: Sociedade Portuguesa de Energia Solar (SPES); 2008. pp. 1-8.
39. Odenthal C, Steinmann WD, Eck M. The CellFlux concept as an alternative solution for sensible heat storage. Energy Procedia. 2015; 69: 957-967.
40. Koçak B, Fernandez AI, Paksoy H. Review on sensible thermal energy storage for industrial solar applications and sustainability aspects. Sol Energy. 2020; 209: 135-169.
41. Tchaya GB, Kamta M, Havet M, Kapseu C. Thermal performance modelling of solar collector with heat storage. Int J Eng Syst Model Simul. 2017; 9: 53-62.
42. Naik NC, Priya RK, Ağbulut Ü, Gürel AE, Shaik S, Alzaed AN, et al. Experimental and numerical analysis of the thermal performance of pebble solar thermal collector. Heliyon. 2024; 10: e24218.
43. Islam MP, Morimoto T. Evaluation of a new heat transfer and evaporative design for a zero energy storage structure. Sol Energy. 2015; 118: 469-484.
44. Tchaya GB, Tchami JH, Kamta M, Kapseu C. Solar energy storage in an indirect solar dryer (ISD) with stone for drying in continuous. J Sol Energy Res. 2018; 3: 81-85.
45. Bilal A, Jamil B, Haque NU, Ansari MA. Investigating the effect of pumice stones sensible heat storage on the performance of a solar still. Groundw Sustain Dev. 2019; 9: 100228.
46. Tchaya GB, Tchoffo Houdji E, Tchami JH, Kapseu C, Kamta M. Regulation of temperature on multitrays in an indirect solar dryer (ISD) with energy storage and three airflow modes. J Eng. 2021; 2021: 6668095.
47. Tchaya GB, Kapseu C, Kamta M. Séchoir solaire indirect variable: Conception Régulation Modélisation. Saarbrücken, DE: Éditions universitaires européennes; 2019.