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Experimental comparison of erythritol and erythritol-granite pebble mixtures as heat storage materials for solar cooking

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Abstract

In this article, a comparison is presented between a pure latent heat storage system (erythritol) and a mixed storage system consisting of equal mass ratios of erythritol and granite pebbles (5 – 10 mm) for a solar cooking application. Two small black stainless cooking pots with a capacity of 1 L were placed inside two larger 5 L cooking pots to form simple storage cooking pots. The space between the pots was filled with thermal energy storage (TES) material. In the first configuration, the space between the pots was filled with 2 kg of erythritol. In the second configuration, the storage system consisted of 1 kg of erythritol and 1 kg of granite pebbles in the same space. The first experimental tests involved charging the storage cooking pots without any load for 4 h, followed by discharging them using heating loads in insulated wonder bags to evaluate off-sunshine cooking performance for another 4 h. The second experimental test involved simultaneous cooking and heat storage alternating between charging and discharging cycles. Experimental results showed that the mixed storage system achieved higher temperatures than the erythritol storage system during charging without cooking. During discharging cycles, the heat utilization rate was faster for the mixed storage system than for the erythritol storage system. Both storage systems enabled the cooking of multiple meals within an 8-h cooking period. However, at the end of the experiments, the erythritol storage system retained higher temperatures than the mixed storage system. Future work will focus on characterizing the thermophysical properties of the mixed storage system, optimizing the erythritol-to-granite mixing ratio for improved thermal performance, and investigating alternative, locally available TES materials – such as sandstone, marble, limestone, and xylitol – for potential use in mixed storage systems.

Keywords: Erythritol; Granite; Heat storage materials; Solar cooking

1. Introduction

Solar cooking is an environmentally friendly cooking method that produces no greenhouse gas emissions.[1] It is particularly suitable for developing regions, where biomass is the primary fuel source for cooking, often leading to adverse health effects due to smoke inhalation. The four major types of solar cookers are solar box cookers (oven cookers), panel cookers, concentrating cookers, and indirect cookers.[2] However, a

common limitation of all solar cookers is their inability to function effectively during cloudy or overcast conditions.[2] In addition, solar cookers cannot operate at night, making it challenging to prepare evening meals. Therefore, integrating thermal energy storage (TES) is essential to enable cooking during periods of low and no sunshine.

Recent research has focused on incorporating TES with various solar cookers,[3-5] including box solar cookers, indirect solar cookers,[6-8] and concentrating solar cookers,[9-11] to enhance performance under cloudy or nighttime conditions. Among these, concentrating solar cookers, particularly parabolic dish solar cookers, are the most efficient in terms of cooking speed and temperature.[2,12,13] Parabolic dish solar cookers are relatively low-cost, and an effective way to improve their performance during non-sunshine periods is to integrate TES directly into the cooking vessel, as reported in recent work.[14-16] The two main types of TES materials used in parabolic dish solar cookers are sensible heat storage materials (SHSMs) and latent heat storage materials (LHSMs), also referred to as phase change materials (PCMs). SHSMs are cost-effective and widely available but have low energy storage density. LHSMs provide higher energy storage density but are expensive when used in large quantities. In addition, LHSMs have low thermal conductivity, which results in slower heat absorption. Table 1 presents a comparative literature review of previous recent work conducted between 2020 and 2024 on solar cookers with SHSMs and LHSMs. Research has investigated various types of TES-integrated solar cookers, including box, parabolic dish, indirect, and photovoltaic-based cookers. Table 1 highlights that most studies have focused on latent heat storage systems,[3,4,7-11,17,18] with erythritol emerging as the preferred LSHM[3,4,9,17,18] due to its phase transition temperature (120°C), which is close to the boiling point of water. When comparing sensible and latent heat storage systems in different solar cookers, latent heat storage systems consistently achieved higher cooking temperatures. However, one notable exception is the sensible heat storage system using thermal oil developed by El Moussaoui et al.,[6] which demonstrated the highest cooking temperatures and the shortest cooking time (0.33 h) – a result comparable to that of Bhave and Kale,[10] where rice was cooked within the same duration. Most recent TES-integrated solar cooker studies have used water as the cooking load,[4,5,7-9,19-21] while fewer studies have conducted practical food cooking tests.[6,8,10,17] The cooking loads used in different studies ranged from 0.37 to 3.89 kg, whereas the storage mass varied from 1.33 to 20 kg. The literature review reveals a significant research gap: very limited work has been conducted on mixed storage systems (latent and sensitive) for solar cookers.

A feasible way to capitalize on the advantages of both SHSM and LHSM is to combine them in a directly mixed/combined storage system. However, research on mixed/combined storage systems for storage cooking pots remains limited,[22,23] especially regarding the direct mixing of SHSM and LHSM in equal mass ratios to reduce storage costs. Granite is a cheap and readily available SHSM, whereas erythritol is a food-grade PCM that has been increasingly used in solar cookers in recent years.[9,17,24]

Erythritol has been extensively studied as a heat storage material for solar cooking applications due to its non-toxic, food-grade nature and high latent heat of fusion. It is also widely available worldwide, mainly as a sugar substitute for people with diabetes. For example, Coccia et al.,[3] used erythritol as the PCM in a portable box solar cooker. Their experimental results showed that erythritol-based TES extended the average load cooling time in the 100 – 125°C range by approximately 351.16% compared to the case without erythritol. Anilkumar et al.,[4] compared three PCMs (erythritol, magnesium chloride hexahydrate, and acetanilide) as TES materials for a solar box cooker. Among these, erythritol, which had the lowest storage mass, was recommended as the most effective PCM. Mawire et al.,[17] compared storage cooking pots using sunflower oil and erythritol as heat storage materials. Erythritol outperformed sunflower oil in terms of stored heat utilization during cooking. Khatri et al.,[9] compared pebbles, stearic acid, and erythritol as heat storage media for storage cooking pots used with parabolic dish solar cookers. Their results showed that erythritol exhibited the highest energy and exergy efficiencies – 52% and 37%, respectively – compared to the other two storage media.

Due to its low-cost, non-toxic nature, and availability, granite has been increasingly used as a TES medium in solar thermal applications in recent years.[25-29] For instance, Li and Ju[25] investigated the thermal cycling performance of granite for concentrated solar power and found that it was a suitable TES material after undergoing multiple thermal cycles. Lugolole et al.[26] demonstrated that small granite pebbles (10.5 mm) outperformed larger pebbles (31.9 mm) in charging efficiency within an oil-packed bed system. In a separate study, Lugolole et al.[27] showed that adding granite pebbles to an oil/pebble bed TES system significantly enhanced the discharging performance of the oil storage system. Saxena et al.[28] compared solar cookers using three different storage materials: blackened granite pebbles, small masonry bricks, and small aluminum balls. Although aluminum balls exhibited the best thermal performance, blackened granite pebbles performed comparably well. Zhang et al.,[29] further found that natural granite stones could enhance heat transfer in a hybrid sensible-latent heat TES system, improving overall efficiency.

Table 1. A summary comparison of recent work (2020 – 2024) on solar cookers with thermal energy storage

Studies	Type of solar cooker	Type of storage material	Storage material	Mass of storage material (kg)	Type of cooking load	Mass of cooking load (kg)	Load cooking temperatures (°C)	Storage cooking time (h)
Coccia et al.[3]	Box	Latent	Erythritol	2.50	Silicone oil	1.50	55 – 125	2.50
Anilkumar et al.[4]	Box	Latent	Erythritol	1.50	Water	1.00	25 – 100	3.00
Goyal and Eswaramoorthy[5]	Box	Sensible	Marble	5.00	Water	1.50	27 – 67	0.50
Verma et al.[19]	Box	Sensible	Marble	15.00	Water	2.00	25 – 100	1.35
El Moussaoui et al.[6]	Indirect-parabolic trough	Sensible	Thermal oil	Not mentioned	Cooking oil; fries	1.00; 1.00	101 – 190	0.33
Tawfik et al.[7]	Indirect-box cooker with bottom reflector	Latent	Paraffin wax	1.33	Water	3.89	75 – 82	1.00
Getnet et al.[8]	Indirect-flat plate with reflectors	Latent	Stearic acid	20	Water	3.00	30 – 95	0.50
Khatri et al.[9]	Parabolic dish	Latent	Erythritol	2.00	Water	2.00	30 – 100	1.67
Bhave and Kale[10]	Parabolic dish	Latent	Solar salt	2.23	Rice, water	0.13 for rice; 0.25 for water	30 – 100	0.33
Senthil[11]	Parabolic dish	Latent	Paraffin wax	Not mentioned	Water	1.00	30 – 65	2.00
Mawire et al.[17]	Parabolic dish	Latent, sensible	Erythritol, sunflower oil	5.44, 3.44	Rice and potatoes, water	0.90, 0.90	25 – 93, 25 – 87	1.70
Dev et al.[20]	PV based with TES	Sensible	Aluminum	7.00	Water	2.00	25 – 96	0.92
Osei et al.[21]	PV based with TES	Latent	Erythritol	2.50	Water	1.50	20 – 100	1.50

Abbreviations: PV: Photovoltaic; TES: Thermal energy storage.

Although recent studies have explored granite and erythritol in storage cooking pots, no research has been reported on directly combining granite and erythritol for a mixed storage system in storage cooking pots. The major innovation and novelty of this study lies in developing and evaluating a mixed storage system using equal mass ratios of granite and erythritol. The key benefits of this mixed storage system include reduced storage costs due to the incorporation of granite, improved thermal conductivity due to granite's high conductivity compared to LHSMs, and increased energy storage density due to erythritol's latent heat properties.

This study compares a pure LHSM (erythritol) with a mixed storage system consisting of equal mass ratios of erythritol and granite pebbles (5 – 10 mm) for a solar cooking application. Two small black stainless steel cooking pots with a capacity of 1 L were placed inside two larger 5 L cooking pots to create simple storage cooking pots. The space between the pots was filled with TES material.

In the first configuration, this space was entirely filled with 2.0 kg of erythritol. In contrast, the second configuration contained 1.0 kg of erythritol and 1.0 kg of granite pebbles. The experiments were conducted using different food items to assess the practical application of these storage cooking pots. This approach contrasts with the common practice of boiling water or another homogenous fluid to evaluate thermal performance, which is beyond the scope of this study. The findings will contribute to understanding the performance of directly mixed combined TES materials in solar storage cooking pots, an area with limited existing literature.

2. Materials and methods

2.1. Experimental method

The cooking experiments were conducted using two 1.2 m parabolic dish solar cookers, as recently reported by Mawire *et al.*[17,24] Figure 1 shows the parabolic dish solar cooker and further details are available in Mawire *et al.*[17] The reflective surface area of the solar cooker is approximately 1.13 m², with a focal point diameter of 60 mm and a total weight of 12.0 kg. During cooking tests, the solar cookers were manually tracked every 15 min optimize solar exposure while simultaneously cooking food and storing thermal energy.

The storage cooking pots consisted of two small black stainless cooking pots (1 L capacity) placed inside two larger stainless steel pots (5 L capacity), forming simple storage cooking pot systems. The space between the inner and outer pots was filled with TES material. In the first configuration, the space was entirely filled with 2.0 kg of erythritol. In contrast, the second storage configuration contained 1.0 kg of erythritol and 1.0 kg of granite pebbles

(5 – 10 mm in diameter). Figure 2 displays the open-storage cooking pot configurations before testing, while Figure 3 shows the closed-storage cooking pots before final assembly. The dimensions of the cooking pots and the thermal properties of the storage materials are provided in Table 2. Notably, Storage Cooking Pot 1 functions as a purely latent heat cooking system, utilizing only erythritol.

Storage Cooking Pot 2 is a mixed TES system, consisting of erythritol and granite pebbles in equal mass ratios

Figure 1. The 1.2 m parabolic dish solar cooker used in the cooking experiments
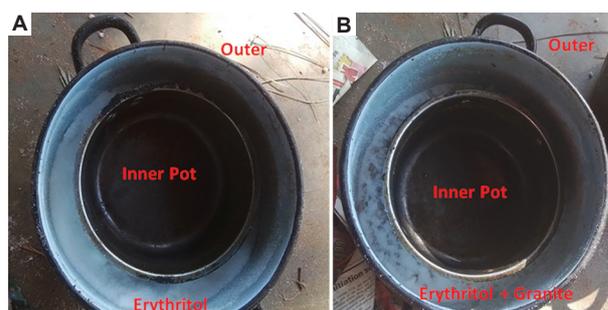

Figure 2. (A) The open inner and outer pots using 2.0 kg of erythritol as the storage material, and (B) the inner and outer pots-containing a mixture of 1.0 kg of erythritol and 1.0 kg of granite pebbles.
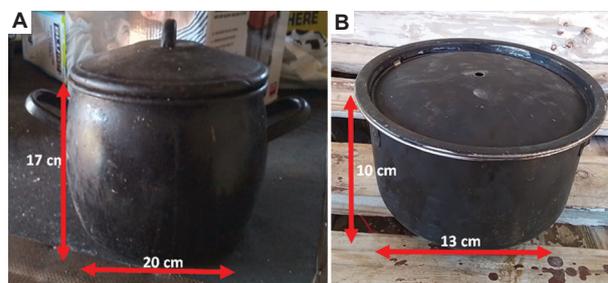

Figure 3. (A) The 5 L closed larger outer pot with dimensions. (B) The 1 L closed smaller inner pot with dimensions.

Table 2. Dimensions of storage cooking pots and thermal properties of thermal energy storage materials

Parameter	storage cooking pot 1	storage cooking pot 2
Diameter of the inner pot (m)	0.130	0.130
Diameter of the outer pot (m)	0.200	0.200
Height of the inner pot (m)	0.100	0.100
Height of the outer pot (m)	0.170	0.170
Volume of the inner pot (m³)	0.001	0.001
Volume of the outer pot (m³)	0.005	0.005
Material of inner and outer pots	Stainless steel	Stainless steel
Storage material	Erythritol	Erythritol, Granite
Storage mass (kg)	2.000	1.000 (Erythritol), 1.000 (Granite)
Thermal conductivity of storage material (W/mK)	0.733 (20°C), 0.326 (140°C)[17]	Erythritol: 0.733 (20°C), 0.326 (140°C)[17]; Granite: 2.120 – 3.120[30]
Specific heat capacity of storage material (kJ/kg·K)	1.380 (20°C), 2.760 (140°C)[17]	Erythritol: 1.380 (20°C), 2.760 (140°C)[17]; Granite: 0.798[26]
Phase change enthalpy of storage material (kJ/kg)	310.6[17]	Erythritol: 310.6[17]; Granite: N/A

(granite pebbles: 5 – 10 mm diameter). To measure food and storage material temperatures, two K-type thermocouples (accuracy of ± 2°C) were placed in each storage cooking pot during both solar and storage cooking experiments. Each storage cooking pot configuration had two thermocouples placed at almost the same positions. The first thermocouple for measuring the storage temperature was placed on the left-hand side inside the larger pot, approximately 2 cm from the top of the storage materials. The second thermocouple was placed flat at the bottom of the inner storage cooking pot. It is also essential to state that these thermocouples moved slightly while manually tracking the parabolic dish. Since this was a do-it-your-design, which anyone with moderate technical ability could implement, it was unnecessary to weld the thermocouples at fixed positions in the cooking pots. The idea was to get a general overview of the cooking process temperatures inside the storage and cooking pots inside of highly accurate readings. In addition, food is inherently non-homogenous, making identical temperature readings impossible. Solar radiation variability further affects thermal profiles. However, to ensure reproducibility, preliminary tests were conducted twice before cooking experiments, using 500 g of water under similar solar radiation conditions. The observed deviation in temperature profiles was <5°C, confirming the consistency of the experimental setup.

The experiments involved two cooking methods: solar cooking and storage cooking. Solar cooking was conducted using direct sunlight; while storage cooking was performed using insulated wonder bag cookers, as described in our previous work.[17] For storage cooking, the preheated storage cookers were placed inside insulated wonder bag slow cookers to assess heat retention and cooking performance. The experiments were conducted in Mahikeng, North-West

province, South Africa. The study consisted of two main experimental setups. In the first experiment, the storage cooking pots were charged without any load for 4 h, after which they were discharged over another 4-h period, using heating loads in insulated wonder bags to evaluate off-sunshine cooking performance. The heating loads consisted of actual food, allowing for the assessment of practical cooking conditions. In the second experiment, the storage cooking pots were charged while simultaneously cooking, following alternative charging and discharging cycles over a 10-h period. Temperature profiles of the storage cooking pots were measured using four K-type thermocouples connected to a portable Sefram DAS240BAT datalogger, powered by a rechargeable lithium-ion battery[31] (R.S. Online, France). The thermocouples were connected to four channels of a 20-channel expansion module, which was connected to the data logger. Ambient temperature was measured using a fifth K-type thermocouple, connected to an additional channel of the 20-channel expansion module. Temperature data was recorded at a 10-s interval throughout the experiments. In addition, a Kipp and Zonen CMP11 pyranometer (Campbell Scientific, Netherlands),[32] which had an accuracy of ±10 W/m². The pyrometer was also connected to one of the channels of the 20-channel expansion module.

2.2. Thermal analysis

During the charging process without any load, the first figure of merit is expressed as[18]:

$$F_1 = \frac{T_{abs} - T_{amb}}{I_{av}} \tag{I}$$

Where T_{abs} is the stagnation temperature of the absorber (empty pot in this case), T_{amb} is the ambient temperature,

and I_{av} is the average solar radiation. Average values at the end of the heating tests were used in the calculations. The total incident solar energy on the dish aperture during the solar cooking period is estimated as[17]:

$$Q_{inc} = I_{av} A_C \Delta t A_C \qquad (II)$$

Where A_C is the dish aperture area estimated from the diameter of the dish area (1.13 m^2), and Δt is the charging time interval (4 h [14,400 s] for Test 1; around 2 h [7,200 s] for Test 2). For the erythritol-based storage system, the energy stored during the solar cooking period is given by[17]:

$$Q_{ste} = m_e c_e (T_{fe} - T_{ie}) \qquad (III)$$

Where m_e is the mass of erythritol, C_e is the specific heat capacity of erythritol, and T_{fe} and T_{ie} are the final and initial erythritol storage temperatures, respectively. For the mixed storage system (erythritol + granite), the stored energy is expressed as:

$$Q_{stmix} = m_e c_e \left(T_{fmix} - T_{imix} \right) + m_g c_g \left(T_{fmix} - T_{imix} \right) \qquad (IV)$$

Where m_g is the mass of granite, C_g is the specific heat capacity of granite, and T_{fmix} and T_{imix} are the final and initial mixed storage temperatures, respectively. The storage efficiency (η_{st}) without any heating load is estimated as the ratio of stored energy to the total incident solar energy. For the erythritol and mixed storage systems, this is given by:

$$\eta_{ste} = \frac{Q_{ste}}{Q_{inc}} , and \; \eta_{stmix} = \frac{Q_{stmix}}{Q_{inc}} \qquad (V)$$

The heat energy of the cooking load is expressed as[17]:

$$Q_{food} = \sum_{i-1}^{N} m_{fd} c_{fd} \left(T_{fdf} - T_{fdi} \right) \qquad (VI)$$

Where m_{fd} is the mass of each food and the cooking fluid in the pot, c_{fd} is the specific heat capacity of each food item and cooking fluid, T_{fdf} is the final maximum temperature of the food and cooking fluid before phase transitions, and T_{fdi} is the initial temperature of the food and cooking fluid.

During storage cooking, the storage cooking efficiency/heat utilization efficiency (η_{stcook}) is defined as the ratio of total heat delivered to the cooking fluid and food to the initial stored energy[17]:

$$\eta_{stcooke} = \frac{Q_{food}}{Q_{ste}} , and \; \eta_{stcookmix} = \frac{Q_{food}}{Q_{stmix}} \qquad (VII)$$

3. Results and discussion

The experimental results from the test conducted on March 10, 2024, are presented in Figure 4. The experiment lasted 8 h (10:00 – 18:00 local time) and was divided into distinct phases:
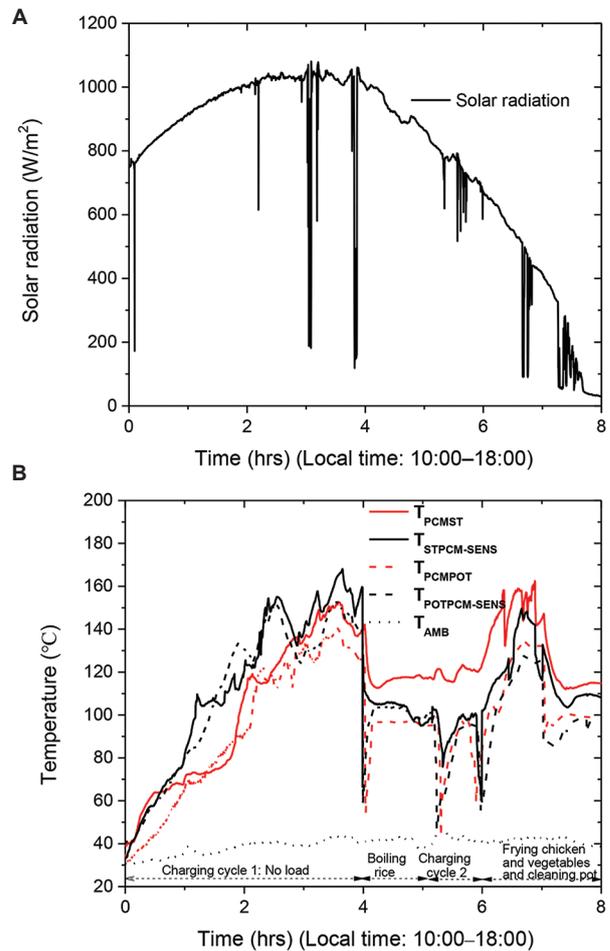

Figure 4. (A) Solar radiation profiles and (B) thermal profiles of the storage cooking pots for the experiment conducted on March 10, 2024 (10:00 – 18:00).

(i)   First 4 h: Charging the two storage cooking pots using solar energy.
(ii) Next 1 h: Cooking 200 g of rice with 400 g of water using the stored heat.
(iii) Following 1 h: Recharging the storage cooking pots with solar energy.
(iv) Final 2 h: Frying 300 g of chicken and vegetables using stored heat, followed by cleaning the pots with 100 g of water.

The experiment was performed on a sunny day, with an average solar radiation was 744 W/m^2 (Figure 4A). Brief cloudy periods were observed, with the longest occurring between 7.2 and 7.6 h into the experiment. The maximum solar radiation recorded was slightly above 1000 W/m^2, achieved between 3 and 4 h into the experiment.

The temperature profiles in Figure 4B indicate faster temperature rises for the mixed storage pot (T$_{STPCM-SENS}$-Storage, T$_{POTPCM-SENS}$-Pot) compared to the pure PCM pot

(T_{STPCM}-Storage, T_{POTPCM}-Pot) during the first 4 h charging period without a load. This difference is attributed to the higher thermal conductivity of granite pebbles, which exceeds that of erythritol (Table 1). Fluctuations observed during charging were due to manual tracking of the parabolic dish solar cookers, as automatic tracking was considered too expensive, especially for end users in sub-Saharan Africa. The temperature drops at 3 h and just before 4 h into the experiment likely correspond to temporary declines in solar radiation. Despite ambient temperatures fluctuating between 30 and 45°C, no significant effect on thermal performance was observed. The maximum temperatures achieved in the mixed and latent heat storage systems during the 4-h charging period were approximately 165 and 150°C, respectively. No clear phase change transition was evident from the temperature profiles, possibly due to non-uniform heating; however, visual confirmation of phase change was obtained by opening the pots.

During storage cooking, the corresponding maximum temperatures inside the pots were around 153 in the mixed storage pot and 140°C in the latent heat storage pot. The mixed storage pot reached higher temperatures during the rice boiling phase, likely due to the higher temperatures attained during the charging phase. While the pure PCM pot exhibited lower cooking temperatures, it maintained a steady temperature throughout the entire rice cooking duration. In contrast, the mixed storage pot experienced a temperature drop toward the end of cooking due to heat loss in the storage material. Unlike the mixed system, the erythritol-based storage system exhibited a more stable thermal performance, with phase transition occurring between 4.2 and 5 h into the experiment, maintaining a nearly constant temperature. The mixed storage pot showed a constant storage temperature for a shorter duration, between 4.2 and 4.6 h, before experiencing a more pronounced drop compared to the erythritol-only system. During the subsequent charging cycle, the erythritol-based pot demonstrated higher storage temperatures due to its lower rate of temperature decline. In the final cooking phase, involving frying chicken and vegetables followed by cleaning the pots, the erythritol-based pot maintained superior cooking and storage temperatures, likely due to its lower temperature drop after cooking rice. This finding suggests that the erythritol pot possesses a higher energy storage density after melting. This observation is supported by Table 2, which shows that liquid erythritol has a larger specific heat capacity than solid erythritol. However, in terms of cost-effectiveness, granite remains a more economical option than erythritol. In addition, granite enhances heat transfer characteristics, thereby reducing storage costs. A detailed cost-benefit analysis has not yet

been carried out, as it was beyond the scope of this study; however, this will be pursued in future research. Further investigations into the thermophysical properties of the mixed storage system will also be conducted in subsequent studies. Despite these differences, both pots effectively cooked food during the storage cooking periods.

The results of Cooking Test 2, which involved simultaneous TES and subsequent energy utilization over a 10-h period, are presented in Figure 5. This test was carried out the day after Test 1, on March 11, 2024. The average solar radiation in Test 2 was 724 W/m², comparable to the 744 W/m² recorded in Test 1. There were brief periods of cloud cover, particularly at the 2-h mark and after 3 and 4 h. The maximum solar radiation levels observed in Test 1 and Test 2 were similar.

The first 4 h of Test 2 involved boiling 200 g of rice in 400 g of water and frying 300 g of chicken and vegetables.
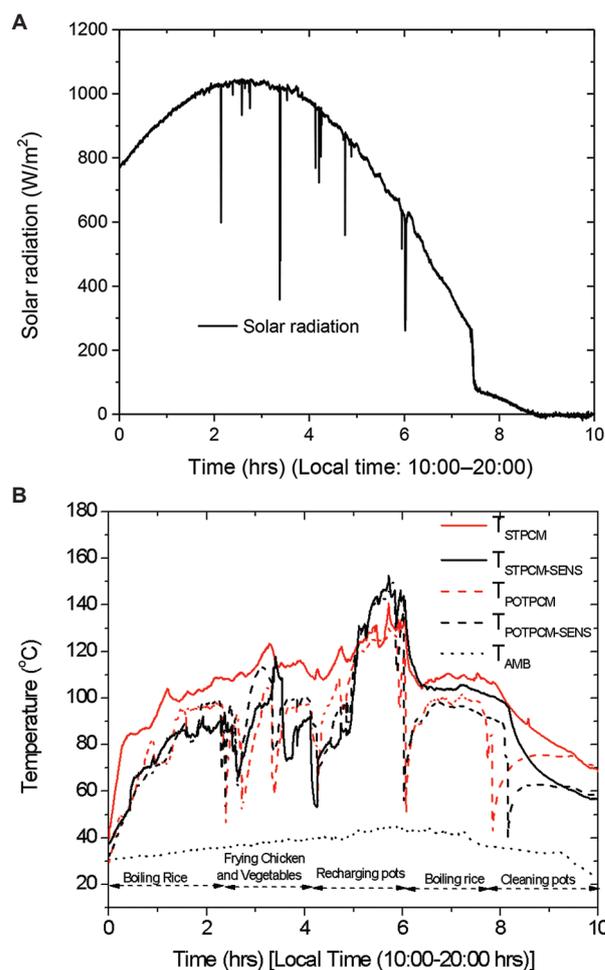

Figure 5. (A) Solar radiation and (B) thermal profiles of the storage cooking pots for the experiment conducted on March 11, 2024 (10:00 – 20:00).

The erythritol-based pot showed higher storage cooking temperatures than the mixed storage pot during these cooking processes, likely due to its slightly higher initial storage temperatures following overnight cooling. Another possible explanation is that heat transfer between the solid matrix of erythritol and granite – before the melting of erythritol – was less efficient than in the pure erythritol system. This may have been influenced by the additional cooking load introduced by water and rice, as Test 1 was conducted with an empty pot. Consequently, the additional cooking load in Test 2 likely affected heat transfer within the mixed storage cooking pot. Ambient temperature, which ranged between 25 and 43°C, did not appear to affect cooking performance, similar to the findings from Test 1. The observed temperature drops after 2 and 3 h may be attributed to corresponding drops in solar radiation, as well as the periodic opening and closing of the pot to check for doneness. The maximum storage temperature during cooking rice reached approximately 90°C in the mixed storage pot, compared to around 110°C in the erythritol storage pot. Despite these differences, both pots successfully cooked rice, although the erythritol-based pot maintained higher cooking temperatures for a longer duration.

During the frying of chicken and vegetables, the temperature in the mixed storage pot increased more rapidly, suggesting improved heat transfer. The cooking temperature of the food in the mixed storage pot was either higher or comparable to that in the erythritol-based pot. The observed fluctuations in temperature, especially during frying, were due to the repeated opening and closing of the pots to check food readiness – an inherent aspect of practical cooking. Between hours 4 and 6, the cooking pots were recharged without food, leading to a temperature increase. During this period, the mixed storage pot exhibited higher temperatures than the erythritol-based pot, confirming its superior heat transfer capabilities, as previously observed in Figure 4B. This observation suggests that the mixed storage system should be heated without any load to fully utilize its TES potential. Between hours 6 and 8 (14:00 – 16:00), 200 g of rice was cooked using 400 g of water. Both pots effectively cooked the rice; however, similar to Test 1, the mixed storage pot experienced a faster temperature drop compared to the erythritol-based pot. After 8 h, 500 g of water was added to the pots for cleaning. Since water was first added to the erythritol-based pot, its temperature initially rose more quickly than that of the mixed storage pot. The maximum temperature reached during cleaning was approximately 75°C for the erythritol-based pot, compared to 63°C for the mixed storage pot. This difference is attributed to the erythritol pot's more efficient heat utilization, as its storage material exhibited a lower temperature drop than that of the mixed storage pot. While the mixed storage pot benefits from a faster temperature rise, this advantage is counterbalanced by its greater temperature drop during heat utilization. However, in terms of cost-effectiveness and faster heat transfer without an initial thermal loading, the use of a mixed storage cooking pot remains a viable option.

It is important to note that these experiments were performed during spring (March 2024) in South Africa, and seasonal variations in solar radiation are unlikely to significantly impact the results. During summer, solar radiation levels are only marginally higher than in spring – by approximately 100 W/m². The maximum difference between summer and winter radiation levels is around 200 W/m², which only slightly accelerates the charging rate in summer. Thus, these experiments can be performed in any season without significant differences in thermal performance. In addition, rainy and cloudy conditions in summer may prevent experiments under clear-sky conditions. In our previous studies,[20] experiments were performed during winter (May – July 2020), and the recorded solar radiation levels were comparable to those presented in this study. The feasibility of solar cooking under winter conditions supports the conclusion that seasonal variations have a minimal impact on performance.

Table 3 presents the thermal performance parameters evaluated across three cooking tests. The results of Cooking Test 3 are provided in Figure A1. The average solar radiation during the solar cooking period was comparable across Tests 1, 2, and 3 (948, 936, and 987 W/m², respectively). Due to the higher initial temperatures of the empty pot, the F_1 values for the mixed storage pot (0.096 and 0.100 °Cm²/W) were higher than those of the erythritol-based pot (0.087 and 0.086 °Cm²/W). This indicates that the mixed storage pot charges more efficiently than the erythritol-based pot. However, the heat storage efficiencies of the erythritol-based pot (3.1 – 4.6%) were higher than those of the mixed storage pot (2.2 – 2.9%), attributed to erythritol's greater specific heat capacity. Conversely, the storage cooking efficiencies were higher for the mixed storage cooking pot (16.7 and 37.1%) than for the erythritol storage cooking pot (13.1 and 31.6%) in no-load solar cooking scenarios. This is because, despite a more pronounced temperature drop, the mixed storage pot attained higher cooking temperatures. However, when cooking with a load, the erythritol-based pot exhibited higher storage cooking efficiency, likely due to the higher storage temperatures achieved during initial charging.

Regarding cost,[33] 600 g of erythritol costs approximately R99 (USD 5.18), equivalent to USD 8.63/kg and USD

Table 3. Thermal performance evaluation of the two storage cooking pots

Test no.	F_{1e} (°C m²/W)	F_{1mix} (°Cm²/W)	Q_{inc} (MJ)	Q_{ste} (MJ)	Q_{stmix} (MJ)	η_{ste} (%)	η_{stmix} (%)	$\eta_{stcooker}$ (%)	$\eta_{stcookmix}$ (%)
Test 1	0.087	0.096	15.4	0.61	0.45	4.0	2.9	13.1	16.7
Test 2	N/A	N/A	9.1	0.42	0.20	4.6	2.2	47.2	21.9
Test 3	0.086	0.100	16.1	0.50	0.37	3.1	2.3	31.6	37.1

17.26 for 2 kg. In contrast, 4 tons of granite[34] costs around R4000 (USD 209), making the cost of 1.0 kg of granite approximately USD 0.21. Thus, the total cost of 2.0 kg of storage for the mixed storage is USD 8.84, compared to USD 17.26 for the erythritol-based pot. This lower storage cost for the mixed storage system supports its broader adoption, especially for large-scale applications where cost efficiency is crucial. Future research will explore the thermal properties and performance of different storage ratios to determine the optimal storage balance for mixed storage systems. In addition, alternative storage materials will be tested.

4. Conclusion

Two storage cooking pots – one containing pure erythritol (2.0 kg) and the other a 50:50 mixture of erythritol and granite pebbles (1 kg:1 kg) – were experimentally evaluated in food cooking tests. The first experiment involved charging the storage cooking pots without a load for 4 h, followed by discharging with food heating loads inside insulated wonder bags for 4 h to evaluate off-sunshine cooking performance. The second experiment involved simultaneous charging and cooking, alternating between charging and discharging cycles for 10 h. The key findings are summarized as follows:

(i) The F_1 values for the mixed storage pot (0.096 and 0.100 °Cm²/W) were higher than those for the erythritol-based pot (0.087 and 0.086 °Cm²/W), indicating that the mixed storage pot is easier to charge.

(ii) The mixed storage pot achieved higher temperatures (165°C and 153°C) compared to the erythritol-based pot (150°C and 140°C). However, due to erythritol's higher specific heat capacity, its heat storage efficiency (3.1 – 4.6%) was greater than that of the mixed storage pot (2.2 – 2.9%).

(iii) During discharging cycles, the mixed storage pot exhibited a faster heat utilization rate compared to the erythritol storage pot. However, at the end of the experimental tests, the erythritol-based pot retained higher temperatures, suggesting superior efficiency in heat retention. However, the storage cooking efficiencies for the mixed storage pot (16.7 and 37.1%) were higher than those for the erythritol storage cooking pot (13.1 and 31.6%) in no-load cooking scenarios.

(iv) Both energy storage systems cooked multiple meals over an 8-h cooking period, including rice, vegetables, and chicken, completing each cooking cycle within 1 h during heat utilization (discharging) tests.

(v) While the mixed storage pot benefited from a faster temperature rise, the greater temperature drop during heat utilization negated this advantage. However, the mixed storage cooking pot remains justifiable in terms of cost and faster heat transfer without an initial thermal load.

(vi) The total storage cost for the mixed storage cooking pot (USD 8.84) was significantly lower than for the erythritol storage cooking pot (USD 17.26). This cost advantage supports the adoption of mixed storage systems, especially in large-scale applications where cost-effectiveness is a key consideration.

Future work will focus on optimizing the thermophysical properties of mixed storage systems. Different mixing ratios of granite and erythritol will be studied to establish the optimal composition for improved thermal performance. In addition, the potential use of other locally and readily available TES materials, such as sandstone, marble, and limestone in South Africa, will be investigated for their feasibility in mixed storage configurations. Further studies will also investigate the use of xylitol as an alternative PCM in combination with SHSMs to enhance the efficiency and affordability of TES systems.

Acknowledgments

Funding

Conflict of interest

Ashmore Mawire is an Editorial Board Member of this journal but was not in any way involved in the editorial

and peer-review process conducted for this paper, directly or indirectly. Separately, other authors declared that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author contributions

Conceptualization: All authors
Formal analysis: All authors
Investigation: Ashmore Mawire
Methodology: All authors
Funding acquisition: Ashmore Mawire
Writing – original draft: All authors
Writing – review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data are available on request from the authors.

Further disclosure

Part of the findings has been presented at the Sustainable Energy Technologies 2024 (SET 2024) Conference, The Longemont Shanghai, Shanghai, China, August 12-14, 2024. The paper was selected to be considered for journal publication.

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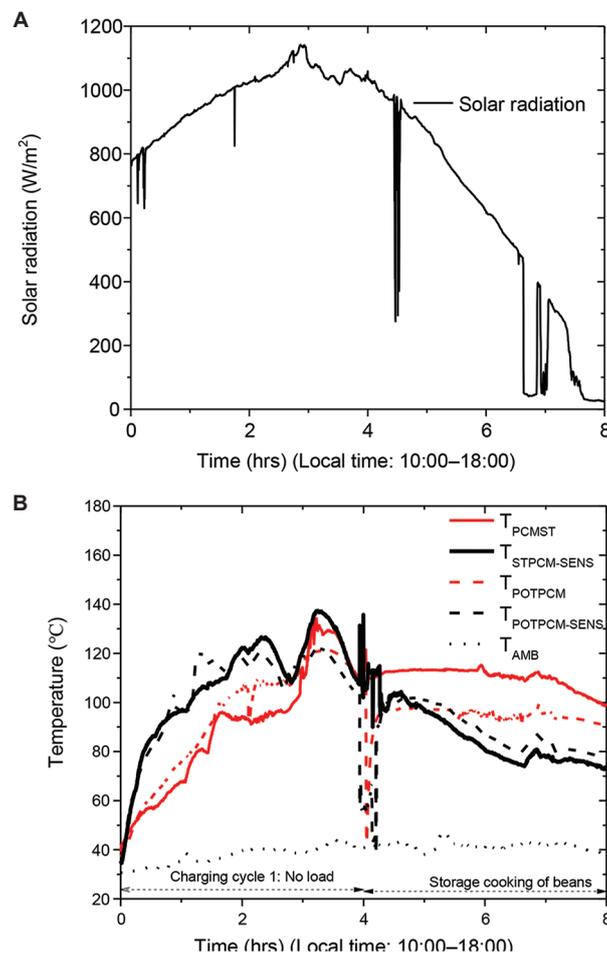
Appendix

Figure A1. (A) Solar radiation and (B) thermal profiles of the storage cooking pots during the experiment performed on March 17, 2024 (10:00 – 18:00). The experiment involved cooking 200 g of sugar beans with 600 g of water (Test 3). The storage cooking pots were initially heated up for 4 h without any load before the cooking began. Consistent with previous tests, the mixed storage pot exhibited higher temperatures during the charging phase, whereas the erythritol-based pot maintained higher cooking and storage temperatures throughout the storage cooking period.