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Performance evaluation of a trapezoidal solar pond using magnesium sulphate ($MgSO_4$)

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ABSTRACT

Emerging global demand for clean and sustainable energy has intensified research into efficient methods of solar energy capture and storage. Among various renewable energy storage technologies, salt gradient solar ponds (SGSPs) have emerged as a reliable and cost-effective solution. This study presents an advanced experimental evaluation of a trapezoidal SGSP using magnesium sulphate ($MgSO_4$) as the salinity medium to enhance heat storage performance and system stability. A laboratory-scale trapezoidal pond with a depth of 30 cm was constructed using 18 mm thick plywood and an optimized 16% $MgSO_4$ concentration (SGSP-M16) was employed to maintain thermal stratification. Experiments conducted over a four-month period in Salem, Tamil Nadu, India, involved detailed energy and temperature analysis across upper convective zone (UCZ), non-convective zone (NCZ), and lower convective zone (LCZ). Results revealed maximum temperature difference of 28 °C among UCZ and LCZ, with LCZ achieving peak energy efficiencies of 25.24%, 26.80%, 28%, and 32.09% from January to April, respectively. These findings confirm the effectiveness of the trapezoidal $MgSO_4$ based SGSP as a sustainable and scalable system for renewable energy storage and efficient thermal management, suitable for applications such as desalination, greenhouse heating, and industrial preheating.

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1. INTRODUCTION

The increasing population and rapid industrial advancements have significantly increased the demand for energy [1]. Fossil fuels remain the primary source of energy production; however, their limited availability has prompted many nations to seek alternative solutions [2], [3]. Renewable energy emerges as the most viable alternative to fossil fuels due to its abundant and environmentally friendly nature [4]. Among the various renewable energy sources, solar energy stands out as one of most extensively utilized options to meet the growing energy demands [5].

Solar radiation reaching Earth's surface is intermittent or mostly influenced by atmospheric settings [6]. One of the major challenges is the storage of solar energy from solar isolation [7]. The salt gradient solar pond (SGSP) is an economical and efficient solar device designed to store solar energy by harnessing solar radiation [8]. The SGSP offers an exceptional solution to this issue, as it can maintain consistent performance and match energy demands even during extended periods of wet weather, lack of significant drop in temperature of pond. Consequently, SGSPs are gaining recognition as an alternative method for generating electricity and industrial heat. As a non-convective system, the SGSP effectively retains solar energy by trapping solar radiation within the pond itself. It is constructed with a salt solution that increases in density with depth, allowing for the long-term storage of heat [9]-[11].

Around 2,500 years ago, the sun was used to heat ancient Roman baths, marking the earliest recorded instance of solar energy being utilized to heat a pool of water. In 1902, Kalecsinsky made the first documented observation of a solar lake at Medve Lagoon in Transylvania, Hungary [12]. During this study, it was noted that at a depth of 1.32 meters, the lake exhibited maximum temperatures of 70 °C in summer along with minimum temperatures of 26 °C in spring.

Energy analysis serves as a valuable tool for assessing thermal efficiency of various techniques [13]. During the context of solar energy systems, energy analysis is typically utilized for determining energy storage as well as losses, thereby identifying the conditions necessary to enhance system efficiency. Additionally, it provides foundational insights into the functioning of SGSP and aids in predicting variations in thermal storage [14]. Numerous researchers have conducted exergy or energy analyses of solar ponds, exploring different geometric configurations and types of salts.

Energy and exergy performance of circular and square-shaped solar ponds was experimentally analyzed using a NaCl salt solution. The findings revealed that the maximum monthly average temperatures in lower convective zone (LCZ) were 86 °C for cylindrical pond and 78 °C for the square pond. Additionally, the cylindrical pond demonstrated maximum energy efficiency of 25.8% and exergy efficiency of 2.44%, whereas square pond achieved energy and exergy efficiencies of 23.65% and 1.91%, correspondingly [15].

Experimental research was conducted on energy analysis of cylindrical-shaped SGSP combined to 4 solar collectors. Findings indicated that integrated solar pond (ISP) achieved energy efficiencies of 21.33%, 23.6%, 24.6%, and 26.5% when paired with 1, 2, 3, and 4 solar collectors. Correspondingly, exergy efficiencies have been 20%, 21.7%, 22.2%, and 23.4%. The study concluded that the ISP stored significantly more thermal energy when utilizing all four solar collectors [16].

In another study, the thermal performance of circular SGSP united to 4 identical solar collectors was experimentally examined. Outcomes demonstrated that in August, maximum as well as minimum temperatures in LCZ were approximately 55.2 and 16.91 °C, correspondingly. LCZ achieved its highest and lowest thermal storage efficiencies of 33% and 29% in August, while in January, these efficiencies dropped to 9.5% and 6%, respectively [17].

Thermal storage performance of the SGSP model has been analyzed through both experimental and numerical methods. The findings revealed that the maximum and minimum heat storage efficiencies were 28.41% and 30.16% in August and 8.27% and 10.74% in January, respectively, for the experimental and numerical studies. Additionally, the highest heat loss from solar pond was recorded as 185 W/m² in January and 474 W/m² in August [18].

Energy distribution as well as efficiency of circular solar pond were analyzed using both numerical and experimental approaches. Maximum energy efficiencies have been observed to be 7.68% for non-convective zone (NCZ) or 9.37% for LCZ, with corresponding energy efficiencies of 0.32% as well as 0.76% recorded in June. The study concluded that exergy efficiency is noticeably less compared to energy efficiency, suggesting that energy stored in solar pond is of low quality, enabling this appropriate for low-temperature applications [19].

Sodium chloride (NaCl) [20] is most frequently utilized salt in solar ponds because of minimal solubility variation with temperature changes. In addition to NaCl, other salts, namely magnesium chloride ($MgCl_2$) [21], sodium carbonate (Na_2CO_3) [22], magnesium sulfate ($MgSO_4$), calcium chloride ($CaCl_2$) [23], composite salts and fertilizer salts [24], and ammonium salts [25] have also been utilized to evaluate the energy performance of solar ponds. In previous investigation, suitability of trapezoidal SGSP using $MgSO_4$ salt solutions was experimentally investigated. The study tested salt concentrations of 4% (SGSP-M4), 8% (SGSP-M8), 12% (SGSP-M12), and 16% (SGSP-M16) $MgSO_4$ in water across three identical trapezoidal SGSPs. The findings indicated that the optimal salt concentration for maximum thermal energy storage was SGSP-M16 [1]. From the literature review, it was observed there is no thermal energy storage analysis performed using $MgSO_4$ in SGSP. Hence, ongoing investigation emphasizes estimating energy performance of upper convective zone (UCZ), NCZ, and LCZ of SGSP-M16 along with outcomes of the experimental results are presented.

2. METHOD

2.1. Construction details

The trapezoidal SGSP constructed using plywood of 18 mm thickness with surface area of 1.7 m² and 30 cm height. They are erected in location Government College of Engineering, Salem, Tamil Nadu, India (11.7128° N latitude, 78.0882° E longitude). The arrangements of the SGSP are given in Figure 1 for better understanding of constructional details. The plywood is preferred for its good insulation property, structural stability and durability. The inside surface of the SGSP is pasted with polyurethane plastic sheet of 2 mm thickness in order to prevent seepage of water and black color coated over the plastic sheet to attract maximum solar radiation.

A PVC column used to mount six PT-100 temperature probs which have accuracy of ± 0.5 °C vertically to obtain vertical temperature profile of water in SGSP. The signals from the temperature probs are processed in a 64-module (Delphin-EK64) data acquisition system for obtaining vertical temperature profile of solar ponds. Intensity of solar radiation at location of solar pond measured by Pyranometer - LPPYRA03 (DeltaOHM) and has an accuracy of ± 1.5 W/m^2.

Concentration of salt in pond water at different level is measured in terms of density. The samples for measuring the density of water are taken using 5 mm flexible plastic tubes which are fixed along with PVC pipe column already mounted for fitting the temperature probes as shown clearly in Figure 2. The sample was then weighed for known volume to calculate the density. The sample weight is measured using Wensar PGB200 digital scale having a accuracy of ± 10^{-4} g and the density measurement is done with the help of 10 mL pycnometer.

2.2. Procedure for developing salt gradient in the solar pond.

According to SGSP principle, pond has 3 different zones namely LCZ, NCZ, UCZ whose depths are 0.11, 0.14, 0.05 m correspondingly. HSZ of the pond is initially submerged in the salt solution with 16% concentration. The NCZ was established by linearly decreasing concentration of salt from uppermost layer of LCZ. Finally, UCZ has been established through filling freshwater. The established pond was confined for 72 hours to attain a linear salinity profile. Figure 2 illustrates the establishment of the distinct zones of solar pond.

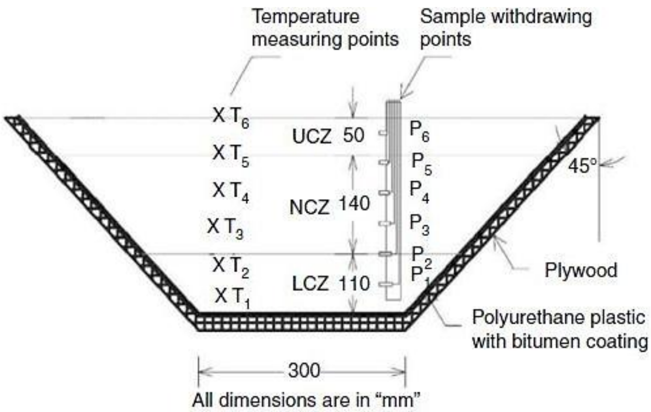

Figure 1. Schematic diagram of SGSP

(a) (b) (c)

Figure 2. Establishment of the different zones of the solar pond (a) formation of LCZ, (b) formation of NCZ, and (c) formation of UCZ

2.3. Experimental procedure

The temperatures at UCZ, NCZ, and LCZ of trapezoidal solar ponds were recorded daily from 10:00 AM-5:00 PM with a time lapse of 15 minutes. It is noted that the highest temperatures are recorded every day between 1:30-2:30 PM and its average was considered for investigating temperature profile of the solar ponds. Similarly, the average intensity of solar radiation between 1:30-2:30 PM was considered for this research. Density of the solar ponds is recorded daily at 2:00 PM. The monthly average density has been considered for examining density gradient of solar pond. Experimental trials were carried out for a period of four months. Monthly average temperatures of various zones, ambient temperature and intensity of solar radiation were taken to estimate energy storage of solar pond.

3. ENERGY ANALYSIS

Energy analysis is common approach to determine efficiency of systems and processes [26]. During context of solar energy systems, it is often utilized to determine energy efficiency as well as losses, providing insights into potential improvements [27]. The SGSP is a device that captures solar energy or reserves this as thermal energy over an extended period [28]. Performing an energy analysis of the SGSP provides valuable insights and helps predict fluctuations in its heat storage [29]. To facilitate this analysis, following assumptions [30] have been made:
- Densities of UCZ and LCZ in the SGSP are assumed to be uniform and constant.
- Mass transfer isn't taken into account.
- Heat transfer is assumed to be one-dimensional.
- The materials used in constructing the solar pond are considered homogeneous and isotropic.

Figure 3 illustrates the energy flows across horizontal surface of UCZ, NCZ, LCZ of pond. One portion of incoming solar energy is reflected from UCZ surface into air, resulting in energy loss. The UCZ also transmits some of incident solar radiation to NCZ, while remaining solar energy is absorbed within the UCZ, causing this to heat up.

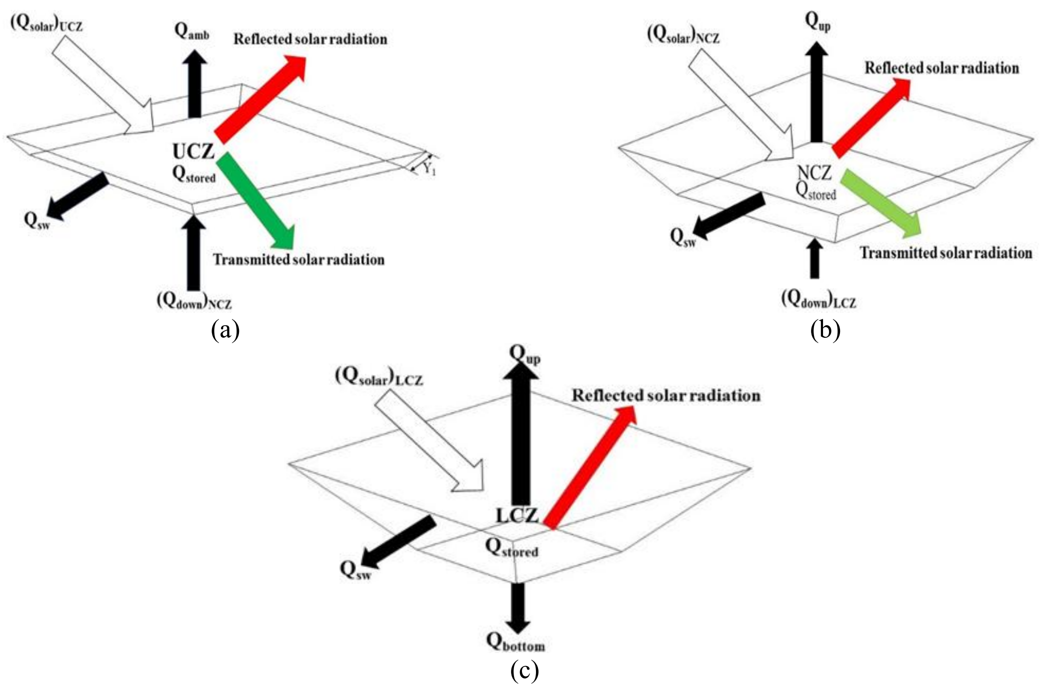

Figure 3. Energy flows across the horizontal surface of (a) energy layout of UCZ, (b) energy layout of NCZ, and (c) energy layout of LCZ

According to the law of conservation of energy, the energy balance equation of UCZ is written as (1)-(3).

$$Q_{stored} = Q_{solar} + Q_{down} - Q_{loss} \tag{1}$$

$$\frac{Q_{solar}}{A} = (1 - a)(1 - \beta) I_s e^{-\mu z} \tag{2}$$

$$\frac{Q_{down}}{A} = \frac{k_s}{x_{NCZ-UCZ}}(\Delta T) \quad (3)$$

The experimental setup of SGSP was built using plywood, which served as an insulating material. As a result, heat dissipation from side along with bottom walls of every SGSP principally occurred through conduction. Therefore, total heat loss in 3 zones was described using Fourier's law of conduction, as shown in (4)-(6).

$$Q_{loss} = Q_{amb} + Q_{sw} \quad (4)$$

$$\frac{Q_{amb}}{A_g} = \left[\frac{k_g}{x_g}(\Delta T)\right] \quad (5)$$

$$\frac{Q_{sw}}{A_{sw}} = 4\left[\frac{k_{sw}}{x_s}(\Delta T)\right] \quad (6)$$

The energy storage efficiency of each zone can generally be represented as (7).

$$\eta = 1 - \frac{Q_{loss}}{Q_{solar} + Q_{down}} \quad (7)$$

4. RESULTS AND DISCUSSION

According to outcomes of suitability experiments, it was determined that SGSP-M16 has the optimal salt concentration for storing the maximum amount of thermal energy. As a result, further experiments were conducted using SGSP-M16 to investigate the density gradient, temperature distribution, and energy distribution within the LCZ, NCZ, and UCZ. These experiments were carried out over a four-month period under the meteorological conditions of Salem and are presented in this study.

4.1. Density profile

Figure 4 depicts correlation among density gradient of SGSP-M16 salt solution and the pond depth over a four-month period. This could be reported that density gradient in LCZ shows little variation, primarily due to the low diffusion of the $MgSO_4$ salt solution. The density profile in the NCZ is slightly higher in January compared to April, which is attributed to temperature fluctuations in the NCZ.

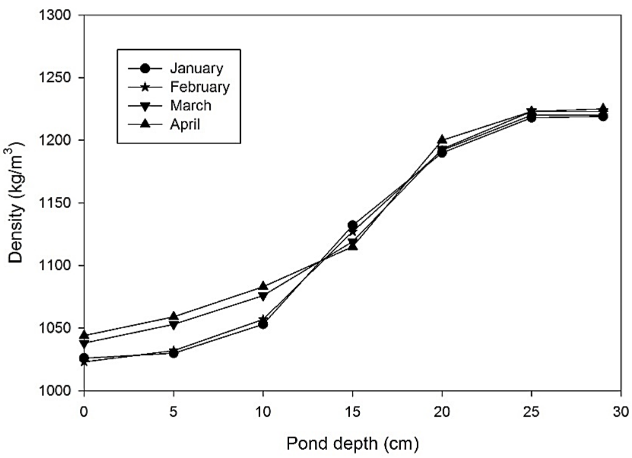

Figure 4. Density profile of $MgSO_4$ SGSP

4.2. Temperature distributions

Figure 5 shows the monthly average temperature fluctuations with respect to pond depth. Maximum as well as minimum temperatures in LCZ were recorded at approximately 60 °C and 50 °C in April and January, correspondingly. It was noted that the circulation of the salt solution in the LCZ helped improve the uniformity of the temperature distribution.

Highest temperature recorded in NCZ has been 53 °C in April, while lowest was 47 °C in January. Temperature distribution in NCZ was nearly linear, indicating stable thermal stratification within the pond, allowing it to function effectively as a transparent insulator. In the UCZ, the temperatures ranged from maximum of 32 °C in April to minimum of 30 °C in January. Largest temperature difference, approximately 28 °C, was observed between the LCZ and UCZ in April.

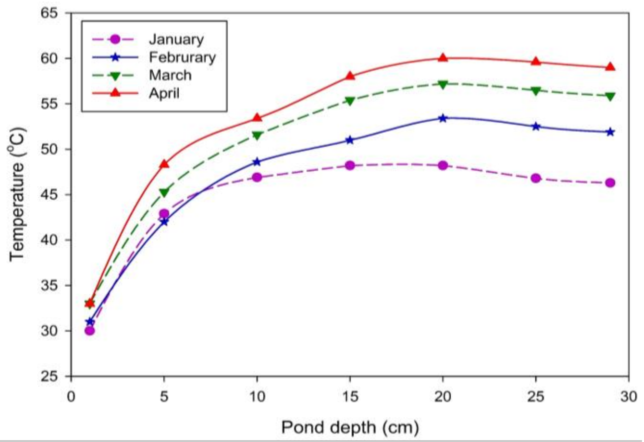

Figure 5. Temperature distribution of MgSO4 SGSP

4.3. Energy analysis

The energy distribution of the SGSP-M16 was estimated using temperature values obtained from experimental work. It was observed that some of the irradiation on the UCZ surface was reflected and some of it was absorbed by the UCZ. The remaining part is transmitted to the LCZ through NCZ.

Figure 6 depicts energy distribution of UCZ of SGSP for four months. Observed in Figure 6 maximum along with minimum energy stored is 31 W/m^2 and 12.6 W/m^2 in April and January for solar insolation of 346 W/m^2 and 178 W/m^2, respectively. Similarly, Figure 7 demonstrates energy distribution of NCZ of solar pond. Greatest and smallest amounts of energy storage were determined to be 49 and 20.13 W/m^2 in April and January, respectively. The received solar radiation in the NCZ is 329 W/m^2 in April and 170 W/m^2 in January.

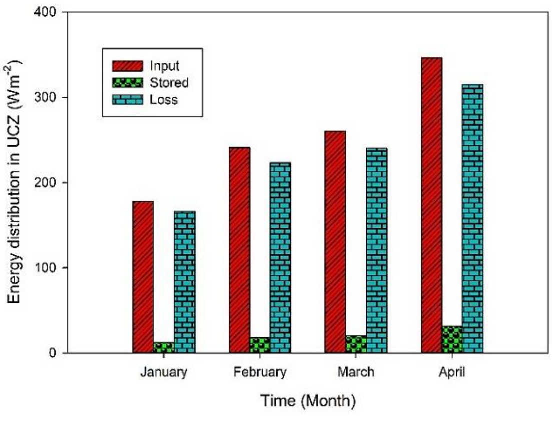

Figure 6. Energy distribution of UCZ of $MgSO_4$ SGSP

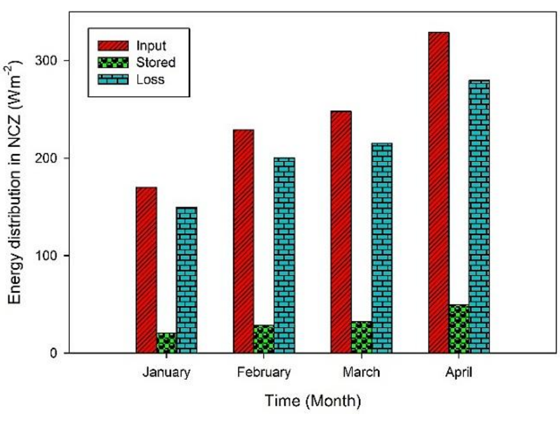

Figure 7. Energy distribution of NCZ of $MgSO_4$ SGSP

The energy distribution of the LCZ is shown in Figure 8. It has been found that the highest and lowest quantity of solar energy build up in LCZ is 95 and 38.62W/m^2 in month of April and January respectively for the solar insolation of 296 W/m^2 and 153 W/m^2. Heat loss of solar pond was estimated utilizing Fourier heat conduction equation. It has been found that the heat losses of the UCZ are 165.4, 223, 240, 315 W/m^2 in month of January, February, March, and April, respectively, while for the NCZ are 149.87, 200, 215, 280 W/m^2. Similarly, LCZ are 114.38, 151, 160, 201 W/m^2 in the months of January, February, March, and April, respectively.

The energy efficiencies with respect to the time of the SGSP-M16 are depicted in Figure 9. It was found that the energy efficiencies of UCZ are 7.08%, 7.47%, 7.87%, and 8.96% in January, February, March, and April, respectively. The estimated energy efficiencies of NCZ are 11.84%, 12.55%, 13.17%, and 15.05% in January, February, March, and April, respectively. Similarly, the energy efficiencies of LCZ are found to be 25.24%, 26.80%, 28%, and 32.09% January, February, March, and April, respectively.

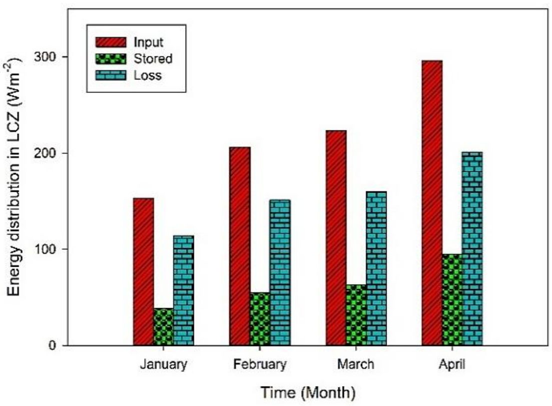

Figure 8. Energy distribution of LCZ of $MgSO_4$ SGSP

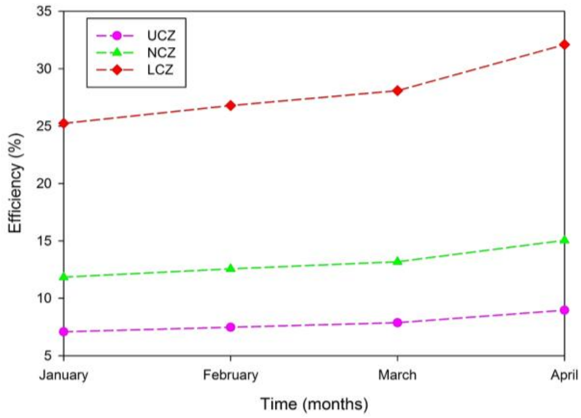

Figure 9. Energy efficiency of $MgSO_4$ SGSP

5. CONCLUSION

The SGSP can be constructed in various geometric shapes, but the trapezoidal shape is generally preferred due to its enhanced performance. Laboratory-scale trapezoidal SGSP with surface area of 1.7 m² has been built for experimentation. The energy analysis of $MgSO_4$ salt utilized in solar pond provided valuable insights into improving thermal energy storage in the trapezoidal SGSP. In April, the maximum average temperatures recorded in UCZ, LCZ, and NCZ with SGSP-M16 were 32 °C, 53 °C, and 60 °C, respectively. The energy analysis revealed that the highest energy efficiencies were 8.96% for UCZ, 15.05% for NCZ, and 32.09% for LCZ in April. In contrast, the energy efficiencies in January were lower, at 7.08% for UCZ, 11.84% for NCZ, and 25.24% for LCZ. Thermal energy stored in system might be effectively applied for low-temperature utilizations. Future work will involve scaling the system for real time deployment, optimizing pond geometry, and integrating phase change materials or nanofluids to enhance energy storage. Furthermore, coupling SGSP with desalination and implementing smart monitoring will support its advancement as a cost effective and sustainable renewable energy storage solution.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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M. Raja	✓	✓		✓	✓		✓	✓	✓	✓		✓	✓	
M. Venkatesan		✓	✓	✓		✓	✓		✓		✓			
M. Dineshkumar				✓	✓		✓	✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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