Experimental Investigation of Sand as a Potential Heat Battery Submerged in Composite Material Containers

Annika Jain[1], **Hitendra Vaishnav**[2]

Received October 11, 2025
Accepted April 18, 2026
Electronic access June 15, 2026

The development of sustainable energy storage systems has garnered attention in recent years. This has led researchers to investigate thermal battery materials more efficient and environmentally-friendly than lithium-ion batteries. In this study, two sand types – Desert Sand and Silica Sand – are investigated as potential heat storage mediums for solar-powered thermal batteries. Current conventional materials, such as phase change materials and lithium-based cells, are not always suitable due to their thermal instability, high production costs and safety concerns. Sand is a more feasible option as it has a higher thermal stability and is relatively easy to obtain. At the same time, there are certain drawbacks, such as sand's low thermal conductivity and average retention of heat. The investigation addressed this by uniformly dispersing Copper Oxide (CuO) and Iron Oxide (Fe_2O_3) nanoparticles within the sands, which were enclosed in four containers shaped as truncated cone. There were sixteen sand-battery configurations, made of Kevlar, Hemp, Carbon Fibre and Glass Fibre. Each configuration was subjected to 120 minutes of solar exposure and a subsequent controlled cooling phase. The temperature of the sand during these phases was monitored using sensors. The final data revealed that the triad of Desert Sand, CuO nanoparticles and Kevlar produced the most effective thermal characteristics, attaining a peak of 147.1°C, holding heat for over 6 continuous hours. In general, Kevlar and Carbon Fibre outperformed the other materials in minimising the heat loss. This study investigates the feasibility of nanoparticle-enhanced sand as a medium for thermal energy storage, with strong implications for sustainable heating applications and future energy infrastructure.

Keywords: Sand Battery, Composite Material, Temperature Sensor, Solar Power

Introduction

In recent years, the interest in developing sustainable energy storage systems has increased significantly to reduce greenhouse gas emissions and limit the planet's rising temperatures[1]. While renewable energy sources, such as solar and wind, have developed greatly in the last decade, they are still highly expensive and, more importantly, intermittent. These power sources fluctuate with daily and seasonal patterns. As a result, with time and developments in technology, this has created a parallel push to find ways to store renewable energy[2].

Thermal Energy Storage systems (TES), also known as thermal batteries, have emerged as a promising solution to this. They have the potential to completely reshape renewable energy storage by providing scalable and cheaper alternatives to the current lithium-ion technology used, particularly in large-scale solar plants[3]. Thermal batteries function by storing excess electricity or power as heat in the electrochemically active material of the battery. They are known for storing energy over a range of temperatures for a long period of time. The stored heat is later released when it is needed[4]. The advantages of this technology are numerous, the primary one being a high-density, long-term energy storage of energy without a loss. This, in turn, leads to further benefits, such as the ability to transport the energy and the freedom for seasonal usage.

In order to improve efficiency of thermal batteries, researchers investigate various factors, including phase change materials' properties, thermal management systems, charging and discharging rates, battery design, and the optimal temperature range. Currently, solutions attempt to balance these factors to obtain the optimal performance[5].

The sensors in the battery provide data that is essential to managing the internal temperature of the battery to avoid failure. The control system aids in processing the data collected by the sensors and, with the help of artificial intelligence (AI), it also continuously improves the ability to predict and manage risks. This enhances risk mitigation, as the system can be used to predict battery behaviour and ensure safer thermal management, which is critical to safe usage in large-scale applications in the industry[6]. There is a constant risk of electrochemical degradation and thermal decomposition, which then leads to a

[1] *Oberoi International School, JVLR, Maharashtra, India*
[2] *On My Own Technology Pvt. Ltd., Lokhandwala, Oshiwara, Mumbai, India*

shortening of the battery's lifetime.

Traditional TES systems utilise materials such as molten salts, lithium, and phase change materials (PCMs) to absorb heat. However, these materials have significant limitations in areas such as thermal stability, cost, and environmental impact. For example, molten salt thermal batteries cannot be used at extremely high temperatures (i.e., 400°C - 700°C), since they create safety and management issues that place stricter requirements on the other components of the battery. Lithium thermal batteries suffer from the risk of thermal runaway from various instances: overheating, overcharging or short circuits. These lead to explosions, posing safety risks. Similarly, using PCMs raises the risk of degradation over time as well as their low thermal conductivity.

Sand has a high thermal stability, low cost, and wide availability. As a result, it presents an attractive alternative as a material for thermal energy storage. Sand has a wide temperature range for heating as well as a high specific heat capacity, providing it with the potential to reach a high energy density. Moreover, sand is also environmentally friendly, making it a sustainable choice for scalable applications or industrial use. However, it has a relatively low thermal conductivity and heat retention capacity, which limits its performance as a thermal energy storage medium. Incorporating nanoparticles (i.e., copper oxide and iron oxide) can enhance the thermal properties of sand, specifically improving its retention capabilities and heat transfer rates.

Research Objective

This research proposes to develop a novel solar-powered thermal battery by utilising different types of sand and nanoparticles. It focuses on developing a high heat-conducting design that is reliable, cheap, and highly efficient.

The research will calculate the heat retention of the sands in varying materials. The research will take into account sand with and without the nanoparticles and investigate the subsequent effect on the heat absorption ability. It will utilize a constructed thermal battery to conduct the experiment, gather data, and draw conclusions.

Thermal energy storage systems have several industrial applications, especially with heat-hungry processes. For instance, they recover waste heat in industrial facilities, storing it and dispatching it as needed, for processes such as preheating materials, generating steam, or powering other processes. Along with lowering costs, this also boosts efficiency. Thermal batteries are also essential in military and aerospace applications, due to their ability to store energy in the long term and overall reliability. They are a low-maintenance solution that has a high power density and rapid activation. Further, thermal batteries can be used to stabilise an electrical grid by storing energy during times of low demand and releasing it in peak hours.

Thus, the data derived from this research can improve environmental sustainability and energy efficiency. With this research, the low efficiencies and relatively high costs of production of thermal energy storage systems can be avoided. The potential usage of renewable energy, specifically solar energy, will also be more effective, as the intermittent energy source's excess energy will be stored for future use over a long period of time.

Literature Review

Mohammed Sajad Naghavi Sanjani et al.[7] have attempted to improve domestic hot water production during fluctuating weather conditions by developing a thermal battery made of phase change materials (PCM) and porous media. To test the system's efficiency in real-world conditions, the researchers employed an experimental approach and tested the battery in August and September, under varying weather conditions. The results indicated that the battery could efficiently provide hot water on sunny days, but required a larger solar collector on cloudy days. The research faced difficulty in measuring the energy storage within the PCM, but noted that the heat loss from the battery was minimal.

Samantha L. Piper et al[8] are addressing the critical problem of developing sustainable PCMs for thermal battery technologies, to ensure the efficient storage and distribution of renewable energy. The researchers investigated this through a series of experiments that probed the thermal stability of various phase change materials. The results indicated that there were two materials that exhibited good thermal stability due to their high efficiency and long-term storage. Along with this, the research discovered that degradation occurred in the samples after a prolonged exposure to higher temperatures.

B. Kalidasan et al[9] have focused on addressing the thermal conductivity, flammability and poor light absorption properties of traditional PCMs such as graphene and silver, to improve TES efficiency. The study uses spectroscopy and microscopy to focus on the chemical stability, microstructural behaviour and thermal properties of graphene-silver nanoparticles. The results demonstrated a significant improvement in the thermal conductivity and stability of the PCMs with the addition of nanoparticles. However, it fails to investigate the durability and performance of the nanoparticles in varying environmental conditions.

Kai Wang et al[10] endeavoured to resolve the inefficiency caused by the intermittency of solar energy by investigating TES systems that can aid in the creation of a stable operation. The researchers conducted a comprehensive review of multiple thermal storage technologies, comparing different types of TES systems (e.g. sensible heat, latent heat), evaluating studies and analysing materials. The study revealed that TES is a reliable technology for storage due to its high storage density and long energy preservation duration. This performance is enhanced with other materials, such as salt mixtures with low melting points.

Methodology

Heat Absorption of Sand Batteries (Theoretical, Without Nanoparticles)

To develop an efficient solar-powered thermal battery, the objective of this research, a series of theoretical and experimental procedures were followed. The data required to achieve the research objective included information about the thermal properties of the two types of sand (Desert Sand and Silica Sand) and the two nanoparticles (Copper Oxide, Iron Oxide). Below is a table detailing the similarities and differences between the two sands of this study.

Table 1: Similarities & Differences of Desert & Silica Sand Desert Sand Silica Sand

Desert Sand	Silica Sand
Similarities	
Both the sands primarily consist of the same quartz, SiO_2 , and are formed due to the erosion of rock over a long period of time.	
Differences	
Along with Silica, numerous other impurities (e.g. clay, organics, feldspar) can be found within Desert sand. This reduces its consistency and thus, causes it to be coarser.	Silica sand is primarily composed of the silicon-dioxide quartz, and contains minimal impurities
Desert sand is dark, ranging between tan, red or brown, particularly due to iron impurities.	Silica sand possesses an off-white, or close to white colour, due to its purity.
Desert sand has a lower heat tolerance in the presence of mixed minerals.	Silica sand is capable of withstanding high temperatures, even with the presence of additional minerals.
Desert sand grains are highly rounded and smooth due to wind polishing.	Silica sand grains are angular, hence they are better suited to interlocking with each other.

The Desert Sand and Silica Sand are varied in terms of their coarseness. Silica Sand is relatively fine, with the particle's diameter ranging between 0.20mm to 0.25mm. In comparison, Desert Sand is significantly coarser. The particles have diameters ranging between 2.10mm to 2.30mm.

Theoretical calculations were conducted with this information, to calculate the amount of time the thermal battery would require reaching a temperature of 150°C, with the nanoparticles, as well as without. Certain assumptions were also considered to recreate the conditions that would be met during the experiment. The properties of the chosen sands can be seen in Table 2 below, and the standard conditions in Table 3. In Table 3, the "Surface Area" column refers to the surface area of the top, circular area of the battery, which absorbs sunlight.

Table 4 represents the theoretically calculated time required for each of the types of sands to heat up, in the conditions of the given data above. The process of calculation involved finding the heat energy (in Joules) required to heat up the sand to a temperature of 150°C, then using the relation between heat and power to find the time required to achieve the same.

Table 2: Relevant Thermal Properties of Sand [11,12]

Sand	Grain Size (mm)	Thermal Conductivity (W/mK)	Melting Point (°C)	Specific Heat Capacity (J/Kkg)	Density (kg/m^3)
Silica	0.06-0.2	0.2-0.7	1713	1000	1800
Desert	0.125-0.5	0.2-0.7	1500	900	1550

Table 3: Constant Values

Mass (kg)	Ambient Temp. (°C)	Aimed Temp. (°C)	Irradiance (W/m^2)	Efficiency	Surface Area (m^2)	Power (W)
0.150	30	150	800	0.65	0.00478	2.49

Table 4: Time Required For Heating (Without Nanoparticles)

Sand Type	Specific Heat Capacity (J/kg K)	ΔT (°C)	Heat (J)	Time Required (seconds)	Time Required (hours)
Silica Sand	1000	120	18000	7240	2.01
Desert Sand	900	120	16200	6520	1.81

The following shows the formulae used to calculate the time required. To obtain the time required in hours, the value of t was simply divided by 3600. The same steps were followed for the three types of sands.

$$Q = mc\Delta T$$
$$P = Q/t$$
$$t = Q/P$$

Heat Absorption of Sand Batteries (Theoretical, With Nanoparticles)

A similar calculation was employed to determine the theoretical amount of time required to heat up the sand combined with the nanoparticles. While the same formulae were utilised, a slight modification was made to adjust the considered specific heat capacity, to include that of the nanoparticles. Table 5 below represents the new specific heat capacity determined.

Table 6 showcases the theoretical time required for the sand to heat up to the required temperature with the nanoparticles. The same procedure was used as explained above, with the constants remaining as the ones in Table 3.

Table 5: Specific Heat Capacity

Nanoparticle	Specific Heat Capacity (Nanoparticles)	Mass (Nanoparticles) (kg)	Sand	Specific Heat Capacity (Sand)	Mass (Sand) (kg)	Total Heat Capacity
Copper Oxide	531	0.005	Silica Sand	1000	0.145	975.93
Copper Oxide	531	0.005	Desert Sand	900	0.145	879.93
Iron Oxide	570	0.005	Silica Sand	1000	0.145	977.1
Iron Oxide	570	0.005	Desert Sand	900	0.145	881.1

Table 6: Time Required For Heating (With Nanoparticles)

Nanoparticle	Sand	Total Heat Capacity	ΔT (ºC)	Heat (J)	Time Required (seconds)	Time Required (hours)
Copper Oxide	Silica Sand	975.93	120	17566.74	7070	1.96
Copper Oxide	Desert Sand	879.93	120	15838.74	6370	1.77
Iron Oxide	Silica Sand	977.1	120	17587.8	7080	1.97
Iron Oxide	Desert Sand	881.1	120	15859.8	6380	1.77

Having established the theoretical time required for heating with and without the nanoparticles, the next critical step was the selection of appropriate materials for the containers, to optimise the efficiency of the battery i.e. its tendency to dissipate heat. Four materials were chosen to be combined with the types of sand and nanoparticles for the experiment: Kevlar, Hemp, Carbon Fibre and Glass Fibre.

Materials for the Battery

Kevlar: Kevlar is a short fibre that has a high strength-to-weight ratio of approximately 3620 megapascals (MPa), making it a robust material. It is composed of lightweight materials that make it a fibrous polymer[13], with a density of 1.44 gcm-3. Its fibres are notable in the context of thermal batteries due to its excellent thermal stability, low weight and high toughness. As a material, Kevlar displays high heat-resistant properties and high tensile strength. The chemical structure of Kevlar is constructed by repeating inter-chain bonds cross-linked with hydrogen bonds, resulting in an extremely high tensile strength. Hence, Kevlar is resistant to high temperatures, making it ideal for thermal batteries. It is also inherently flame resistant, protected against temperatures reaching to 427°C.

Hemp: Hemp is a light-coloured, strong fibre that is naturally obtained from the hemp plant, *"Cannabis sativa"*[14]. Batteries often use Hemp as a material due to its advantages in terms of efficiency and the environment. It is a low-cost, recyclable, carbon-negative material, implying that for every amount of Hemp utilised, it withdraws a certain amount of carbon-dioxide from the atmospher[14]. Hemp also has a high energy density, charging speed and low thermal conductivity. This allows for the regulation of thermal performance and offers protection against overheating. Hemp can absorb up to 20% of its weight in moisture.

Carbon Fibre: Carbon Fibre is a thin material made of filaments of carbon that are used to strengthen the material. It is high in stiffness and tensile strength, but has a low weight-to-strength ratio[15]. The strength of carbon fibre influences its thermal conductivity and stability, giving it a high heat tolerance and making it resistant to thermal expansion. Further, it also makes the material lightweight. As this research delves into phase changing materials, it has also been noted that carbon fibres offer a significant improvement in the thermal conductivity of batteries. They are especially suitable for the thermal management of the battery[16]. In addition to this, carbon fibre has a high energy density[17].

Glass Fibre: Glass Fibre is a lightweight material, with a high tensile strength and thermal stability[18]. In terms of its thermal properties, glass fibre has a high thermal conductivity and fire resistance, resulting in high melting and boiling points. Due to its chemical and biological resistance, glass fibre is also recognised as a highly durable material that works effectively in a variety of surroundings, especially since it can be easily moulded[19].

Below is a short summary of the information discussed above:

Table 7: Summary of Material Properties

Material	Key Properties	Advantages in Thermal Battery
Kevlar	• Excellent thermal stability • Lightweight • High tensile strength	• Resistant to high temperatures • Flame-resistant • Does not melt or combust
Hemp	• Low-cost, eco-friendly • Highly efficient • High energy density	• Good heat retention • High storage efficiency • Flame-resistant
Carbon Fibre	• High tensile strength • Lightweight • High energy density	• High heat tolerance • Resistant to thermal expansion • Enhances heat transfer
Glass Fibre	• Lightweight • High tensile strength • Durable	• Resistant to thermal expansion • High heat resistance • High melting and boiling points

Container Design & Structure

The design of the container itself was decided by exploring a variety of three-dimensional structures, such as cuboids, cylinders and cones, that the above materials could be moulded into. Each structure had its own advantages and disadvantages, which resulted in the final structure being a truncated cone.

While the cylindrical structure offers a more regulated form of heat transfer, it proved to be disadvantageous with the chosen materials as it is very difficult to mould. Not all the materials, specifically Carbon Fibre and Hemp, can be easily constructed into a cylinder, which would result in a highly costly process. Furthermore, if a cylinder is still used, the final result will likely not be durable i.e. it will be vulnerable to deformations or cracks when the cylinder's temperature increases, due to the incompatibility of the material with the shape. The shape of a cuboid is highly useful in terms of moulding, as it is easy to achieve with the four materials, as well as increasing the heat absorbed by the material. However, in order to achieve the latter, the surface area of the cuboid exposed to the sun has to increase. This means the length and the breadth will have to be increased, requiring a larger amount of material. In the long-run, this would prove to be highly inefficient due to the cost of the materials and the need to increase the size each and every time, to increase the efficiency of the battery.

The conical structure can be modified to accommodate the advantages of the cuboid and the cylinder, while mostly avoiding their drawbacks. While a regular cone does not have a surface area that can be exposed to absorb heat, a truncated cone has a flat surface that can do this. Further, more material does not have to be utilised in order to increase the efficiency of the truncated cone, as the exposed surface can simply be increased by reducing the height, if necessary. The construction of such a shape with the materials is also easily possible, thus reducing the difficulty and costliness of constructing the battery.

The shape and dimensions of the truncated cone are depicted in Figure 1 below. The two radii, the height and the thickness has been chosen in consideration of the 150g of sand that will be tested. All units depicted in the diagrams are in millimetres (mm).

The four containers were constructed using a predefined mould. The truncated cone shape was first modelled using a computer-aided designing (CAD) software known as Fusion 360. Following this, using the instructions for printing a CAD model on a 3D-printer, polylactic acid (PLA) was used to print the structure with the given dimensions defined by the model in Figure 1. The 3D-printer used was the Creality Ender 3D-Printer. PLA is a biodegradable thermoplastic that is derived from the lactic acid of corn, maize or milk. It is a stiff, brittle material, the reason for which it was used as a model for the truncated cones of the specific materials required for this experiment. Each of the four chosen materials – Hemp, Kevlar, Glass Fibre and Carbon Fibre – were layered onto the mould by hand for a long period of time, with a significant weight placed upon them to ensure the final result would be durable. A different mould was made for each of the materials. After a

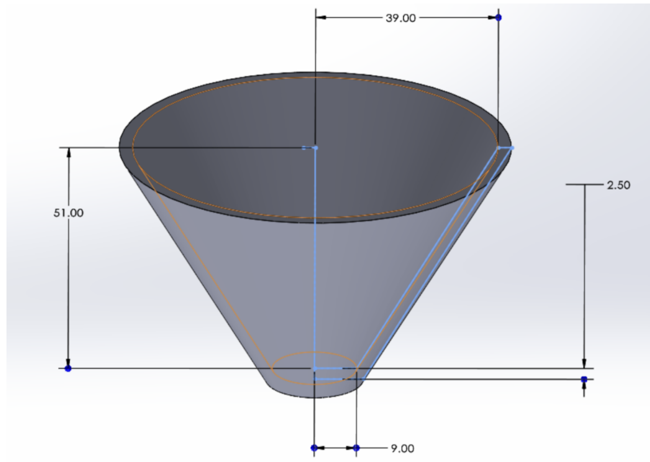

Fig. 1 Truncated Cone with Measurements [All units depicted in the diagrams are in millimetres (mm).]

period of three hours, the mould of PLA was removed by slipping it out from underneath the specific material, leaving the container for sand. Figure 2 showcases the final results that were utilised in the experiment.

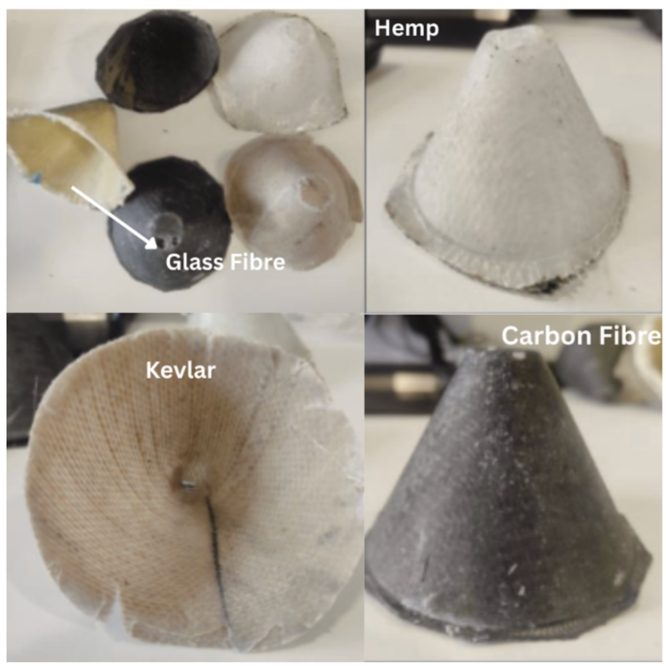

Fig. 2 Final Containers

Prior to 3D-printing, the uniformity of the containers was maintained by ensuring that the measurements for each were the same. Following the print, this uniformity was verified by first ensuring the layers of each material had the same thickness. A single layer was then applied onto the mould, and finally, the cone wall thickness was measured using a ruler.

Heat Dissipation of Sand Batteries (Theoretical, Without Nanoparticles)

With the information about the container, theoretical calculations were then undertaken to determine how much time was required for the containers to dissipate the heat collected. The data involved eight samples. The formula assumes that conduction takes place within the container. With the nanoparticles, there were sixteen samples in total. When calculating the time required for the samples with and without the nanoparticles, certain values were taken as constants in order to conduct the calculations and ensure uniformity. They can be seen in Table 8 below. TA is the temperature of the sand within the container, remaining constant at 150°C. The sample calculations for the affected surface area of the cone are below Table 8.

Table 8: Constant Values

T_A (°K)	Area (m^2)	Thickness (d) (m)
423	0.0139	0.00150

$$surface\ area = (\pi(0.039+0.009)(0.0591)+(\pi(0.039^2+(0.0090.009))))$$

$$surface\ area = 0.013937832$$

Table 9 shows the theoretical values calculated as the final temperatures of each container, accounting for the different types of sand and materials. It is a predictive benchmark against which the experimental results can be compared. This value assumes ideal conditions for the experiment (e.g. perfect heat transfer, negligible losses) and therefore, will serve as a reference point for evaluating the accuracy and reliability of the experimental data.

Table 9: Temperature At Which Dissipation Occurs (Without Nanoparticles)

Sand	Material	Conductivity (K) (Wm/K)	Heat (J)	Heat * Thickness	K * Area	T_B (°K)	T_B (°C)
Silica	Kevlar	4	18000	27	0.0558	907	634
Silica	Hemp	0.5	18000	27	0.00695	4310	4030
Silica	Carbon Fibre	11	18000	27	0.153	599	326
Silica	Glass Fibre	0.62	18000	27	0.00864	3550	3270
Desert	Kevlar	4	16200	24.3	0.0558	859	586
Desert	Hemp	0.5	16200	24.3	0.00695	3920	3650
Desert	Carbon Fibre	11	16200	24.3	0.153	581	308
Desert	Glass Fibre	0.62	16200	24.3	0.00864	3240	2960

The following shows the formula used to calculate the values in Table 9, where the final temperature T_B is calculated. Here, K is the constant of conductivity, A is the surface area of the object, T_B is the final temperature, T_A is the initial temperature, Q is the heat and d is the thickness of the container.

$$Q = \frac{KA(T_B - T_A)}{d}\ (Equation\ 3)$$

$$T_B = \frac{Qd}{KA} + T_A$$

Heat Dissipation of Sand Batteries (Theoretical, With Nanoparticles)

The same calculation was used to determine the theoretical temperature at which the heat would dissipate in the containers where the sand was mixed with nanoparticles. Table 10 below represents the values determined for this set of data, including the additional heat taken into consideration. The assumptions that were made for these calculations were the same as the ones displayed in Table 8.

Table 10: Temperature At Which Dissipation Occurs (With Nanoparticles)

Nanoparticle	Sand	Material	Conductivity (Wm/K)	Heat (J)	Heat * Thickness	K * Area	T_B (°K)	T_B (°C)
Iron Oxide	Silica	Kevlar	4	17600	26.4	0.0558	896	623
Iron Oxide	Silica	Hemp	0.5	17600	26.4	0.00695	4220	3950
Iron Oxide	Silica	Carbon Fibre	11	17600	26.4	0.153	595	322
Iron Oxide	Silica	Glass Fibre	0.62	17600	26.4	0.00864	3480	3200
Iron Oxide	Desert	Kevlar	4	15900	23.8	0.0558	850	577
Iron Oxide	Desert	Hemp	0.5	15900	23.8	0.00695	3850	3580
Iron Oxide	Desert	Carbon Fibre	11	15900	23.8	0.153	578	305
Iron Oxide	Desert	Glass Fibre	0.62	15900	23.8	0.00864	3180	2900
Copper Oxide	Silica	Kevlar	4	17600	26.4	0.0558	896	623
Copper Oxide	Silica	Hemp	0.5	17600	26.4	0.00695	4220	3950
Copper Oxide	Silica	Carbon Fibre	11	17600	26.4	0.153	595	322
Copper Oxide	Silica	Glass Fibre	0.62	17600	26.4	0.00864	3472	3200
Copper Oxide	Desert	Kevlar	4	15800	23.8	0.0558	849	576
Copper Oxide	Desert	Hemp	0.5	15800	23.8	0.00695	3850	3580
Copper Oxide	Desert	Carbon Fibre	11	15800	23.8	0.153	579	305
Copper Oxide	Desert	Glass Fibre	0.62	15800	23.8	0.00864	3170	2900

Circuit Diagram(s) & Structure

Figure 3 above is the Block Diagram of the circuit utilised in the experiment, with its various components and connections.

[!ht]

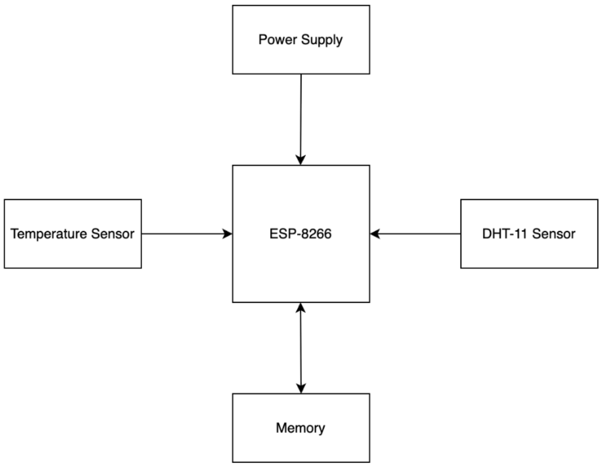

Fig. 3 Block Diagram of Circuit

[!ht]

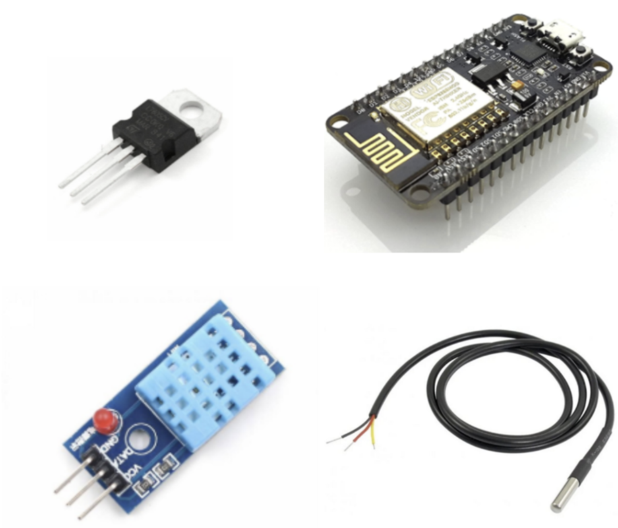

Fig. 4 IC7805 (Voltage Regulator), ESP-8266, DHT-11 Sensor, DS18B20 Sensor respectively[20–22]

The power supply of this circuit is an adapter. This is connected to an IC7805 (Figure 4), which is a voltage regulator that converts the given power supply into a constant 5V output. It also has an operating current of 5mA. The memory is being stored in a Micro SD Card Reader 2V26, which is a memory module. It has a 3.3V voltage regulator that is used to provide an adequate energy supply to the SD card.

The ESP-8266 is a microcontroller processor with seventeen general-purpose input and output pins (GPIOs). It is a module that can be connected to Wi-Fi, and contains the ability to process data, as well as read and control GPIOs. The processor is a standalone, wireless transceiver, that operates on low power. It supports Inter-Integrated Circuits (I2C), which is a communication protocol that is used for short-range communication between devices. Along with this, this microprocessor is capable of Serial Parallel Interface (SPI), which means it can send one piece of data or multiple pieces of data simultaneously.

The DHT-11 Sensor is a digital sensor to measure ambient temperature and humidity instantaneously. In order to do this, the sensor utilises a thermistor and a capacitive humidity sensor. The temperature range of this sensor is 0°C to 50°C, and its humidity range is from 20% to 80%. The sensor itself has four pins: VCC, GND, Data Pin, and a not-connected pin. It is of a small size, which means it also has a low power consumption.

The temperature sensor utilised is a DS18B20 sensor. It is a programmable, waterproof digital sensor probe that is designed to measure the temperature in any environmental conditions. It has been used to measure the temperature of the sand at specific time intervals, as the sand is being heated up. The operation of the sensor is based on a 1-wire serial communication protocol. It has three wires in the colours of red, black, and brown. While red and black are the positive and negative wires, respectively, the brown wire is used to collect and transmit the data. The probe of the sensor is made of a thermoresistive material i.e. the temperature will change as per the temperature of the material whose temperature is being measured.

Experimental Setup

The experimental setup includes two types of sand (Desert Sand, Silica Sand), four different materials for the battery (Kevlar, Hemp, Glass Fibre, Carbon Fibre) and two types of nanoparticles (Copper Oxide, Iron Oxide). Figure 5 below is an image of the circuit used in the experiment and the setup. The following steps were followed to achieve the setup in Fig-

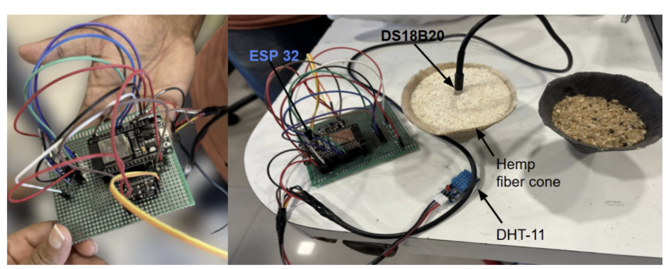

Fig. 5 Circuit & Experimental Setup

ure 5, for a setup without the nanoparticles:

1. 150g of the chosen sand was measured, and placed into the specific material container.
2. The memory card of the circuit was connected to a laptop and a folder for data-logging was created.
3. The memory card was then repositioned into the circuit.
4. The DS18B20 temperature sensor was placed into the sand, such that the entire sensor was completely submerged.
5. The DHT-11 sensor was placed at a small distance, to capture the ambient temperature and humidity.
6. The system was exposed to the sun for a period of two hours.
7. Temperature and humidity readings were taken at thirty-minute intervals.
8. After two hours, the system was brought into a sealed chamber.
9. It was left to cool down to room temperature, while readings continued to be taken at thirty-minute intervals.

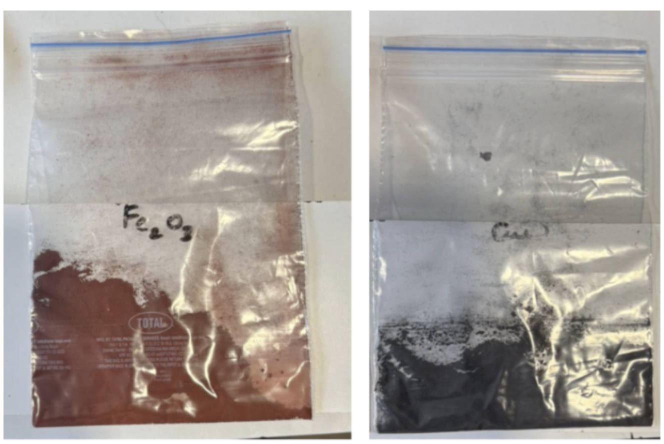

Fig. 6 Nanoparticles (Fe_2O_3) – Right; Cu_2O – Left)

A similar set of steps were followed to achieve the setup with the nanoparticles, which are shown in Figure 6 above. Instead of 150g of sand, 145g of sand was used. The additional 5g added was the nanoparticles. The ESP processor aided with attaching the sensors as well as collecting data in the SD card attached to the circuit. The same circuit structure was used to collect the data for all the types of sand batteries created for the research, as mentioned in the above methodology section.

Results

The temperature data collected every thirty minutes for each combination is summarised above in Table 9, thereby confirming both the fundamental material behaviour and the predictions of the thermal models. It is important to note here that certain combinations (e.g. Silica Sand, Kevlar and Fe_2O_3 have been excluded as they were anomalies, showing very little temperature difference after two hours. The heating tests across the sixteen sand battery prototypes below showed that adding the nanoparticles i.e. Copper Oxide (CuO) or Iron Oxide (Fe_2O_3 to the sand enhanced the heat absorption. The strongest result came from the Desert Sand combination with Kevlar and CuO nanoparticles (i.e. sample S10), which peaked at 147.1°C after 120 minutes.

Table 11: Experimental Reading of the Sand Heating (All Trials & Conditions)

ID	Sand Type	Container Material	Nanoparticle	Ambient Temp. (°C)	Temp. @ 30 min	Temp. @ 60 min	Temp. @ 90 min	Temp. @ 120 min
S1	Silica	Kevlar	None	33.2	68.4	102.1	119.3	128.4
S2	Silica	Kevlar	CuO	33.5	74.6	110.2	126.9	138.7
S3	Silica	Kevlar	Fe_2O_3	33.4	71.3	106.4	122.6	132.2
S4	Silica	Carbon Fibre	None	33.6	66.3	100.2	115.6	122.8
S5	Silica	Carbon Fibre	Fe_2O_3	34.1	72.3	108.4	122.8	134
S6	Silica	Hemp	None	32.9	61.5	94.2	106.5	112.3
S7	Silica	Hemp	CuO	33.1	65.7	98.3	113.4	121.3
S8	Silica	Glass Fibre	None	33.8	65.1	95.3	109.7	119.2
S9	Silica	Glass Fibre	CuO	33.9	69.7	104.2	118.1	127.3
S10	Desert	Kevlar	CuO	33	77.1	114.7	134.9	147.1
S11	Desert	Carbon Fibre	None	33.7	67.3	101.6	118.4	126.2
S12	Desert	Carbon Fibre	CuO	34	75.2	111.2	129.7	137.6
S13	Desert	Hemp	None	33.3	60.4	89.6	103.5	109.4
S14	Desert	Hemp	Fe_2O_3	33.4	65	97.3	110.6	118.9
S15	Desert	Glass Fibre	None	34.2	63.4	93.1	106.2	111.8
S16	Desert	Glass Fibre	CuO	34	70.8	106.4	122.3	132.6

Experimental temperatures from Table 9 above also reflect that Kevlar and Carbon Fibre canisters provide better thermal insulation, speeding up the rate of heat retention, as well as the extent of the same. Sample S2, which combined Silica Sand, Kevlar and CuO peaked at 138.7°C, while Sample 5, with Silica, Fe_2O_3 and Carbon Fibre peaked at 134.0°C. Both these results surpassed the performance of any sample without nanoparticles, indicating that the nanoparticles are critical to improving the efficiency of the battery.

Although the Hemp containers offer a low-cost, biodegradable and hence, eco-friendly option, they consistently lagged throughout the experiment, with and without the nanoparticles. The reason behind this performance compromise was the material's moisture retention, which led to a relatively high thermal leakage when compared with other materials. Glass Fibre, with nanoparticles, performed adequately from a mechanical perspective, but allowed heat to escape more quickly than desired.

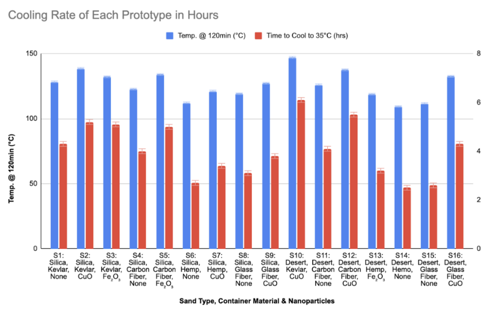

Fig. 7 Cooling Rate of Each material in Hours

The values presented above in Figure 7 are the mean values of the temperature at 120 minutes as well as the time taken to cool down. Two trials were conducted for each sample. The graph also represents the error bars for each of the dependent variables; an uncertainty of $\pm 0.5°C$ for the measured temperature and an uncertainty of ± 0.1 seconds for the time taken to cool down. Since these values are very minute in comparison to the collected data, they are moderately visible on the graph.

Alongside the heating tests, the cooling dynamics of each prototype was probed inside a chamber held at a constant ambient temperature of 25°C. The purpose of this was to mimic typical indoor thermal loss, as it would be in the application of the battery. Figure 7 above reflects the results of this aspect of the experiment, for all sixteen samples in Table 9.

The resulting cooling curves showed that the Kevlar and Carbon Fibre materials retained heat for noticeably longer periods of time, with the decreasing temperature persisting between 4.5 to 6 hours. This can be seen in sample S10, where the Desert Sand with Kevlar and CuO nanoparticles exhibited the slowest cooling, taking 6.1 hours to descend to 35°C. This effect arises from the slow thermal conductivity of Kevlar and the increased heat transfer in the sand, enhanced by the CuO nanoparticles.

In contrast, the samples using Hemp and Glass Fibre lost heat at a faster rate, with cooling curves indicating that they crossed 35°C in times between 2.5 to 3.8 hours. As mentioned before, these materials have a higher value of thermal leakage, reducing their efficiency in the long-run.

Discussion & Conclusion

Data Collection Procedure

This research has demonstrated that sand, when enhanced with Copper Oxide (CuO) or Iron Oxide (Fe_2O_3 nanoparticles, is a highly efficient medium for the storage of thermal energy. Amongst the sixteen samples tested in the experiment, the most suitable combination was S10, which was Desert Sand, Kevlar and CuO nanoparticles. As mentioned earlier, it achieved a peak temperature of 147.1°C and sustained heat for over 6 hours during the cooling time. Compared to the experimental run without the CuO particles and with Silica Sand, there was a 14.6% improvement in the performance of the experimental battery. The table below displays a similar comparison of the performance of S10 with the other samples.

Table 12: Comparison of Performances

Sample	Container Material	Nanoparticle	Sample Temp. @ 120 min	S10 Temp. @ 120 min	Percentage Improvement (%)
S1	Kevlar	None	128.4	147.1	14.6
S2	Kevlar	CuO	138.7	147.1	6.06
S3	Kevlar	Fe_2O_3	132.2	147.1	11.3
S4	Carbon Fibre	None	122.8	147.1	19.8
S5	Carbon Fibre	Fe_2O_3	134	147.1	9.78
S6	Hemp	None	112.3	147.1	31.0
S7	Hemp	CuO	121.3	147.1	21.3
S8	Glass Fibre	None	119.2	147.1	23.4
S9	Glass Fibre	CuO	127.3	147.1	15.6
S11	Carbon Fibre	None	126.2	147.1	16.6
S12	Carbon Fibre	CuO	137.6	147.1	6.90
S13	Hemp	None	109.4	147.1	34.5
S14	Hemp	Fe_2O_3	118.9	147.1	23.7
S15	Glass Fibre	None	111.8	147.1	31.6
S16	Glass Fibre	CuO	132.6	147.1	10.9

The following is a sample calculation for the comparison of S1 with S10.

$$\frac{147.1 - 128.4}{128.4} \times 100 = 14.563 \approx 14.6\%$$

Comparison with Theoretical Values & Research Literature

The results are also closely aligned with the theoretical data derived early in the investigation. The observed behaviour from both sets of information show the critical role that nanoparticles play in accelerating heat absorption and improving heat retention.

Based on other available literature, it is likely that with an increase in the concentration of nanoparticles, the thermal conductivity of the sand will also increase[23]. This is because an increased number of nanoparticles makes their concentration denser and more viscous, increasing the friction between them. Thus, heat is transferred more efficiently between the particles, improving thermal conductivity. Along with this, compared to coarse sand, fine sand is more capable of storing energy faster and for a longer period of time. According to a study[24], fine sand has a higher energy storage rate for the same amount of material, reducing the heat discharge times by 63.74%. Finally, in this study, the CuO particles performed better than the Fe_2O_3 ones likely attributable to copper's inherent atomic properties. Copper oxide has more free electrons, allowing it to transfer heat more easily due to its relatively free structure. On the other hand, iron oxide has a very tightly-packed lattice structure, preventing the movement of electrons.

The results of this experiment can be supported by the work of Balakrishnan et al.[25], who undertook a similar experiment with Cu-Water and Al2O3-Water nanofluids. Much like this experiment, the results of the research displayed an extraordinary improvement in the water's heat conductivity. With the Cu nanoparticles, thermal conduction increased by 31%, while with Al2O3, it rose by 42%. There is a larger percentage improvement in the thermal performance due to the larger quantities of nanoparticles used in this experiment. However, the results suggest the same: as compared to a substance without nanoparticles, a substance with nanoparticles has an improved thermal conductivity.

In summary, this study demonstrates that adding nanoparticles, particularly CuO, significantly enhances the thermal energy storage capacity of sand. The most effective sample, S10 (Desert Sand, Kevlar and CuO) reached 147.1°C and retained heat for over six hours. The experimental results of the study closely aligned with the trend displayed by the theoretical values. From this, the conclusion drawn is: higher nanoparticle concentrations improve thermal conductivity whereas finer sand improves energy storage efficiency. In terms of nanoparticles, CuO performed better than Fe_2O_3 due to its greater electron mobility, thus allowing a more efficient heat transfer.

Evaluation of Errors

1. In the experiment, the high humidity of the atmosphere could have acted as a source of systematic error while measuring the temperature because humidity would have affected the rate of heat transfer between the air and temperature sensor. The experiment was conducted during Mumbai's monsoon season, which was measured to have a humidity of 80%. The high humidity would have resulted in lower temperature readings than what was actually the case, for all the different materials.
2. Since the Desert sand was coarse, inconsistencies in its physical properties would have also introduced a minor error. The variations in the grain size, and thus density, could have altered the sand's thermal conductivity and heat capacity compared to what the theoretical values suggested. This would have had an effect on all the samples tested with Desert sand.
3. Another uncontrollable variable that would have affected the experimental results would be the variation in solar irradiance during the heating period. Unpredictable factors such as changes in cloud positions, the angle of the Sun and other atmospheric conditions would have directly impacted the amount of heat absorbed by the sand. Despite being conducted on two different days at the same time, due to the aforementioned reasons, the two trials of the experiment could have small inconsistencies in the maximum temperatures reached, unrelated to the properties of the sands, nanoparticles and materials being tested.

The following table is a representation of the percentage error between the theoretical and experimental values of the two top-performing samples, S10 and S2. A sample calculation for S10 at 120 minutes is also demonstrated below.

Table 13: Theoretical Vs Experimental Values

Time (minutes)	Theoretical Temperature (°C)	Experimental Temperature (°C)	Error Rate (%)
S10: Desert Sand, Kevlar & CuO			
0	32.56	33.0	-1.35
30	78.56	77.1	1.86
60	112.96	114.7	-1.54
90	135.76	134.9	0.63
120	146.96	147.1	-0.10
S2: Silica Sand, Kevlar & CuO			
0	33.15	33.5	-1.06
30	76.05	74.6	1.91
60	107.85	110.2	-2.18
90	128.59	126.9	1.31
120	138.25	138.7	-0.33

$$\begin{aligned}\%error &= \frac{32.56-33}{32.56}\times 100\\ &= -1.351\\ &\approx -1.35\%\end{aligned}$$

Further Applications

These findings create several pathways for practical applications of sand-based thermal batteries, in both industrial and residential settings. This is particularly true for off-grid or remote regions, especially in locations where there is a high solar exposure. However, there are still several areas open for further investigation. For example, long-term testing in real-world conditions with variable ambient climates is still essential to assess the model's viability. Furthermore, additional modifications can be made to improve the design of the battery so as to optimise solar energy collection. In conclusion, this study provides the foundation for a sustainable, cost-effective thermal solution that, with continued development, could aid with a transition to cleaner and more reliable renewable energy systems.

References

1 Flavio Odoi-Yorke, et al. "Optimisation of Thermal Energy Storage Systems Incorporated with Phase Change Materials for Sustainable Energy Supply: A Systematic Review." Energy Reports, vol. 10, Elsevier BV, Nov. 2023, pp. 2496–512, https://doi.org/10.1016/j.egyr.2023.09.044. Accessed 14 Feb. 2025.

2 IEA. "Global Energy Review 2025 – Analysis - IEA." IEA, 24 Mar. 2025, www.iea.org/reports/global-energy-review-2025.

3 "The Future of Energy: Large-Scale Solar Worldwide." ReNew: Technology for a Sustainable Future, no. 134, 2016, pp. 24–27. JSTOR, http://www.jstor.org/stable/renetechsustfutu.134.24. Accessed 6 Jan. 2026.

4 Wang, Haojie, and Qingyan Chen. "Impact of Climate Change Heating and Cooling Energy Use in Buildings in the United States." Energy and Buildings, vol. 82, Oct. 2014, pp. 428–36, https://doi.org/10.1016/j.enbuild.2014.07.034. Accessed 8 Mar. 2020.

5 Hamid, N., et al. "Challenges in Thermal Management of Lithium-Ion Batteries Using Phase Change Nanocomposite Materials: A Review." Journal of Energy Storage, vol. 100, Elsevier BV, Sept. 2024, pp. 113731–31, https://doi.org/10.1016/j.est.2024.113731. Accessed 19 May 2025.

6 Odoi-Yorke, Flavio, et al. "Optimisation of Thermal Energy Storage Systems Incorporated with Phase Change Materials for Sustainable Energy Supply: A Systematic Review." Energy Reports, vol. 10, Elsevier BV, Nov. 2023, pp. 2496–512, https://doi.org/10.1016/j.egyr.2023.09.044. Accessed 19 May 2025.

7 Naghavi Sanjani, Mohammad Sajad, et al. "Experimental investigation on solar water heater integrated with thermal battery using phase change material and porous media." Sustainability 15.8 (2023): 6439.

8 Piper, Samantha L., et al. "Sustainable materials for renewable energy storage in the thermal battery." RSC Sustainability 1.3 (2023): 470-480.

9 Kalidasan, B., Pandey, A. K., Rahman, S., Yadav, A., Samykano, M., & Tyagi, V. V. (2022). Graphene–Silver Hybrid Nanoparticle based Organic Phase Change Materials for Enhanced Thermal Energy Storage. Sustainability, 14(20), 13240. https://doi.org/10.3390/su142013240.

10 Wang, Kai & Qin, Zhen & Ji, Chenzhen & Tong, Wei. (2020). Thermal Energy Storage for Solar Energy Utilization: Fundamentals and Applications. 10.5772/intechopen.91804.

11 Khan, Huda. "AZoM." AZoM, 4 Oct. 2022, www.azom.com/article.aspx?ArticleID=22095. Accessed 22 May 2025.

12 Mini, K. M., et al. "BioFibre Composites in Building and Construction." Elsevier EBooks, Elsevier BV, Jan. 2022, pp. 335–65, https://doi.org/10.1016/b978-0-12-824543-9.00019-0. Accessed 22 May 2025.

13 "What Is Kevlar®?" Dupont.com, 2020, www.dupont.com/what-is-kevlar.html. Accessed 22 May 2025.

14 "Hemp Batteries." Hemp Acres, 2024, www.hempacresusa.com/blogs/blog/hemp-batteries. Accessed 22 May 2025.

15 g-innovative. "What Is Carbon Fibre? — Innovative Composite Engineering." Innovative Composite Engineering, 15 Jan. 2015, www.innovativecomposite.com/what-is-carbon-Fibre/. Accessed 22 May 2025.

16 A. Babapoor, et al. "Thermal Management of a Li-Ion Battery Using Carbon Fibre-PCM Composites." Applied Thermal Engineering, vol. 82, Elsevier BV, Mar. 2015, pp. 281–90, https://doi.org/10.1016/j.applthermaleng.2015.02.068. Accessed 25 May 2025.

17 Park, Soo-Jin, and Min-Kang Seo. "Element and Processing." Interface Science and Technology, Elsevier BV, Jan. 2011, pp. 431–99, https://doi.org/10.1016/b978-0-12-375049-5.00006-2. Accessed 25 May 2025.

18 "The Properties of Glass Fibre." PFH Private Hochschule Göttingen, 2025, www.pfh.de/en/blog/properties-glass-fibre. Accessed 25 May 2025.

19 "Fibreglass – Types, Properties, and Applications — Phelps Industrial Products." Phelpsgaskets.com, 2025, www.phelpsgaskets.com/blog/Fiberglass--types-properties-and-applications-across-industries. Accessed 25 May 2025.

20 "5 Piece Voltage Regulator 7805 : Amazon.in: Industrial & Scientific." Amazon.in, 2025, www.amazon.in/5-piece-voltage-regulator-7805/dp/0070530572. Accessed 1 Aug. 2025.

21 "How to Make an ESP8266 Work?" Arduino Forum, 12 Sept. 2016, forum.arduino.cc/t/how-to-make-an-esp8266-work/407391. Accessed 1 Aug. 2025.

22 "QBM DS18B20 Waterproof Digital Temperature Sensor-1M(100cm)-Unique 64-Bit ID-Waterproof Temperature Sensor-Heat Resistant Thermal Cable-Black : Amazon.in: Industrial & Scientific." Amazon.in, 2025, www.amazon.in/QBM-Temperature-ID-Waterproof-Sensor-Heat-Cable-Black/dp/B0D5CSCGLP. Accessed 6 Aug. 2025.

23 Joshi, Yogesh, et al. "Influence of Nanoparticle Concentration on Thermophysical Properties and Heat Transfer Performance of Al2O3 Nanosuspension for Refrigeration System." Materials Today Proceedings, vol. 56, Elsevier BV, Jan. 2022, pp. 995–1000, https://doi.org/10.1016/j.matpr.2022.03.227. Accessed 13 Jan. 2026.

24 Niksiar, Paniz, et al. "Experimental Study of a Silica Sand Sensible Heat Storage System Enhanced by Fins." Energies, vol. 17, no. 21, MDPI AG, Oct. 2024, p. 5402, https://doi.org/10.3390/en17215402. Accessed 13 Jan. 2026.

25 Balakrishnan, S., et al. "Impact of Nanoparticle Concentration on Thermal Properties of Nanofluids in Heat Exchangers." E3S Web of Conferences, edited by N. Nwulu et al., vol. 619, EDP Sciences, 2025, p. 05008, https://doi.org/10.1051/e3sconf/202561905008. Accessed 13 Jan. 2026.