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Original Article

Energy Efficiency of Solar Water Heater from Alternative Materials

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Abstract: *This research investigates the energy efficiency of solar water heaters constructed from alternative materials, emphasizing their relevance in regions with inadequate electrical infrastructure and low financial capacity. The study identifies and evaluates alternative materials to reduce production and installation costs, making solar heating systems more accessible. The research highlights the significant environmental and economic benefits of solar heaters, including reduced CO_2 emissions and lower operating costs compared to traditional gas and electric systems. The prototype developed demonstrates a thermal efficiency of 58%, showcasing the potential of alternative materials in sustainable energy solutions. The findings underscore the importance of continuous research and development to enhance efficiency and promote large-scale adoption of solar water heaters, contributing to the diversification of the energy matrix and environmental preservation. This work advances knowledge in the field of solar radiation utilization for water heating and provides a foundation for future research and practical applications.*

Keywords: *Energy Efficiency, Sustainability, Alternative Materials, Solar Heater.*

I. INTRODUCTION

The growing demand for sustainable energy sources and the need to reduce dependence on fossil fuels have driven research and the development of alternative technologies around the world. In Mozambique, a country with vast solar potential and deficiencies in electricity and water supply infrastructure, it is crucial to develop capacities to meet these needs in a sustainable way [1]. According to an analysis conducted in Mozambique, it was found that, despite the country having a high solar potential, by 2021 only a few systems had been installed [2]. Especially noteworthy are the domestic forced circulation and multifamily systems, installed under the SOLTRAIN project. The study shows that solar water heating systems can reduce electricity consumption in grid-connected homes by up to 76%, depending on the configuration and weather conditions [3]. Gas heating systems, on the other hand, are efficient in providing hot water, but rely on fossil fuels, which can limit their efficiency due to fluctuations in gas prices.

The environmental impact of solar thermal heating systems is significantly lower compared to traditional gas and electric systems. Replacing fossil fuel-based heating systems with solar systems can reduce CO_2 emissions by up to 1.5 tons per year per household (Fig. 1a) [4]. While the initial cost of installing solar thermal systems is higher, the operating costs are significantly lower as solar energy is free, and maintenance is minimal. In contrast, gas-powered systems have a lower initial cost, but operating costs can be high due to the price of gas and the need for regular maintenance (Fig. 1b) [5].

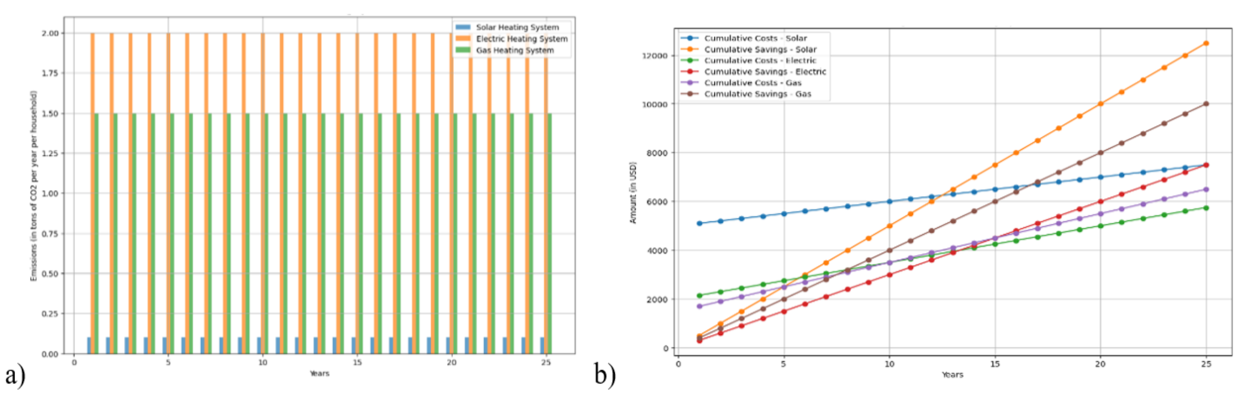

Figure 1: a) Estimated GHG Emissions of water Heating Systems Over their Lifetime, and b) Cumulative Costs and Savings of Eater Heating Systems Over Their Lifetime

As illustrated in Fig 1b), the solar heater has a high initial cost. However, between 10 to 15 years, a significant return on investment is observed, resulting in remarkable energy savings compared to other systems. In addition, when considering the reduced environmental impact due to the minimal emissions of pollutants from solar energy, these systems become extremely attractive for research and development to reduce the barrier of high initial cost.

Mozambique has a rural population and a history of instability, facing economic and political uncertainty. With poor electrical infrastructure and low financial capacity, solar heating systems are a viable and sustainable solution [6]. Solar energy is abundant and free, which can alleviate financial pressure on low-income families. Additionally, the Renewable Energy Plan for Mozambique highlights the diversification of the energy matrix and the implementation of solar systems to reduce dependence on fossil fuels and decrease the need for deforestation to obtain woody biomass. Despite the benefits mentioned, the adoption of solar water heaters faces significant challenges, such as the high initial cost and the lack of adequate infrastructure for installation and maintenance. Public awareness and acceptance of these technologies are still limited, which can hinder large-scale adoption [3] [7].

The literature review shows that solar water heating systems are efficient and sustainable alternatives to traditional gas and electric systems. They offer significant environmental and economic benefits, particularly for regions with inadequate electrical infrastructure and low financial resources. Ongoing research and development of accessible technologies are crucial to overcoming current barriers and promoting large-scale adoption of these solutions for reducing emissions through clean energy [8].

The research aims to achieve several important contributions. Firstly, the identification of alternative materials that can reduce the production and installation costs of solar heating systems. Secondly, the development of solutions that make these systems more accessible to the general population, especially in rural areas. Additionally, the promotion of sustainable practices will contribute to environmental preservation. Finally, the creation of a prototype and a theoretical framework can be used in future research and academic demonstrations, encouraging the advancement of knowledge in the field of solar radiation utilization for water heating.

II. LITERATURE REVIEW

A. Mozambique's solar potential

Mozambique has significant and untapped solar potential. The country's global solar irradiation varies between 1,785 and 2,206 kWh/m^2/year, representing an estimated potential of 23,000 GW [9]. This resource is abundant and consistent in most parts of the country, especially in the provinces of Niassa, Nampula, Cabo Delgado and Zambézia and Tete, which have the highest levels of irradiation [10].

According to PROLER, the Mozambique Renewable Energy Atlas has identified 189 sites for grid-connected power plants, close to existing substations, with a total capacity of 599 MW. This potential makes the sun the most abundant renewable resource in Mozambique, with around 600 MW of projects with grid connection feasibility. These data confirm the abundance of solar energy in the country [10].

Solar energy plays a crucial role due to Mozambique's vast solar potential. The country has a high solar incidence, making solar energy a viable option to meet energy needs, especially in rural and remote areas where electrical and thermoelectric infrastructure are limited [11]. The implementation of solar energy projects in Mozambique has the potential to significantly improve access to electricity and thermal energy, promote sustainable development, and reduce dependence on non-renewable energy sources [12].

In addition, solar energy contributes to the diversification of Mozambique's energy matrix, which currently relies heavily on hydropower. Diversification is essential to increase the resilience of the country's energy system and reduce the risks associated with climate change and water resource variability [11]. Solar energy can also help Mozambique achieve its sustainable development goals, including Sustainable Development Goal 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030 [12] [13].

B. Types of solar heaters

There are two main types of solar heaters: passive and active. In passive systems, such as thermosiphon, water circulation occurs naturally due to the difference in density between hot and cold water. These systems are simple and do not require pumps or electronic controllers, but their efficiency may be limited in cold weather [2].

Active systems, on the other hand, use pumps to circulate water or heat transfer fluid between the solar collector and the thermal reservoir. These systems allow for greater control and efficiency, making them ideal for large commercial, industrial, and residential buildings with high hot water demands. However, they require electrical power to run the pumps and controls, which can increase operating costs [2] [14]. Figure 3 shows the classification of solar heaters.

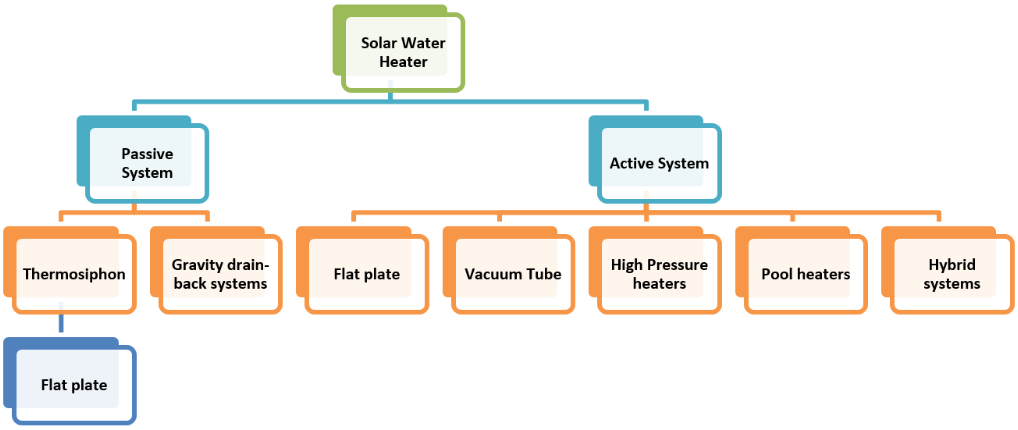

Figure 3: Classification of solar water heaters

These heaters can be classified by their thermal energy conversion capacity. Figure 4 shows the temperature capability generated by each type of system, indicating its application.

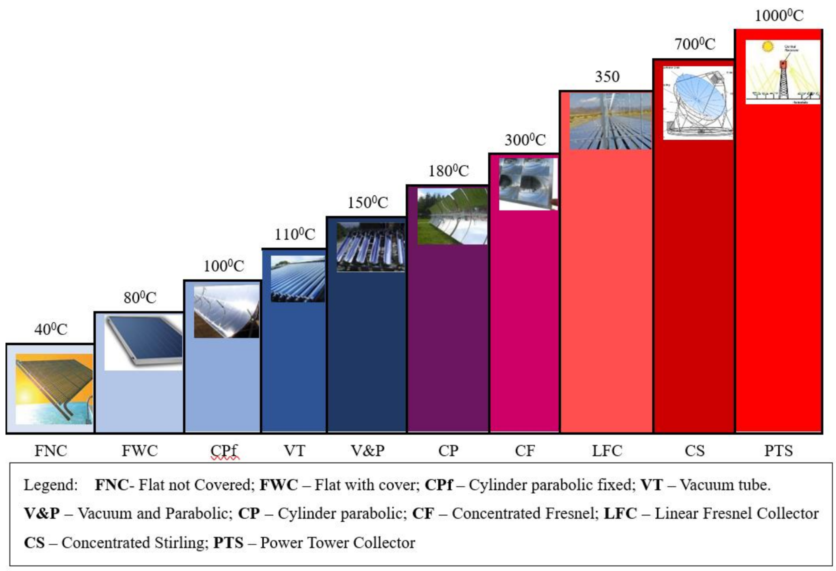

Figure 4: Operating Levels of Different Solar Heaters

Figure 4 shows that flat collector plates for swimming pools are in the lowest temperature range, followed by those used in homes. At the other end, with high temperature values are the collectors producing steam used in power plants [1].

C. Working principles of Solar heaters

Solar water heating systems work by capturing solar energy and transferring it to water, providing an efficient and sustainable solution for water heating. Solar collectors are devices installed in locations with maximum solar exposure, such as rooftops. They capture solar radiation and convert it into thermal energy. Solar radiation strikes the absorb surface of the collectors, which is usually black to maximize heat absorption. This heat is transferred to a fluid (water or a mixture of water and anti-freeze) that circulates through tubes in the collector [14].

In passive systems, water circulation occurs naturally due to the density difference between hot and cold water, a process known as thermosiphon. These systems do not require pumps or electronic controllers. In active systems, pumps are used to circulate the fluid between the solar collectors and the thermal storage tank. These systems allow for greater control and efficiency [14].

The thermal storage tank, or boiler, is an insulated tank where the heated water is stored. The water heated in the solar collectors is transferred to the thermal storage tank, where it is stored for later use. The tank's insulation helps minimize heat loss [15]. In direct systems, water is heated directly in the solar collectors and stored in the tank. In indirect systems, a heat transfer fluid is heated in the solar collectors. This heat is then transferred to the water through a heat exchanger [16].

Active systems typically include electronic controllers to monitor and adjust fluid circulation. Temperature sensors monitor the water temperature in the collectors and the storage tank. When the temperature in the collectors is higher than in the tank, the pump is activated to circulate the fluid and transfer the heat [17].

Solar water heating systems offer several benefits, such as energy savings, reduced dependence on conventional energy sources, and environmental sustainability. Well-maintained systems can last 15 to 20 years, providing a reliable and efficient energy source [18].

D. Mathematical Formulas Involved

Solar water heating systems involve several mathematical formulas to calculate the system's efficiency and performance.

a) Solar energy incident ($Q_{\_solar}$)

The solar energy incident on the collectors can be calculated by (Eq. 1):

$$Q_{\_solar} = I \times A \times t \quad \text{(Eq. 1)}$$

Where: $Q_{\_solar}$ - Solar energy incident (J); I- is the average solar irradiance (W/m^2) converted from the illuminance with the rnatio 1 lux ≈ 0.0079 W/m^2 according to Michael, Johnston & Moreno ([19].

A- is the area of the solar collector (m^2); t - is the average daily sunshine time (s). Useful Thermal Energy ($Q_{\_usef}$)

The useful thermal energy acquired by water is given by (Eq. 2) [13]:

$$Q_{\_usef} = m \times Cp \times \Delta T \quad \text{(Eq. 2)}$$

Where: Q_usef – Useful thermal energy (J); m - It is the mass of heated water (kg); c - It is the specific heat of water (approximately 4186 J/kg°C); Δt- It is the variation in water temperature (°C).

b) Thermal Efficiency (η)

The thermal efficiency of the system is the ratio of the useful thermal energy to the incident solar energy that can be calculated by Equation (3):

$$\eta = (Q_{\_usef})/(Q_{\_solar}) \times 100\% \quad \text{(Eq. 3)}$$

Where: η - Thermal Efficiency (%); $Q_{\_usef}$- Useful thermal energy (J); $Q_{\_solar}$- Incident solar energy (J)

c) Economic Cost and Benefit Analysis

The cost and benefit analysis were conducted considering the acquisition and installation costs including the price of the solar collector, additional materials, and labor. The total initial cost ($C_{\_initial}$) was calculated using Eq. 4:

$$C_{\_initial} = C_{\_equipament} + C_{\_installation} \quad \text{(Eq. 4)}$$

d) Operational and Maintenance Cost Estimates

Operational costs include regular maintenance and occasional repairs. The annual operational cost (Operational) is estimated using Eq. 5:

$$C_{\_Operacional} = C_{\_\ Maintenance} + C_{\_\ Repairs} \quad \text{(Eq. 5)}$$

e) Economic Benefits Estimate

The annual energy savings ($E_{\_\ economy}$) can be calculated by the difference in energy consumption with and without the solar collector, as expressed by Equation 6:

$$E_{\_\ economy} = E_{\_without\ collector} - E_{\_\ with\ -collector} \quad \text{(Eq. 6)}$$

Where: $E_{\_economy}$ is the energy saved (kWh over a certain period). $E_{\_without\ collector}$ is the energy used without the solar heater (kWh over a certain period). And E_with-collector is the energy used with the solar heater installed (kWh over a certain period).

Assuming energy savings equals the useful energy provided by the solar system per day:

$$E_{\_\ economy} = E_{\_\ usef} = m \cdot Cp \cdot \Delta t \quad \text{(Eq. 7)}$$

Where: $E_{\_usef}$ is the electrical energy needed to heat water from ambient temperature to the temperature at the collector outlet or hot water reservoir (J). For conversion, 1 kWh = (3.6 x 106) J. Installing a solar system is expected to reduce electricity bills. Equation 9 estimates this reduction:

$$R_{\_bill} = E_{\_economy} \cdot C_{\_electricity} \quad \text{(Eq. 8)}$$

Using Equation 9, it is noted that the reduction in bills ($R_{\_bill}$) depends on the source and the local cost of energy.

III. MATERIALS AND METHODS

A. Materials

The following are listed all the materials used in the construction and assembly of the flat solar water heater, as well as the equipment used for the collection and analysis of experimental data.

Table 1: Materials used in the construction and assembly of the flat solar water heater

Material	Discription
Galvanized pipe	¾" diameter, 5m length
AFZELIA QUANZENSIS Wooden Planks	Length (02) 1.40m and (02) 0.70m, cross-section 3cm x 12cm
Connectors	(18) PPR ¾" T-joints, (1) IPS ¾", (02) Simple unions, (04) Articulated; (04) IPS ¾" Elbows
Flat glass	132x67.5cm, 5mm thickness
Plastic sheeting	135x70cm greenhouse plastic sheeting
Flat zinc sheet	135x70cm, 4.5mm thickness
Corrugated zinc sheet	132x65cm, 2mm thickness
Aluminum thermal blanket	120x100cm
PVC buckets (recycled)	(02) 20 L reservoirs each, maximum diameter 30cm, height 30cm
Flat zinc sheet	100x35cm, 4.5mm thickness
Mechanical float	(01) Short stem ¾"
Flexible tube for "hot water draw"	30cm length
Thermal blanket	For collector insulation 100cm x 30cm
L-shaped metal bracket	For system structure 30x30x3cm, 580cm length
Oil paint (spray)	500ml for structure protection
Ball valve	¾" valve for water flow control
Assembly equipment	
Reference solar heater	Heater made of conventional materials like aluminium, copper, and tempered glass for energy efficiency comparison
IPS pipe	For connecting collector and water reservoir buckets
Teflon tape	To ensure leak-free connections
Aluminum foil	For insulating pipes at the hot water outlet of the collector
Clamps	For insulating pipes at the hot water outlet of the collector
Welding machine	Essential for assembly
PPR pipes	Essential for assembly
Drill	For drilling and screwing
Screws	Essential for assembly
Angle grinder	For cutting zinc sheet, pipe, tubes, and metal brackets
Metal brackets	For heater structure
Paint	For rust protection

B. Solar Heater Construction Method

The prototype heater was built according to a standardized protocol, ensuring consistency and reproducibility of the results. This section details the design, assembly, and essential care during construction, ensuring that each step of the process is executed with precision and attention to detail. Fig 5 presents some equipment used in the construction.

Figure 5: Equipment Used in the Assembly of Solar Heater Components

a) Solar Collector Frame Construction

The *Chanfuta* wood (*Afzelia Quanzensis*) planks were cut and assembled to form the base structure of the solar heater. A smooth zinc plate was attached to the base of the frame for support. Fig. 6 shows a) a network of galvanized steel pipes where water circulates in the collector, b) preparation of the wooden frame for the assembly of the collector pipes. C) Collector mounted with plastic canvas covering, d) Collector mounted with glass covering.

Figure 6: Solar Collector Assembly Steps

b) Instruments Used for Data Collection

In addition to the construction and assembly equipment, specific instruments were used to collect data on the variables of interest to test and estimate the energy efficiency of the solar heater. Table 2 lists the main equipment and their descriptions.

Table 2: Equipment used for Data Collection

Material-Equipment	Description	Illustration
Anemometer	It measures wind speed and air temperature. The air velocity measurement range is 0.3~3 (± 5%). Air temperature, -10C~45C ± 2. Resolution: 0.2C, 0.2m/s.	
Pyranometer	MX2202: HOBO MX Temp/Light Waterproof temperature/light level logger leverages the power of Bluetooth Low Energy (BLE). To radiation measurement	
Data Logger	LogEt 8 TE: Multi-use PDF Temperature Data Logger (-40°C to 85°C). To record temperature and humidity over time.	
Thermocouples	Waterproof DS18B20 Digital Temperature Sensor to collect dates in different points	

c) Final Assembly

After assembling the collector and installing the pipes in the reservoirs, they were mounted on the metal structure to allow water circulation and heat transfer by thermosiphon. The hot water reservoir was placed at the bottom, and the feed water reservoir was positioned at the top, as illustrated in figure 6. The metal structure supporting the collector was designed to allow inclination adjustments between 15 and 30 degrees, optimizing performance in both summer and winter.

Side View Rear View

Figure 7: Solar Heater in Trials and Data Collection

IV. RESULTS AND DISCUSSION

A. Energy Efficiency

After the literature search, alternative materials were selected according to local availability, cost and thermophysical capacity. Table 3 shows the materials used in the construction of the heater.

a) 

Legend: a) Alternative material collector plate; b) Alternative solar heater; c) Prototype under testing

Figure 81: Solar heater made by alternative materials

a) Preliminary Data

The initial data for the calculation of the energy efficiency of the solar heater have been summarized and are presented in table 3 below.

Table 3: Initial Parameters for Energy Efficiency

#	Parameter	Average Value	Unit
1	Water density (ρ)	1000	kg/m^3
2	Ambient water temperature (T_{amb})	25	°C
3	Average water temperature at the collector outlet (T_f)	50	°C
5	Water temperature in the hot water reservoir (T_{usef})	42	°C
6	Solar collector area (A)	0,81	m^2
7	Average solar irradiance (I)	0,800	kW/m^2
8	Water mass in collector plus in reservoir (m)	26	kg
9	Local air flow	0,2	m/s
10	Local relative humidity (Hr)	94.5	%
11	Specific heat of water (Cp)	4186	J/kg°C

Table 3 presents collected data that includes critical variables such as water density, volume of water in the collector, temperatures at different points in the system, area of the solar collector, average solar irradiance, and other environmental and physical factors.

b) Orientation and Tilt of Solar Collectors

According to Jacome & Chagas [20], the orientation and inclination of solar collectors are crucial factors for optimizing the efficiency of solar energy systems. The ideal orientation varies according to the hemisphere: in the southern hemisphere, collectors should be oriented to the north, while in the northern hemisphere, they should face south [21].

The inclination of the collectors should be adjusted to maximize exposure to sunlight throughout the year, considering the location's latitude and the seasonal variations of the solar path [20], [21]. For Maputo, Mozambique, which is located at a latitude of approximately -25,97° (latitude: -25,9655°, longitude: 32,5832°), the solar collectors should be oriented towards true north. The ideal inclination for fixed collectors is about 22,55°. Seasonal adjustments can be made to further optimize energy harvesting: 45,1° in summer and 3,5° in winter, or 48,1° in summer, 0,9° in winter, and 27,7° in autumn and spring [22].

c) Data Collecting

The temperature data for the estimation of energy efficiency were collected using a data logger with sensors connected to the external surface of the collector, at the water inlet to the collector, and at the water outlet from the collector. The results were repeated over 3 days, and the average data was compiled and presented in Figure 9 below.

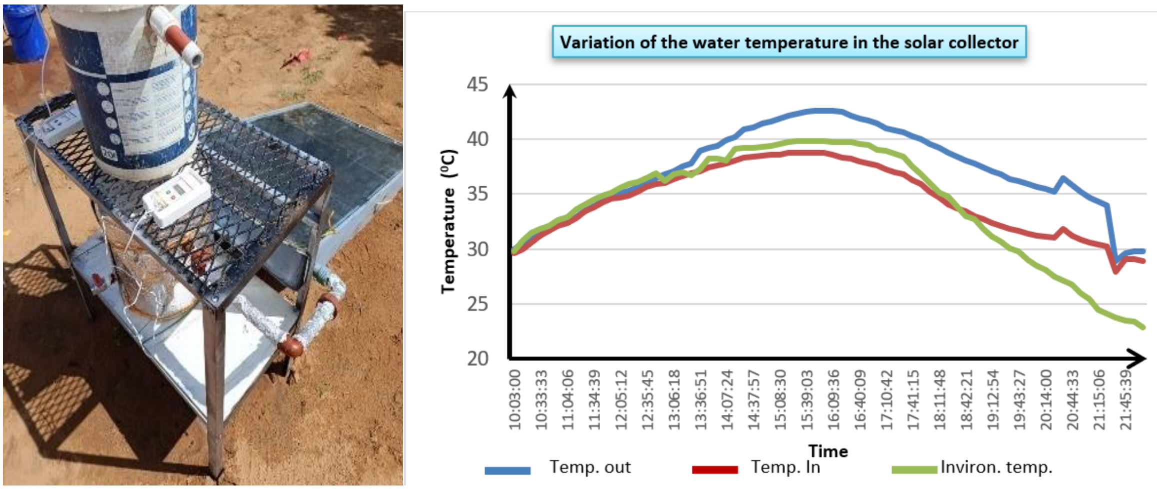

Figure 9: Data Collection in the Heater and Graphs of Temperature Variation in the Water

The energy efficiency of the solar collector built with alternative materials was determined based on Eq. 3, and table 4 presents a summary of the parameters calculated to obtain the efficiency of the prototype.

Table 4: Energy Efficiency Calculation Parameters

Ref	Parameter	Source Equation	Value	Unit
1	Incident Solar Energy ($Q_{\_solar}$)	Eq. 1	1,296	kWh/day
2	Useful Thermal Energy ($Q_{\_usef}$)	Eq. 2	2720.9	kJ
			0.756	kWh/day
3	Thermal Efficiency (η)	Eq. 3	58	(%)

Table 4 shows the energy captured and converted into useful energy by the prototype collector, allowing the determination of thermal efficiency, which resulted in 58%.

Vendramin et al. [20] reported an average efficiency of 52.8% using materials like expanded polyethylene, PVC pipes, aluminium, glass, and insulation blankets. The discussed prototype thermal collector achieved 58% efficiency, higher than Vendramin's system but lower than the solar collector's daily average of 60.6%.

The energy efficiency of 58% achieved exceeds the comparative study's results from Abreu et al. [23], where efficiencies ranged from 35.7% to 46.3% depending on the orientation of the tubes. This indicates that this prototype implemented more effective solutions, standing out as a promising alternative when compared to the systems analyzed.

Bortoletto & Pezzuto [24] reported an average efficiency of 55% for low-cost solar heaters with alternative thermal reservoirs. This is slightly lower than the 58% efficiency of the prototype, indicating that the prototype performs better than some low-cost alternatives but still has potential for further optimization.

Carioli [25] found thermal efficiencies between 60% and 70% in systems with stratified reservoirs. These higher efficiencies highlight the importance of advanced design features, such as stratified reservoirs, which can significantly improve thermal performance. The prototype's efficiency of 58% is within the lower range of these findings, suggesting that incorporating similar design features could enhance its performance.

Technological advancements in the use of alternative materials for solar water heaters have shown improvements in thermal efficiency. The results of this research indicate that there is potential for further improvements with the development of the final design. Investing in research and development can lead to significant advances in the efficiency of thermal collectors.

In summary, while the prototype's efficiency of 58% is a commendable achievement, it is essential to explore and implement advanced design features and materials to reach higher efficiency levels observed in other studies. Continuous innovation and optimization will be key to achieving significant improvements in thermal collector performance.

d) Cost-Benefit Analysis

To find cheaper materials for solar heaters that can help low-resource populations, we conducted a cost-benefit analysis. The solar heater has a 26-liter capacity and 58% efficiency. The results are based on the costs in Table 5.

Table 5: Annual Total Cost of Solar Heater

Ref	Parameter	Value	Unit		Parameter	Reference	Value	Unit
1	Equipment Cost	13,000	MZN		Initial Cost	Eq. 4	13,000	MZN
2	Installation Cost	0	MZN		Operational Costs (annual)	Eq. 5	500	MZN
3	Annual Maintenance Cost	0	MZN		Daily Energy Savings	Eq. 7	0,76	kWh/day
4	Annual Repair Cost	500	MZN		Annual Energy Savings	365days	275,87	kWh/year
5	Electricity Cost	8,122	MZN/kWh		Reduction in Electricity Bills (Annual)	Eq. 8	2,538.00	MZN

Table 5 provides an estimate of the reduction in electricity bills when using the prototype for solar water heating daily. The estimated value (2,538.00 MZN) is significant considering the small volume of water heated by the prototype. This value corresponds, on average, to an annual saving of 2,538 * 2 = 5,076 MZN per person, considering two showers daily. Considering the average number of members in Mozambican households, which ranges from 6 to 8 people, the reduction in electricity bills is significant [12].

V. CONCLUSION

The results of this study demonstrate that the use of alternative materials in the construction of solar water heaters can be a viable and sustainable solution for regions with inadequate electrical infrastructure and low financial capacity. The developed prototype showed a thermal efficiency of 58%, which is comparable to other low-cost solutions available on the market. Additionally, the cost-benefit analysis indicated a significant reduction in electricity bills, making the solar heater an economically advantageous option for low-income families. These findings are important as they highlight the feasibility of sustainable and accessible technologies that can contribute to reducing dependence on fossil fuels and mitigating CO_2 emissions.

The implementation of solar water heaters with alternative materials can also promote the diversification of the energy matrix and environmental preservation in countries like Mozambique, which have great solar potential. However, it is necessary to continue investing in research and development to improve efficiency and reduce the initial costs of these systems. Public awareness and acceptance of these technologies are crucial for large-scale adoption. In summary, this work contributes to the advancement of knowledge in the use of solar radiation for water heating and provides a theoretical and practical basis for future research and academic demonstrations.

For future studies, it is recommended to investigate new alternative materials that can further increase the thermal efficiency of solar water heaters. In addition, the optimization of the design of solar collectors and the incorporation of advanced technologies such as the integration of heat storage materials, stratified reservoirs, can significantly improve the performance of the systems. Additional studies should also focus on economic feasibility analysis in different regional contexts and the implementation of public awareness programs to increase the acceptance and adoption of these technologies. Continuous research and development of innovative solutions are essential to overcome current barriers and promote the large-scale use of sustainable and affordable solar water heaters.

The authors declares that there is no conflict of interest concerning the publishing of this paper.

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