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THERMAL EFFICIENCY OF FLAT PLATE SOLAR COLLECTORS USING COCONUT SHELL AND BAMBOO CARBON ABSORBERS IN SOLAR WATER HEATERS

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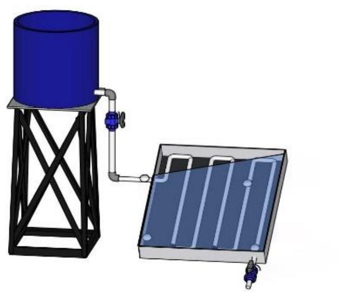

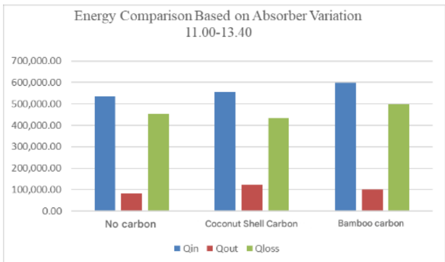

Abstract
Utilizing solar energy through *solar water heaters* is one solution to reduce dependence on fossil fuels and support the use of environmentally friendly energy. The performance of this system is influenced by the ability of the absorber plate to absorb and conduct heat. The problem in this study is how the effect of carbon-based absorber coatings on improving the thermal performance of flat plate solar collectors compared to absorbers without carbon coatings. The study was conducted experimentally using a 75 × 75 cm collector with a 3 mm cover glass and copper pipes. Testing was carried out for three days for each absorber variation with a 20-minute interval at 08.00–16.00. The parameters measured included inlet and outlet water temperatures, collector temperature, pipe temperature, and solar radiation intensity. Thermal efficiency was calculated based on the ratio of energy absorbed by water to solar radiation energy. The results showed that the collector without carbon coating had an efficiency of 18.7% with a water volume of ≥50°C of 15.77 liters. Bamboo carbon increased the efficiency to 21.2% with a volume of 23.66 liters, while coconut shell carbon provided the best performance with an efficiency of 25.4% and a volume of 28.51 liters. It was concluded that coconut shell carbon is the most effective absorber coating and has the potential as an efficient and sustainable local material.

Keywords: solar water heater, solar collector, carbon absorber, thermal efficiency, solar energy

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1. Introduction

The increasing global demand for energy, driven by population growth and industrialization, has intensified dependence on fossil fuels. This reliance gives rise to two major issues: the depletion of energy reserves and the escalation of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which significantly contributes to global climate change [1][2]. Therefore, the development of renewable energy has become a strategic solution to reduce dependence on fossil fuels while simultaneously lowering carbon emissions.

Solar energy is one of the most promising renewable energy sources due to its abundance, sustainability, and environmental friendliness, especially in tropical regions such as Indonesia, which receive high solar radiation intensity throughout the year [3]. The thermal utilization of solar energy, particularly in solar water heating systems, has developed rapidly because it offers relatively higher energy conversion efficiency compared to photovoltaic systems for heating applications [4]. In this system, the solar collector functions to absorb solar radiation and convert it into thermal energy, which is then transferred to the working fluid [5]. Flat-plate collectors are the most widely used type due to their simple construction, relatively low cost, and ability to effectively utilize both direct and diffuse radiation [6]. Their thermal performance is strongly influenced by the characteristics of the absorber material, particularly its ability to absorb radiation and transfer heat. An ideal absorber material should have high absorptivity, low emissivity, good thermal conductivity, and stability under operating temperatures [10]. Therefore, improving the quality of absorber materials is a key factor in enhancing collector efficiency.

Various approaches have been undertaken to improve absorber performance, including the use of selective coatings, nanomaterials, and carbon-based materials [15]. Carbon-based materials offer advantages such as dark color with high absorptivity and good thermal conductivity [17]. In addition, the porous structure of biomass-derived carbon can increase the specific surface area, thereby enhancing interaction with solar radiation [14]. This makes carbon a promising candidate for absorber coatings in solar collectors. However, system efficiency is still limited by heat losses to the environment, indicating the need for materials that not only optimally absorb radiation but also support effective heat transfer [16].

Although research on carbon-based materials continues to grow, studies specifically comparing the thermal performance of different types of biomass-derived carbon as absorber coatings in flat-plate collectors remain limited. In particular, there is a lack of direct comparative studies between coconut shell carbon and bamboo carbon under identical operating conditions in solar water heating systems. In fact, these two materials possess different structural characteristics and thermal properties, which may significantly influence collector performance.

Based on this research gap, this study aims to analyze and compare the thermal efficiency of flat-plate solar collectors using coconut shell carbon and bamboo carbon as absorber materials under uniform testing conditions. The main contribution of this research is to provide a direct comparative evaluation of two locally sourced biomass-based carbon materials within the context of practical application in solar water heating systems. The findings are expected to offer a scientific basis for selecting efficient, low-cost, and environmentally friendly absorber materials, as well as to support the optimization of solar energy utilization in Indonesia [19].

2. Materials and Methods

This study uses an experimental method with a comparative design to analyze the effect of variations in absorber coating materials on the thermal performance of flat-plate solar collectors in solar water heating systems. The study was conducted by comparing two types of biomass-based materials, namely coconut shell carbon and bamboo carbon, as absorber surface coatings. The experimental approach was chosen to obtain empirical data directly through system testing under controlled operational conditions.

Quantitative data analysis techniques were used using basic equations for heat transfer and solar collector efficiency. The measurement data were processed to determine useful energy and thermal efficiency, then compared between the two material variations. The analysis was conducted descriptively and comparatively to identify the best-performing material and explain the relationship between material characteristics and system thermal performance.

2.1. Material

The main materials used in this study include the components of a solar water heating system with a flat plate solar collector, while the test objects focused on a variety of carbon-based absorber materials, namely coconut shell carbon and bamboo carbon. The following are the main components of the flat plate solar collector system used in this study.

1. Coconut shell carbon

Coconut shell carbon has the ability to absorb heat that supports it as an absorber material in solar collectors. This material has a high surface area (800–1500 m^2/g) due to the dominance of micropores, thus increasing the absorption of radiation. Its thermal conductivity ranges from 0.1–0.3 W/m·K which allows heat transfer to the pipe, and the high fixed carbon content (70–85%) provides good thermal stability. The combination of these properties makes coconut shell carbon effective as an absorber material in *solar water heater systems*.

Table 1 Coconut Shell Carbon Specifications

Specification	Description
Surface Area (BET)	500–1200 m²/g
Thermal Conductivity	0.08–0.25 W/m·K
Fixed Carbon Content	60–80%

2. Bamboo carbon

Bamboo carbon has thermophysical properties that support its use as an absorber material in solar collectors. This material has a specific surface area ranging from 500–1200 m²/g with a micro-mesoporous pore structure that helps distribute heat more evenly. Its thermal conductivity is in the range of 0.08–0.25 W/m·K, thus enabling heat transfer although relatively lower than coconut shell carbon. In addition, the fixed carbon content of 60–80% indicates quite good thermal stability. With these characteristics, bamboo carbon has the potential to be used as an absorber material, especially in supporting heat distribution on the collector surface.

Table 2 Bamboo Carbon Specifications

Specification	Description
Surface Area (BET)	800 – 1500 m²/g
Thermal Conductivity	0.1 – 0.3 W/m·K
Fixed Carbon Content	70 – 85%

3. Thermocouple

Thermocouples function to measure the temperature of the water entering and leaving the collector (Tin and Tout) which is used as the basis for calculating heat energy (Qout).

Figure 1 Thermocouples

Tabel 3 Thermocouples Specification

Specification	Description
Operating Temperature	0° - 400°
Power Supply	2xAA 1.5 V
Diameter	10.6 cm x 7.1 cm
Cable Length	100 cm
Type	K- Type

4. lux Meters

Lux meter functions to measure the intensity of sunlight which is then used as a basis for estimating solar radiation (Qin) on the collector.

Figure 2 Lux Meters

Tabel 3 Lux Meters Specification

Specification Description	
Model Name	AS803
Weight	85g
Diameter	160mm x 48mm x 25mm
Measuring Range	0-200,000 Lux
Power Supply	1.5V
Resolution	1 Lux

The main components include a *solar water heater system* with a flat-plate solar collector as the primary medium for heat energy absorption, and copper pipes as the working fluid flow path. Water is used as the working fluid, flowing from the collector to the storage tank. Furthermore, transparent glass covers the collector to reduce heat loss, and a steel frame supports the structure.

The measuring instruments used in this study consisted of a lux meter to measure the intensity of solar radiation, and thermocouples to measure temperatures at several points, namely the inlet water temperature, outlet water temperature, pipe temperature, and collector temperature. In addition, *a stopwatch* was used to record the time during the heating process. The combination of these instruments allows for comprehensive monitoring of thermal parameters, so that the data obtained is more accurate and able to represent the performance of the solar water heater *system* in converting solar energy into heat energy effectively.

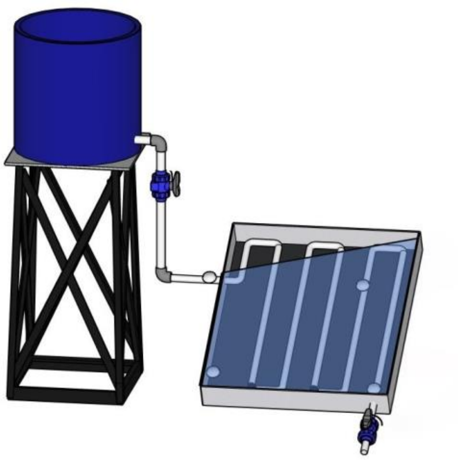

Figure 3 Solar Water Heater System

Table 3 Solar Collector Specifications

Component	Specifications
Collector Dimensions	75 cm x 75 cm
Collector Water Capacity	1.25 L
Pipe Length	75 CM
Glass Thickness	3 MM
Collector Tilt Angle	5°

2.2 Method

This research uses an experimental method with a quantitative approach to analyze the thermal performance of a solar water heater system. This approach is used because the analysis is based on numerical data in the form of temperature, solar radiation intensity, and collector thermal efficiency. All experimental activities were conducted using equipment designed according to the research requirements to represent the actual operating conditions of the system.

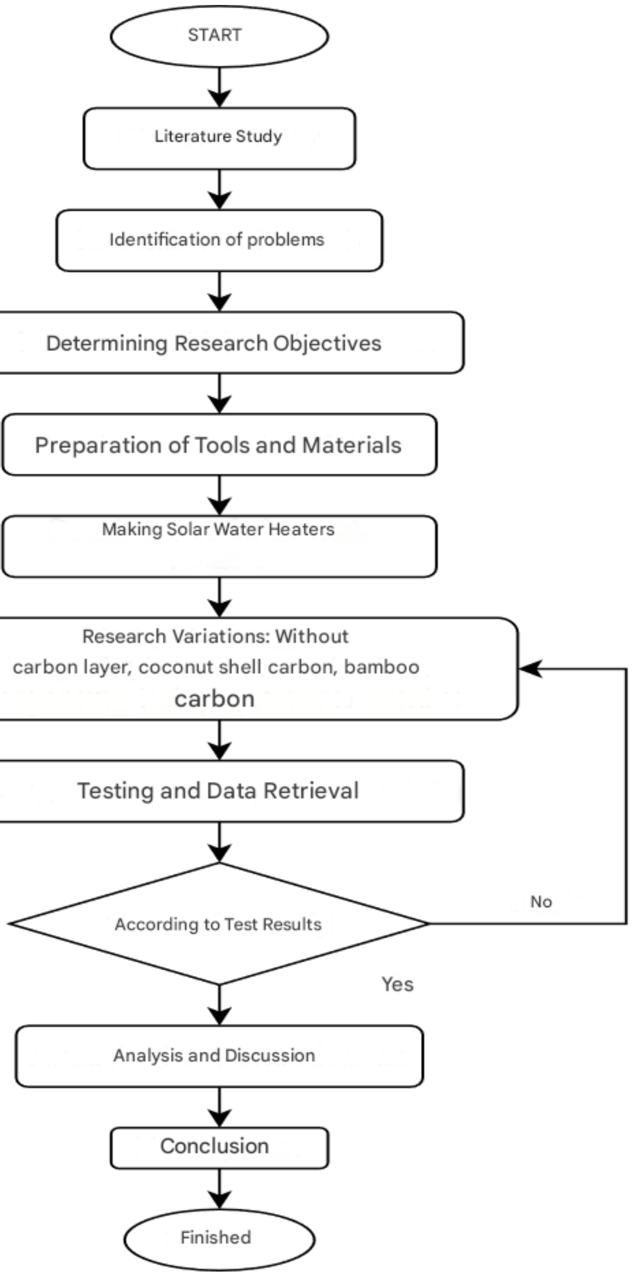

Figure 4 Research Flowchart

The research entitled "Comparative Analysis of Thermal Efficiency of Flat Plate Solar Collectors with Variations of Carbon-Based Absorber Materials" began with the preparation of tools and materials in the Electric Vehicle Laboratory, Building A7, First Floor, Faculty of Engineering, Surabaya State University, carried out in the Energy Conversion Laboratory, Building A8, 4th Floor, Faculty of Engineering, Surabaya State University. The Testing Process was carried out on October 8, 2026 to October 18, 2026 at the Ketintang Football Field, Surabaya State University to utilize direct solar radiation. The research stages are arranged systematically in the form of a flow diagram to ensure that each process runs in a structured manner and produces valid data. These stages are illustrated in the following flow diagram figure 4.

The research variables consist of independent variables and dependent variables. The independent variable in this study is the type of carbon-based absorber material, namely coconut shell carbon and bamboo carbon. The dependent variable is the thermal performance of the solar collector expressed in the form of thermal efficiency (%) and hot water output (L). Variations in absorber materials are used to determine the effect of material characteristics on absorption and heat transfer capabilities, while efficiency parameters are used to evaluate the overall performance of the solar water heater system.

The input energy represents the solar radiation energy received by the solar collector surface during the test process. Solar radiation intensity was measured using a lux meter positioned parallel to the collector surface to represent the actual irradiation conditions. However, it should be noted that a lux meter measures illuminance based on visible light and does not directly represent total solar irradiance.

To obtain irradiance values in W/m^2, the measured lux values were converted using a standard conversion factor based on general solar radiation characteristics [20]. This conversion introduces a degree of uncertainty because it depends on assumptions regarding the spectral distribution of sunlight and sensor sensitivity. Nevertheless, this approach is considered acceptable for comparative analysis, as all absorber variations were tested under the same measurement conditions and procedures..

It is stated as :

$$1 \text{ Lux} = 0.0079 \ (W/m^2) \tag{1}$$

The water temperature increase (ΔT) is calculated based on the difference between the collector outlet water temperature (Tout) and the collector inlet water temperature (Tin). This calculation aims to determine the magnitude of the change in water temperature during the heating process, as shown in Equation

$$\Delta T = Tout - Tin \tag{2}$$

After obtaining the temperature increase value, the solar energy received by the collector (Qin) is calculated. This value is calculated by multiplying the solar radiation intensity (It), the collector surface area (Ac), and the duration of irradiation (Δt). This calculation shows the total radiant energy received by the collector during the testing process, as shown in Equation

$$Qin = It \cdot Ac \cdot \Delta t \tag{3}$$

The heat energy absorbed by water (Qout) is calculated using the mass of water (m), the specific heat of water (Cp), and the temperature increase (ΔT) previously obtained. The mass of water is obtained by multiplying the volume of water by the density of water (1 kg/L). This step indicates the amount of energy successfully absorbed by the working fluid, as shown in Equation

$$Qout = m \cdot Cp \cdot \Delta T \tag{4}$$

Once the input and absorbed energy are known, the energy lost to the environment (Qloss) is calculated. This value is obtained from the difference between the solar energy received by the collector (Qin) and the energy absorbed by the water (Qout). This energy loss occurs due to heat transfer by conduction, convection, and radiation to the surrounding environment, as shown in Equation 1.

$$Qloss = Qin - Qout \tag{5}$$

The thermal efficiency of the collector (η) is calculated by comparing the energy absorbed by the water (Qout) to the solar energy received by the collector (Qin), then multiplied by 100% to obtain a value in percentage form[15]. This efficiency value indicates the level of effectiveness of the collector in converting solar radiation energy into heat energy, as shown in Equation

$$\eta = \frac{Qout}{Qin} x \ 100\% \tag{6}$$

Data analysis was conducted using a descriptive quantitative approach that aims to describe the characteristics of the data and the relationships between research variables. The data obtained were then tabulated and presented in graphical form, then explained systematically and concisely to facilitate interpretation and answer the research objectives. The parameters analyzed included solar energy received by the collector (Qin), heat energy absorbed by water (Qout), energy lost to the environment (Qloss), and collector thermal efficiency (%). The input energy (Qin) was calculated based on the intensity of solar radiation, collector surface area, and irradiation time, while the output energy (Qout) was determined from the mass of water, specific heat of water, and the increase in water temperature. The collector thermal efficiency was calculated by comparing the energy absorbed by water to the solar energy received by the collector. This analysis was used to determine the effect of variations in carbon material in the absorber on the thermal performance of the solar water heater.

2.3 Experimental Procedure

1. Preparation Stage
   - a. Studying various references and previous research related to solar collectors, carbon materials, and relevant studies to establish a clear theoretical foundation and research direction.
   - b. Determining the specifications of the flat plate solar collector to be used, as well as preparing the required equipment such as digital thermometers, solar radiation measuring instruments (solar meter), and water tanks. In addition, the main materials, namely coconut shell carbon and bamboo carbon, are prepared.
   - c. Assembling or modifying the flat plate solar collector so that it can be used interchangeably with three types of absorber materials to be tested. The absorber surface is coated evenly with each carbon material.
   - d. Testing the equipment and system beforehand to ensure that all components function properly and that there are no leaks or technical errors. This is carried out to prevent measurement inaccuracies during data collection.
2. Experimental Stage
   - a. Installation of Absorber Material, The first carbon material (e.g., coconut shell carbon) is evenly coated onto the absorber plate of the solar collector. The surface is maintained uniformly to ensure consistency in testing..
   - b. Experimental Data Collection, the collector is placed in an open area under direct sunlight. Water is allowed to circulate within the system. Data on inlet and outlet water temperatures, as well as solar radiation intensity, are recorded every 20 minutes for 8 hours.
   - c. Repetition for Other Materials, after completing data collection for one material, the collector is cleaned and recoated with another carbon material. The data collection process is then repeated under the same conditions.
3. Final Testing Stage
   - a. Analyzing the collected data to calculate the thermal efficiency of the solar collector for each type of carbon material.
   - b. Data Verification and Validation, all recorded data, including inlet and outlet water temperatures, solar radiation intensity, and measurement time, are rechecked to ensure accuracy and consistency. Any abnormal or inconsistent data may require repetition of the experiment on a different day.
   - c. Processing the collected data using thermal efficiency equations. Each dataset is analyzed systematically for each absorber material to determine the average efficiency values.
   - d. Comparing the efficiency results of the different carbon materials to identify which material provides the best performance and how material characteristics influence system performance.
   - e. Documenting the entire research process, results, and conclusions in the final report.

f. Presenting the research results in the form of graphs and tables and preparing them for presentation or discussion.

3. Results and Discussion

The performance evaluation of the solar water heater system was conducted on a flat plate solar collector with various absorber layers, namely an absorber coated with carbon material in the form of coconut shell charcoal and bamboo charcoal and an absorber without a carbon layer as a comparison. Tests were conducted under the same operating conditions for each variation so that the results obtained could be compared objectively. Each variation was tested three times in repetition to ensure data consistency and increase the reliability of the experimental results. During the testing period, weather conditions tended to vary, but were generally sunny so that the intensity of solar radiation received by the collector could be considered quite representative in evaluating system performance. Based on the testing procedure, the following results were obtained.

Table 4. Average energy produced during 20 minutes from 08.00-11.00 for 3 days

No	Time	Variations of absorber layers								
		Without carbon layer			Coconut shell carbon layer			Bamboo carbon layer		
		Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)
1	08.00-08.20	228,853	35,790	193,063	185,603	56,858	128,745	150,818	31,221	119,597
2	08.20-08.40	365,024	110,416	254,608	282,551	108,131	174,420	227,436	91,632	135,804
3	08.40-09.00	428,527	148,490	280,037	383,033	135,037	247,996	365,490	137,322	228,168
4	09.00-09.20	370,454	116,000	254,454	344,174	96,963	247,211	433,654	170,066	263,588
5	09.20-09.40	573,125	107,116	466,009	370,278	120,569	249,709	358,038	84,271	273,767
6	09.40-10.00	567,758	103,816	463,942	440,206	135,291	304,915	443,074	124,630	318,444
7	10.00-10.20	710,586	116,254	594,332	464,549	121,077	343,472	452,936	127,676	325,260
8	10.20-10.40	539,045	105,593	433,452	490,799	137,575	353,224	489,308	77,672	411,636
9	10.40-11.00	495,123	84,018	411,105	560,761	122,092	438,669	616,536	87,825	528,711
Total Average Energy		**475,388**	**103,055**	**372,334**	**391,328**	**114,844**	**276,485**	**393,032**	**103,591**	**289,442**

Based on Table 4, the average energy generated during the time period of 08.00–11.00 shows an increasing trend as the intensity of solar radiation increases. In the variation without a carbon layer, the Qin value tends to be the highest compared to other variations, with a peak reaching 710,586 J at 10.00–10.20, but is followed by a large Qloss value, indicating significant heat loss. Meanwhile, the use of a coconut shell carbon layer shows more stable performance with a relatively higher Qout value compared to without a layer at several time intervals, as well as lower heat loss. Based on tabel 5, it can be seen that the energy performance shows a clear difference in each absorber variation. Without the use of carbon, the input energy (Qin) value was recorded at 534,095 with an output energy (Qout) of 81,860, so that the energy loss (Qloss) reached 452,235. In the coconut shell carbon variation, there was an increase in Qin to 555,956 and Qout to 121,680, but the Qloss decreased slightly to 434,276, indicating an improvement in energy absorption and utilization. Meanwhile, the use of bamboo carbon produced the best performance with the highest Qin of

598,921 and Qout of 100,390, although the Qloss increased to 498,532. Overall, bamboo carbon was able to absorb more energy than the other variations, but was not fully effective in minimizing energy loss, while coconut shell carbon showed a better balance between increasing input energy and reducing energy loss.

Table 5. Average energy produced during 20 minutes from 11.00-13.40 for 3 days

No	Time	Variations of absorber layers								
		Without carbon layer			Coconut shell carbon layer			Bamboo carbon layer		
		Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)
1	11.00-11.20	488,102	101,278	386,824	577,456	129,453	448,003	610,787	108,639	502,148
2	11.20-11.40	683,710	80,464	603,246	534,575	125,646	408,929	586,931	98,232	488,699
3	11.40-12.00	630,395	118,284	512,111	623,369	122,092	501,277	576,072	114,985	461,087
4	12.00-12.20	627,455	71,834	555,621	569,813	118,538	451,275	700,094	93,409	606,685
5	12.20-12.40	453,089	73,103	379,986	484,524	124,123	360,401	584,440	99,247	485,193
6	12.40-13.00	470,790	51,274	419,516	556,727	126,915	429,812	554,542	88,333	466,209
7	13:00 -13:20	358,521	76,656	281,865	561,353	113,462	447,891	661,041	104,578	556,463
8	13:20-13:40	560,700	81,987	478,713	539,827	113,208	426,619	517,462	95,694	421,768
Total Average Energy		**534,095**	**81,860**	**452,235**	**555,956**	**121,680**	**434,276**	**598,921**	**100,390**	**498,532**

Table 6. Average energy produced during 20 minutes from 13.40-16.00 for 3 days

No	Time	Variations of absorber layers								
		Without carbon layer			Coconut shell carbon layer			Bamboo carbon layer		
		Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)	Qin (J)	Qout (J)	Qloss (J)
1	13.40-14.00	556,633	99,247	457,386	472,667	107,877	364,790	459,299	66,503	392,796
2	14.00-14.20	338,999	40,613	298,386	432,578	96,709	335,869	384,862	85,033	299,829
3	14.20-14.40	355,005	57,619	297,386	298,841	84,525	214,316	417,355	95,947	321,408
4	14.40-15.00	338,041	79,195	258,846	258,716	73,103	185,613	360,278	79,956	280,322
5	15.00-15.20	241,264	55,842	185,422	183,119	84,018	99.101	281,518	66,757	214,761
6	15.20-15.40	198,305	49,497	148,808	191,954	34,013	157,941	210,773	72,595	138,178
7	15:40 -16:00	155,807	28,158	127,649	145,568	37,313	108,255	211,182	61,427	149,755
Total Average Energy		**312,008**	**58,596**	**221,735**	**283,349**	**73,937**	**183,236**	**332,181**	**75,460**	**224,631**

Based on table 6 in the time range of 13.40–16.00, it can be seen that variations in the type of absorber have a significant effect on the amount of energy produced and lost. In conditions without a carbon layer, the average value of incoming energy (Qin) was recorded at 312,008, with outgoing energy (Qout) of 58,596 and energy loss (Qloss) of 221,735. When using coconut shell carbon absorber, the Qin value decreased to 283,349, but was followed by an increase in Qout to 73,937 and a decrease in Qloss to 183,236, which indicates an improvement in energy utilization. Meanwhile, the use of bamboo carbon produced the best performance with the highest Qin value of 332,181, Qout of 75,460, and Qloss of 224,631

Table 7 Comparison of Solar Collector Performance Based on Absorber Variation

Absorber layer variations	Without carbon layer	Coconut shell carbon layer	Bamboo carbon layer
Energy input (J)	440,497	410,211	441,378
Useful energy (J)	81,170	103,487	93,147
Energy lost (J)	348,768	297,999	337,535
Collector efficiency (%)	18.7	25.4	21.2

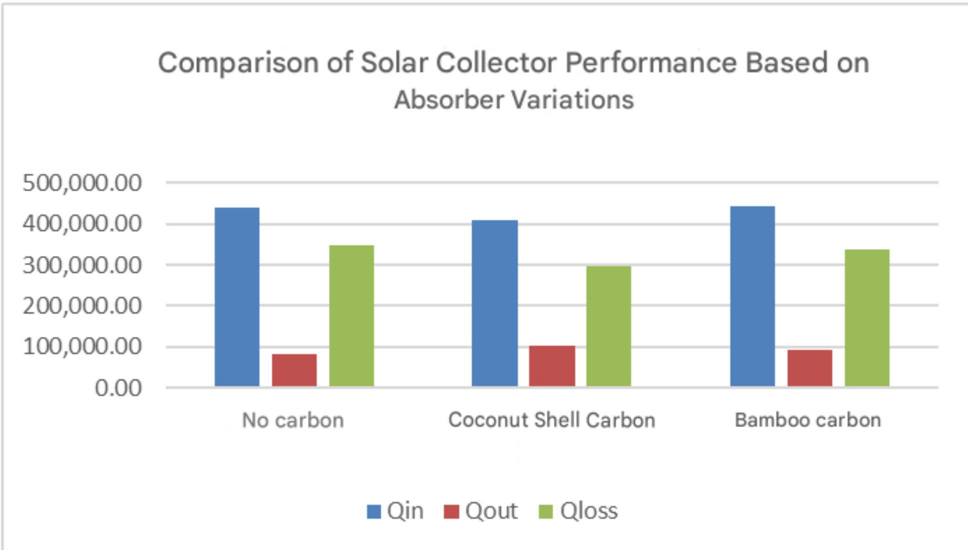

Figure 4 graph Comparison of Solar Collector Performance Based on Absorber Variation

Based on the table and graph titled "Comparison of Solar Collector Performance Based on Absorber Variations," clear differences can be observed in energy distribution and collector efficiency for each absorber type. The configuration without a carbon layer shows an energy input (Q_{in}) of 440,497 J, which is relatively high; however, it only produces useful energy (Q_{out}) of 81,170 J with an efficiency of 18.7%. This indicates that a large portion of the absorbed energy is not effectively utilized and is instead lost to the environment (Q_{loss} reaches 348,768 J). This low performance is associated with the limited radiative absorption and heat retention capability of a conventional absorber surface.

In the case of coconut shell carbon, the Q_{in} decreases to 410,211 J, yet it yields the highest Q_{out} of 103,487 J and the greatest efficiency of 25.4%. This phenomenon demonstrates that higher energy input does not necessarily translate into higher system efficiency. From a physical perspective, coconut shell carbon possesses a well-developed porous structure and relatively favorable thermal conductivity, which enhance solar absorptivity while reducing heat losses through convection and re-radiation. Its micro-porous structure also contributes to improved heat retention, allowing more effective heat transfer to the working fluid.

Meanwhile, bamboo carbon exhibits the highest Q_in at 441,378 J, but only achieves a Q_out of 93,147 J with an efficiency of 21.2%. Although its solar absorption capability is high, the overall performance is inferior to that of coconut shell carbon. This suggests that a significant portion of the absorbed energy is not efficiently transferred to the fluid but is instead dissipated to the surroundings. In terms of material characteristics, bamboo carbon generally has high porosity; however, its pore distribution and thermal stability may contribute to increased heat losses, particularly if not supported by adequate thermal conductivity.

From the perspective of heat transfer theory, collector performance is governed by the balance between solar absorption (absorptivity), heat conduction within the material, and heat losses through convection and radiation. The higher efficiency observed in coconut shell carbon indicates a more optimal combination of thermal properties, enabling effective energy absorption and transfer to the working fluid with minimal losses. In contrast, for bamboo carbon, despite high absorption, heat loss mechanisms remain dominant, reducing overall efficiency.

When compared with previous studies, these findings are consistent with research indicating that carbon-based materials with controlled pore structures and moderate thermal conductivity tend to deliver superior performance in flat-plate solar collectors. Coconut shell carbon, in particular, is often reported to exhibit better thermal stability and heat adsorption capacity compared to other biomass-derived carbons, thereby enhancing system efficiency.

4. Conclusion

This study demonstrates that the use of carbon-based absorber coatings significantly improves the thermal performance of flat plate solar collectors in solar water heater systems. Among the tested materials, coconut shell carbon provides the highest efficiency compared to bamboo carbon and uncoated absorbers, indicating its superior capability in enhancing solar energy absorption and heat transfer.

The findings highlight the potential of biomass-derived carbon, particularly coconut shell carbon, as a low-cost and environmentally friendly alternative absorber material for improving solar collector performance. This has practical implications for the development of more efficient and sustainable solar water heating systems, especially in regions with high solar energy potential.

However, the study is limited by environmental variability, measurement constraints, and the scale of the experimental setup. Therefore, future research is recommended to involve more precise radiation measurement instruments, variations in collector tilt angle, and testing under broader operational conditions. Expanding the range of absorber materials and conducting larger-scale experiments are also necessary to enhance the applicability of the results.

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