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SIMULATION AND EXPERIMENTAL VALIDATION OF OPTIMAL TILT ANGLES ON THE THERMAL PERFORMANCE OF A SERPENTINE ACTIVE FLAT-PLATE SOLAR WATER HEATER IN A TROPICAL SAVANNA CLIMATE

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ABSTRACT

Conventional fixed-tilt flat-plate solar water heaters often suffer from reduced efficiency due to seasonal variations in solar radiation, leading to greater dependence on unreliable and costly grid electricity for hot water supply in Nigerian pre-primary educational institutions. This study simulated, fabricated, experimentally tested, and validated an active serpentine flat-plate solar water heater (collector area 2.04 m², storage tank capacity 65 dm³) designed to provide hot water at 50 °C for pre-primary schools in Bauchi, Nigeria. System sizing and optimal collector tilt angles (monthly, quarterly, and annual) were determined using MATLAB. Thermal performance was simulated in TRNSYS 16 with Typical Meteorological Year (TMY) data for Bauchi. The prototype was tested under monthly optimal tilt during February–April 2025, with hourly temperature measurements using calibrated thermocouples. Model accuracy was assessed via root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE). Simulation results showed that monthly optimal tilt outperformed quarterly and fixed-latitude configurations, achieving the target 50°C by 09:00 h in most months and a peak of 82°C in April. Experimental validation indicated strong agreement (highest RMSE = 2.71°C in March; NSE = 0.92 in April), with experimental peaks reaching 85°C at 15:00 h in April. Economic analysis revealed that the ₦439,616 initial investment could be recovered within the 15-year lifespan at minimum of 210 clear sunny days per year using Jos Electricity Distribution (JED) Band B tariffs. The findings confirm that adjustable monthly optimal tilt enhances reliability, economic viability and sustainability. Future studies should include long-term durability tests, evacuated-tube comparisons, and larger-scale institutional applications.

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Keywords: *solar water heater, optimal tilt angle, experimental validation, economic viability*

INTRODUCTION

Solar energy is abundantly available worldwide, particularly in tropical regions, where it can be harnessed throughout the year in both direct and indirect forms. Solar thermal energy has wide applications, including water heating, space heating, food drying, incubation, refrigeration, air conditioning, pasteurization, and distillation (Abur, 2023). Among these, solar water heating has proven to be highly beneficial in terms of cost-effectiveness and environmental sustainability.

Hot water is required in various sectors, including industries, households, and commercial enterprises such as textile, dairy, and edible oil processing plants, as well as for bathing, sterilization, laundry, and personal care services (hair salons). Large quantities of hot water are also consumed by hotels, hospitals, educational institutions, paper industries, and food processing facilities. Solar water heating systems help reduce energy costs and lower carbon dioxide (CO_2) emissions by decreasing reliance on fossil fuels (Kalogirou, 2009).

Despite certain limitations-such as the low power density of solar radiation, which necessitates large collector areas, and the seasonal variation in solar availability that may require auxiliary heating — solar water heating remains a cost-effective and environmentally friendly option for domestic hot water production (Oguche *et al.,* 2020).

The basic operating principle of a solar water heater involves the absorption of solar radiation by absorber materials, which convert the radiant energy into useful thermal energy to raise the temperature of water. A working fluid circulates through pipes attached to the collector, absorbs heat, and transfers it to a storage tank. To minimize heat losses, the collector, connecting pipes, and storage tank are properly insulated (lagged) (Herez, *et al*., 2023).

Solar water collectors are generally classified according to the temperature range at which they effectively deliver heat: low-temperature, medium-temperature, and high-temperature collectors (Emmanuel et al., 2020). Low- and medium-temperature collectors are particularly suitable for domestic, institutional, and small commercial applications such as homes, hospitals, hairdressing salons, restaurants, and offices (Herez, *et al.*, 2023).

Globally, a significant portion of hot water demand is still met through conventional energy sources, raising serious environmental concerns and contributing to rising energy costs. This challenge is more pronounced in developing countries, where electricity supply is often unreliable and largely limited to urban areas (Odoi-Yorke *et al*., 2023).

Nigeria, as a developing nation, is currently facing an acute energy crisis exacerbated by inflation and the high cost of conventional energy sources (World Bank, 2025). In addition, the heavy reliance on fossil fuels for power generation has adverse environmental consequences. To promote ecological balance and sustainable development, there is a strong need to shift toward environmentally friendly renewable energy sources such as solar, wind, and geothermal energy (Abur, 2023).

Nigeria is blessed with abundant solar resources, receiving an average of 11 to 12 hours of sunshine daily throughout the year. This makes solar water heating technically viable in most parts of the country. However, electricity supply remains erratic and inaccessible in many rural and semi-urban areas, especially amid rapid industrialization and declining generation capacity. Since solar energy is uniformly distributed across the country, solar water heating systems do not suffer from geographical limitations (Ikemba *et al.*, 2024).

Studies conducted by Ekechukwu (2011) indicate that about 84% of Nigerian households require approximately 100 litres of hot water daily, with hot water heating accounting for nearly 50% of recurrent household energy expenditure In many rural and semi-urban communities, the lack of reliable grid electricity or high tariffs makes conventional hot water heating unaffordable. Furthermore, most public educational institutions, particularly pre-primary schools, lack adequate facilities for hot water supply-a basic requirement for proper hygiene and cleaning of children, especially during colder periods (Addie, 2025).

In light of the above, this study aims to simulate, develop, evaluate, and validate an active flat-plate solar water heater designed specifically for pre-primary educational institutions. The specific objectives are to assess the annual thermal performance of the system based on monthly, quarterly, and annual optimum tilt angles, in comparison with the conventional fixed tilt at the local latitude (Adamu *et al.,* 2025).

MATERIALS AND METHODS

Materials

Construction and description of the solar water heater system

The copper pipe turns was built from 12 mm internal diameter and 12.5 mm external diameter copper pipe with the number of turns running out through the surface area which was spaced at 121 mm across the areas of the collector. The absorber plate was made from aluminium sheet which was placed across the entire surface area of the collector where the copper tube/pipes were fastened on the absorber plate. The glass glazing was installed on the top of the casing which was sealed with silicon paste. The system consists of a flat plate solar collector of varying optimal tilts with a surface area of 2.04 m^2 and a horizontal insulated storage tank of volume 65 dm^3, connecting pipes, 20 W solar panel and a 4.8 W (0.0064 hp) pump, 0.042 kg/s brushless DC pumps. The supporting frame for the collector is made from 50 mm × 50 mm × 5 mm to provide rigidity needed whilst 40 mm × 40 mm × 3 mm formed the casing. The flat plate collector has 12 evenly spaced turn of copper tubes. The absorber plate was painted with black matte paint to achieve high absorptivity. The absorber underneath was insulated with saw dust to reduce conduction heat losses. Aluminum sheet of 2 mm thickness form the hot water storage tank as well as the outer covering after lagging with fiberglass. The hot water storage tank was linked to a source of water from the main water supply through water charging point. The solar DC pump was also connected along the inlet point to the collector. The solar panel was mounted at the side of the glazing cover. Figure 1 and 2 show dimensions of the horizontally placed hot water tank and the serpentine solar collector respectively.

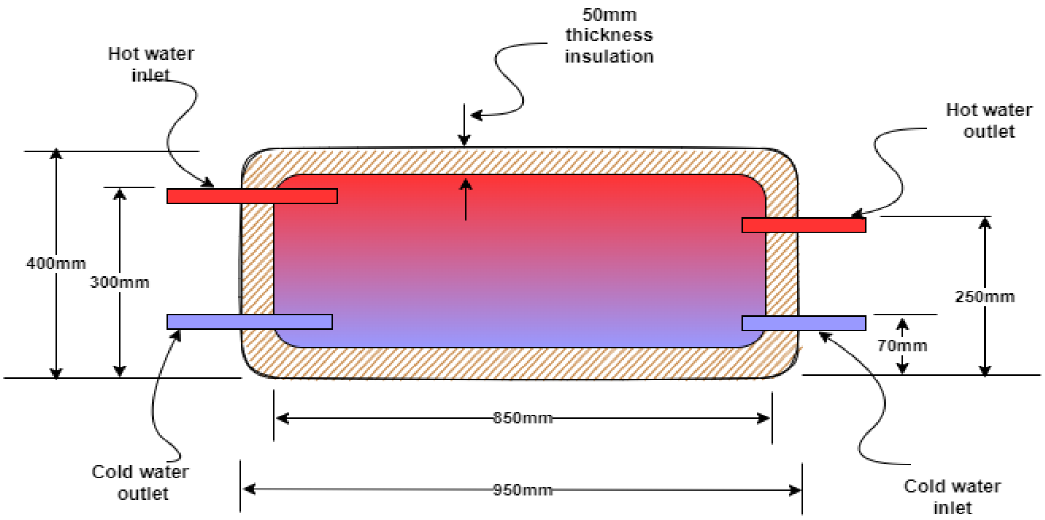

Figure 1. The Horizontally placed Hot Water Storage Tank.
Source: Own elaboration

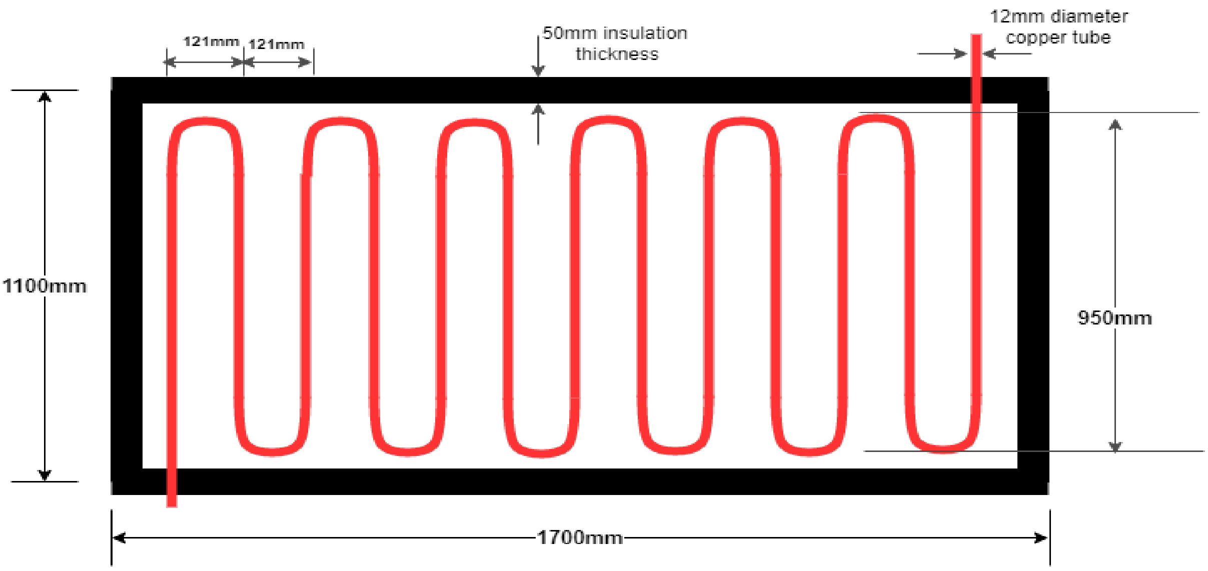

Figure 2. Dimension of the Serpentine Solar Collector.
Source: Own elaboration

Methods

System design and parametric optimization

A parametric approach was adopted for the design and optimization of the active serpentine flat-plate solar water heater using TRNSYS 16 software. Initial component sizing was performed with standard engineering equations to establish baseline parameters (collector area, pump capacity, riser tube configuration, and insulation thickness). These parameters were then varied parametrically within the TRNSYS environment to identify the optimal combination of design variables that maximises thermal performance under Bauchi climatic conditions.

The collector area was initially sized based on the daily hot water demand using the energy balance equation recommended by Duffie and Beckman (2021):

$$Q = mC_{pw}(T_{out} - T_{in}) \tag{1}$$

where:
- Q is the quantity of heat in joules; m is the mass of water in kg;
- C_{pw} is the specific heat capacity of water [J/kgK],
- T_{out} is the outlet water temperature [°C],
- T_{in} is the inlet water temperature [°C].

The electrical pump power requirement was estimated using the relation (Duffie and Beckman, 2021):

$$P = \frac{\dot{m}\Delta P}{\rho} \tag{2}$$

where:
- P is the power [W];
- $\dot{m}$ is the mass flow rate [kg/s];
- ρ is the density of water [kg/m^3].

The number of riser tubes and centre-to-centre spacing in the serpentine collector were determined from the expression given by Johnson (2015) as expressed in equation 3:

$$N_P = \frac{A_C}{(W-D)+D} \tag{3}$$

where:
- A_C is the area of the collector, [m^2];
- D is the diameter of the tube [m];
- W is the centre to centre distance of the riser tube (pipes) [m].

Insulation thickness for the horizontal cylindrical storage tank was calculated using Fourier's law of heat conduction to minimise standby heat losses in equation 4:

$$Q_L = 2\pi L\left(T_f - T_a\right) / \left[ln\left(\frac{r_2}{r_1}\right)/K + 1/h_o r\right] \tag{4}$$

where:
- T_f and T_a are the final and ambient temperatures of the water respectively [°C];
- r_1 and r_2 are radii of inner and outer hot water tanks respectively [m]; h_o is the convective heat transfer coefficient of outer tank [W/m^{2}K];
- K is the thermal conductivity of the insulating material [W/mK].

The preliminary values obtained from Equation 1 to 4 served as the starting point for parametric optimization in TRNSYS 16. Design variables, including collector tilt angle, mass flow rate, and storage tank configuration, were systematically varied within realistic ranges until the configuration that delivered the highest useful energy gain while meeting the target outlet temperature of 50°C was identified.

System performance simulation

The system was simulated using TRNSYS 16 software based on optimized values of variables involved for the solar water heating process (table 2). Weather condition of solar water heater location (Bauchi) was based on Typical Metrological Year (TMY). Bauchi weather data and solar water heater variables such as optimized tilt, water tank were selected from the system and unified. Optimized design parameters for components were selected while model equations written using the TRNSYS 16 software equation editor to describing the process flow at each of the components. Printers were placed at appropriate locations for reading.

To facilitate the study of the solar water heater, refer to table 1 for the recommended average day for the simulation and table 2 for optimal tilts while tables 2 to 5 are collector, tank and pump characteristics respectively. The schematic model used for the simulation, and the logic for the solar pump flow control is shown in figures 1 and 2 respectively.

Table 1. Recommended Average Days for the Months.

Month	Day	n^{th} day of the year	Simulation start time	Simulation stop time
January	17	17	408	432
February	16	47	1128	1152
March	16	75	1800	1824
April	15	105	2520	2544
May	15	135	3240	3264
June	11	162	3888	3912
July	17	198	4752	4776
August	16	228	5472	5496
September	15	258	6192	6216
October	15	288	6912	6936
November	14	318	7632	7656
December	10	344	8256	8280

Source: Based on: Klein (1977) and Duffie and Beckman, 1991)

Table 2. Optimal Tilt Angle.

Month	β_{opt} [°] monthly	β_{opt} [°] quarterly	β_{opt} [°] annually
January	44		
February	38	34	
March	26		
April	14		
May	2	4	
June	2		
July	0		24
August	10	12	
September	18		
October	30		
November	42	42	
December	46		

Source: Own elaboration

Table 3. Design Parameters of the Serpentine Flat Plate Solar Collector.

Parameter	Design value
Length, mm	1700
Width, mm	1200
Absorber plate thickness, mm	4
Absorber plate conductivity, W/mk	237
Serpentine spacing, mm	0.13
No of bend	13
Serpentine length, mm	950
Inner tube diameter of fluid passage, mm	12
Outer tube diameter of fluid passage, mm	12.5
Absorptance of the absorber plate	0.90
Emissivity of the absorber plate	0.20
Number of glass cover	1
Insulation material (back and edge insulation), W/m^{2}K	5

Source: Own elaboration

Table 4. Solar Pump Parameters.

Parameter	Value
Rated flow rate, L/hr	60
Rated power, Watt	100
Pump efficiency, %	80

Source: Own elaboration

Table 5. Hot Water Storage Tank Parameters (Tank is Placed Horizontally).

Parameter	Value
Tank volume, litres	65
Height, mm	850
Tank insulation thickness, mm	40
Conductivity of Fibre glass, W/m^{2}K	5

Source: Own elaboration

System cost estimation

The cost implication for the development of the various components of the flat plate solar water heater is show in table 6.

Table 6. Estimated cost for the production of the active solar flat plate collector water heater as at January, 2025.

No	Component	Total Cost ₦
1	Storage tank	28,001.00
2	Collector	125,540.00
3	Supporting frames for tank/collector	106,500.00
4	Plumbing/Pipe Fittings	65,800.00
5	Labour	24,000.00
	Total	**349,841.00**

Source: Own elaboration

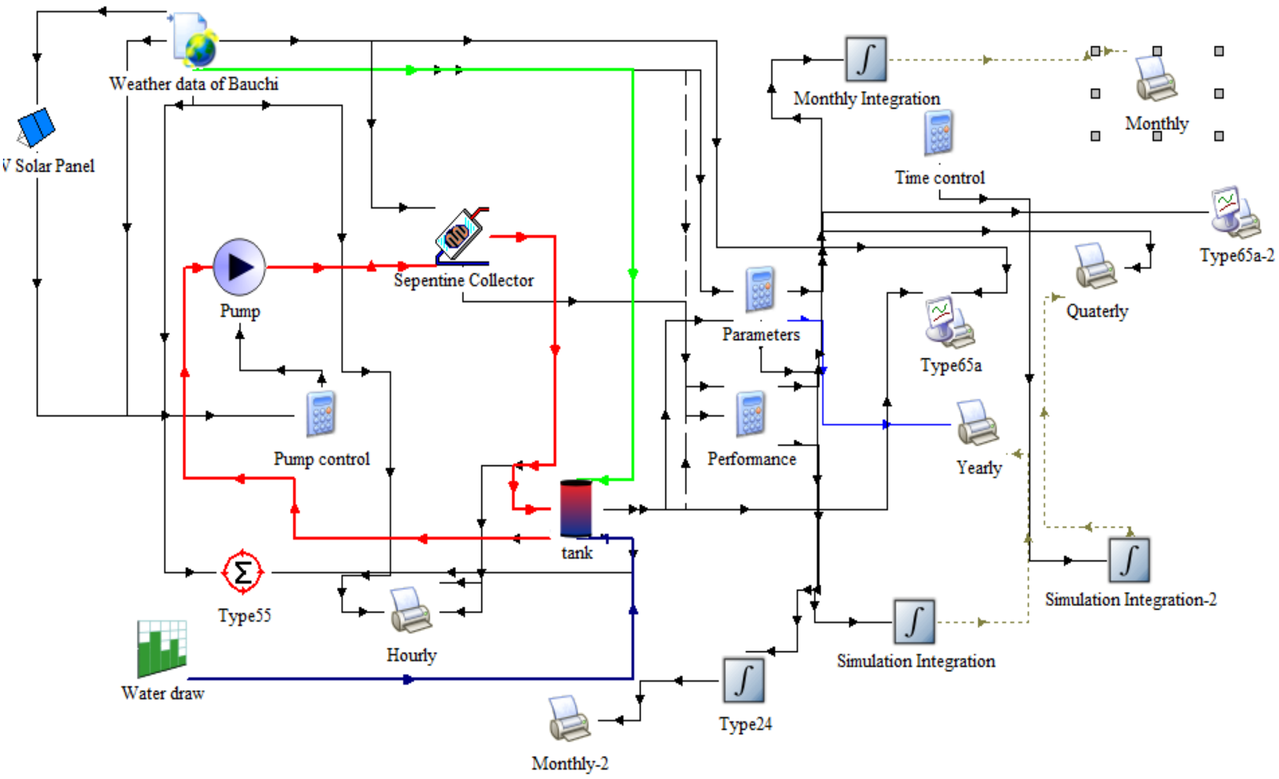

Figure 1. TRNSYS model of the serpentine active solar water heater.

Source: Own elaboration

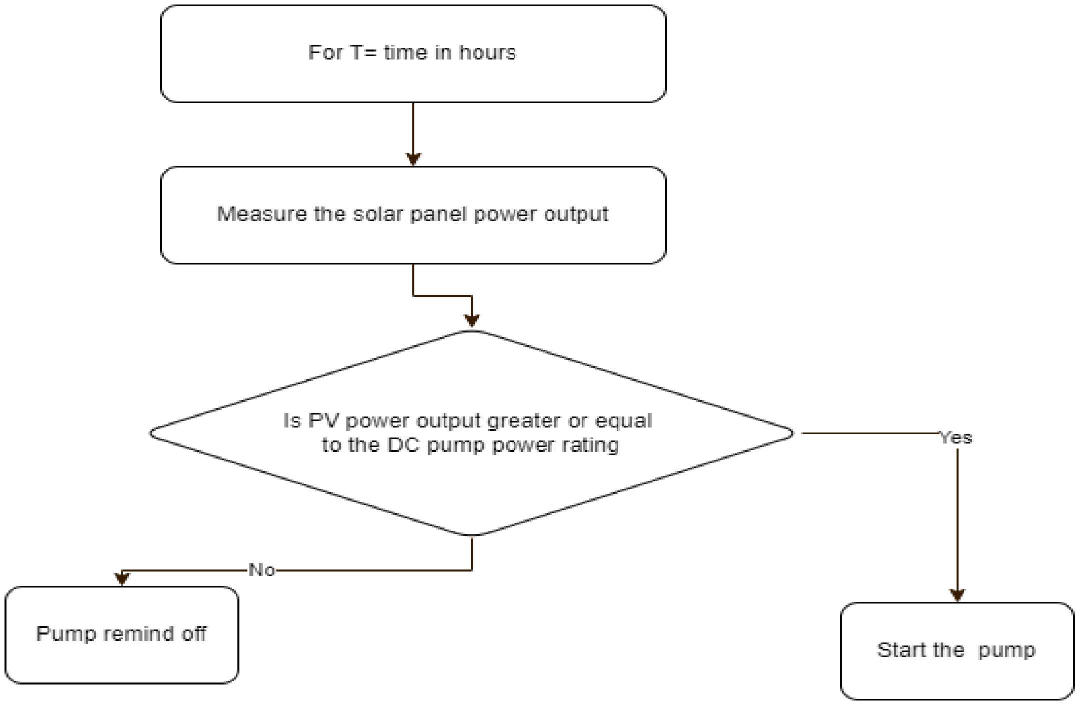

Figure 2. The logic for the solar pump flow control

Source: Own elaboration

Validation of simulated model

Statistical tools of Roots Mean Square Error (RMSE) and the Nash-Sutcliffe coefficient of efficiency (NSE) given in Equations 5 and 6 respectively as reported by Zwalnan (2015) are deployed to validate the developed system.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{n}} \tag{5}$$

where:
- $X_{obs,}$is the observed values, i
- $X_{model,i}$ is the predicted values, i

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{\sum_{i=1}^{n}\left(X_{obs,i} - \bar{X}_{obs,i}\right)^2} \tag{6}$$

$$E_U = \frac{\rho_w V_w C_{pw}(T_{hot} - T_{cold})}{3600000} \tag{7}$$

where:
- $\bar{X}_{obs,i}$ is the mean of the observed values.

Annual cash flow

The annual economic benefit, expressed as the cost savings from using the solar thermal system instead of grid electricity from Jos Electricity Distribution (JED) for hot water production, was determined using Equation 7:

$$CF_i = CJED \times E_U \tag{7}$$

where:
- CJED is the unit cost of electricity from Jos Electricity Distribution (JED) [₦/kWh]

Data for economic analysis

Estimated economic life, n of system = 15 years (SRCC, 2017; FSEC, 2017) P_i is the initial investment = ₦439,616:00. Average density of water at temperatures between 25 and 50°C=988.05kg/m^3. Specific heat capacity of water=4,200J/kgK. Price of electricity = ₦209.50 kWh, ₦63.26 kWh (Tarrif A and B respectively, Jos Electricity Distribution, 2025).

Experimentation

The developed flat-plate solar water heater was experimentally tested at the Mechanical Engineering Department, Federal Polytechnic Bauchi. On each test day, the experiment began by draining the storage tank and refilling it with fresh water at 07:00 h. Inlet and outlet water temperatures were measured at hourly intervals throughout the day using calibrated thermocouples. No water was drawn from the system during the experimental period.

The system was evaluated under monthly optimal tilt conditions during the months of February, March, and April 2025, with measurements taken between 08:00 h and 16:00 h. Solar radiation intensity was recorded using a pyranometer, while ambient temperature was monitored with a digital thermometer. For analysis and reporting, the recorded values of solar radiation, ambient temperature, and tank inlet water temperature were averaged over the three experimental days in each month.

RESULTS AND DISCUSSION

Simulated system performance

Figures 3 to 14 present the simulated hourly thermal performance of the active flat-plate solar water heater for the representative average days of each month from January to December. The results reveal a consistent diurnal pattern across all months, characterized by a steady rise in collector outlet water temperature from morning hours, reaching peak values in the mid-afternoon, followed by a gradual decline. Significant variations in collector outlet temperatures were observed in January, April, May, June, July, November, and December (Figure 3, 6, 7, 8, 13, and 14). In contrast, performance in September and October showed negligible differences across the various tilt scenarios (Figure 10 and 11). These monthly disparities are primarily attributed to fluctuations in solar radiation intensity, ambient temperature, wind speed, and relative humidity, all of which directly influence the collector's heat gain and overall system efficiency. In March, virtually no variation was recorded among the different optimal tilt angles (Figure 5). This uniformity can be explained by the solar geometry near the equinox, when the sun's declination is close to zero, delivering nearly equal amounts of incident radiation across a wide range of surface tilts (Stanciu,and Stanciu, 2014). The simulation results demonstrate that the system reliably achieves the target outlet temperature of 50°C by 09:00 hours in most months when using the monthly optimal tilt. The only exception occurred with the quarterly optimal tilt in December, which yielded a lower temperature of 41.09°C (Figure 14). This shortfall is likely due to the frequent cloudy skies and harmattan dust haze commonly experienced in Bauchi during this period, which substantially reduce available beam radiation. Consequently, hot water at the desired temperature would be available from 09:00 hours onwards for the greater part of the year. However, auxiliary heating may be required in December under quarterly or fixed-latitude tilt configurations to meet the target temperature. The best overall performance was recorded in April, where the monthly optimal tilt produced a peak collector outlet temperature of 82°C at 15:00 hours (Figure 6). A clear performance hierarchy emerged among the tilt strategies: monthly optimal tilt consistently outperformed quarterly optimal tilt, which in turn surpassed the fixed collector tilted at the local latitude of Bauchi (Oko, 2012). Furthermore, a gradual decline in outlet water temperature was evident after 15:00 hours across all months and tilt scenarios, reflecting the natural decrease in solar irradiance during the late afternoon coupled with increasing heat losses.

Overall, the predicted performance clearly demonstrates the superiority of monthly optimal tilt adjustment, followed by quarterly adjustment, with the fixed latitude tilt exhibiting the lowest thermal output in Bauchi's climatic conditions.

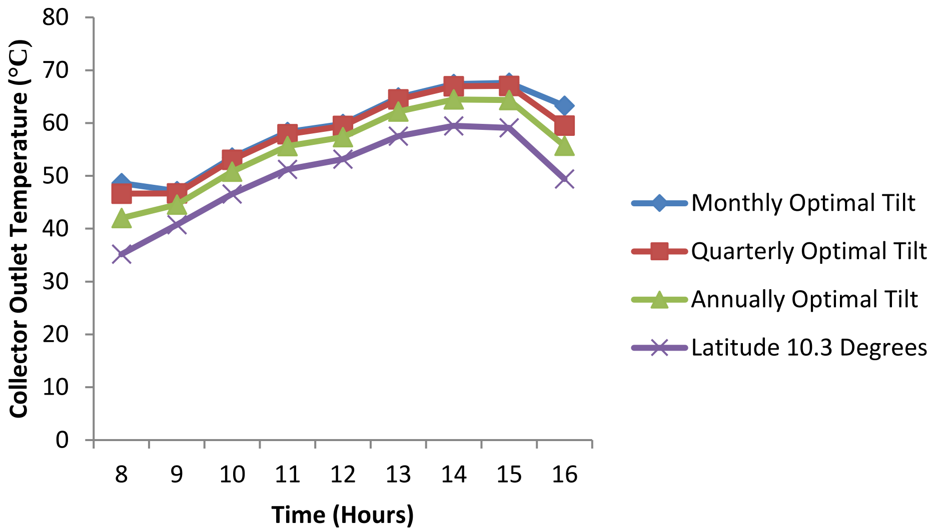

Figure 3. Comparison of tank inlet temperature on different optimal tilt angle scenario for January average recommended day.

Source: Own elaboration

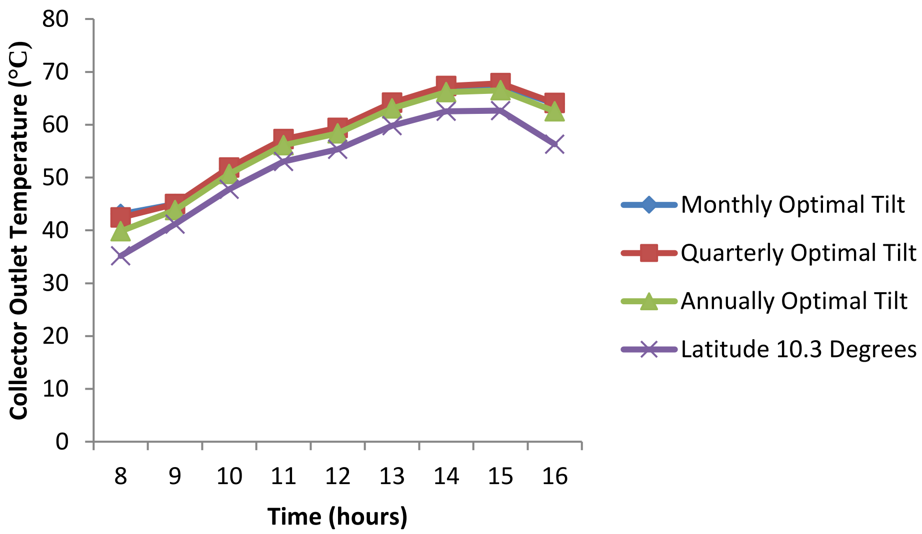

Figure 4. Comparison of tank inlet temperature on different optimal tilt angle scenario for February average recommended day.

Source: Own elaboration

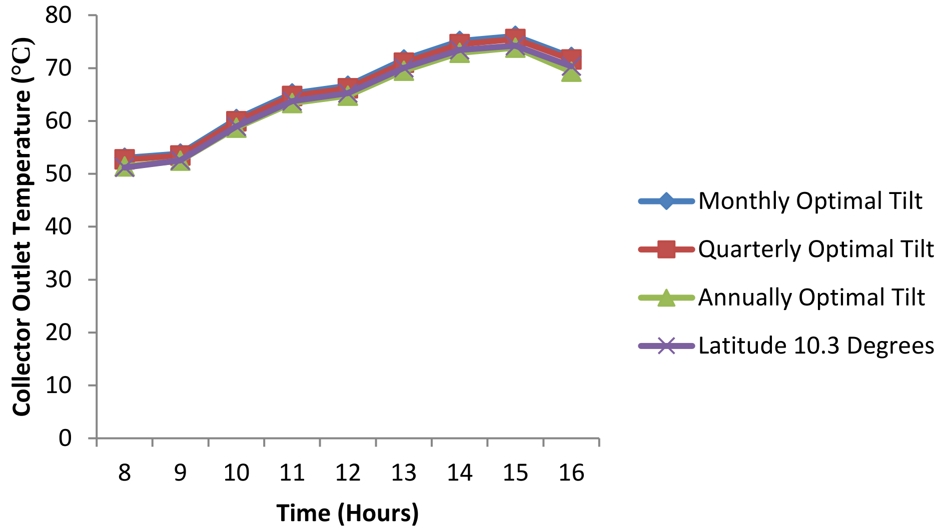

Figure 5. Comparison of tank inlet temperature on different optimal tilt angle scenario for March average recommended day.

Source: Own elaboration

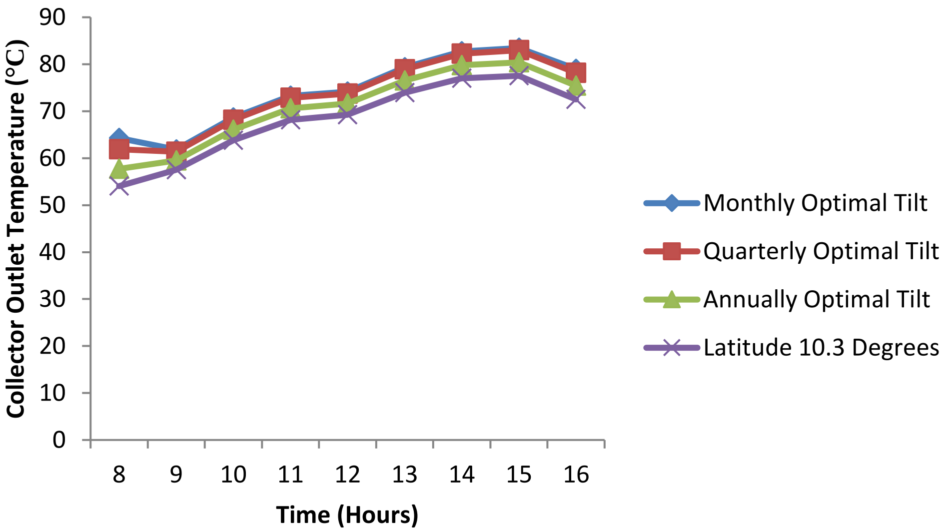

Figure 6. Comparison of tank inlet temperature on different optimal tilt angle scenario for April average recommended day.

Source: Own elaboration

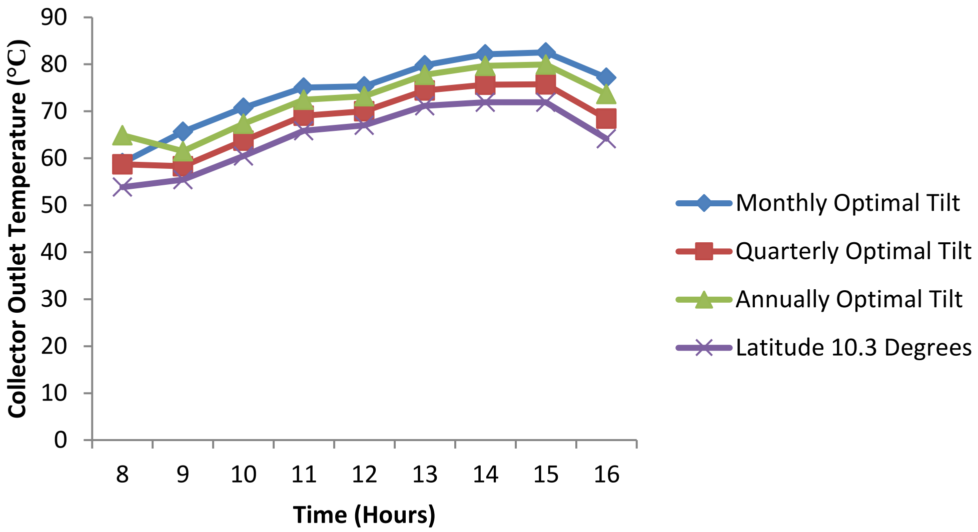

Figure 7. Comparison of tank inlet temperature on different optimal tilt angle scenario for May average recommended day.

Source: Own elaboration

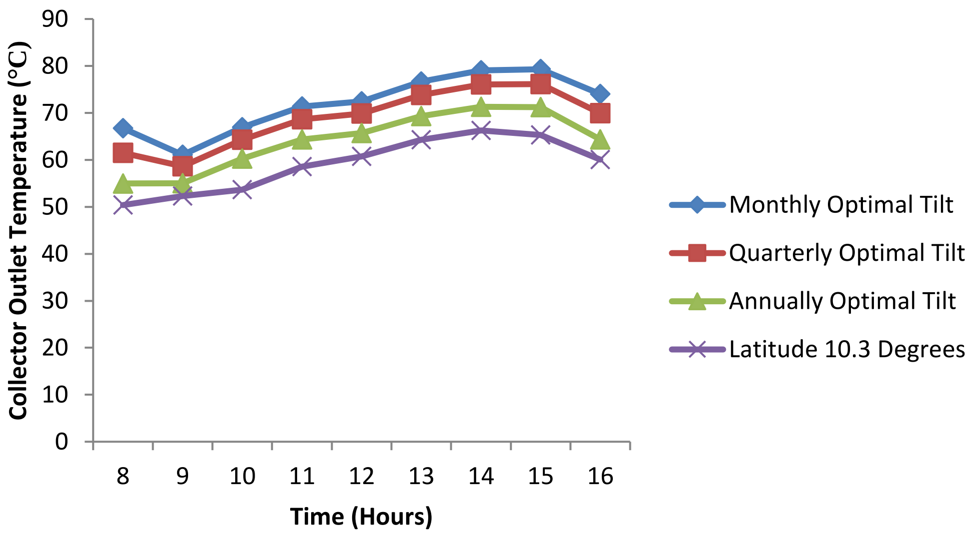

Figure 8. Comparison of tank inlet temperature on different optimal tilt angle scenario for June average recommended day.

Source: Own elaboration

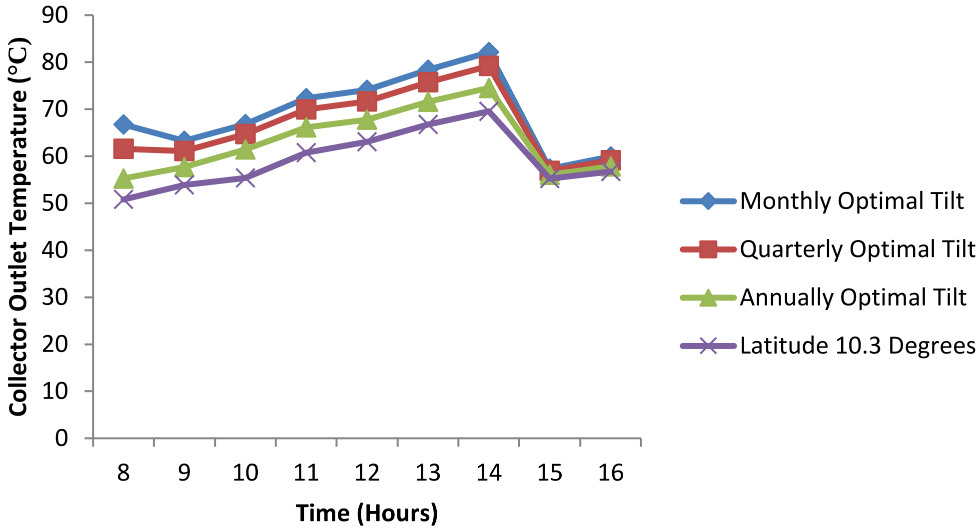

Figure 9. Comparison of tank inlet temperature on different optimal tilt angle scenario for July average recommended day.

Source: Own elaboration

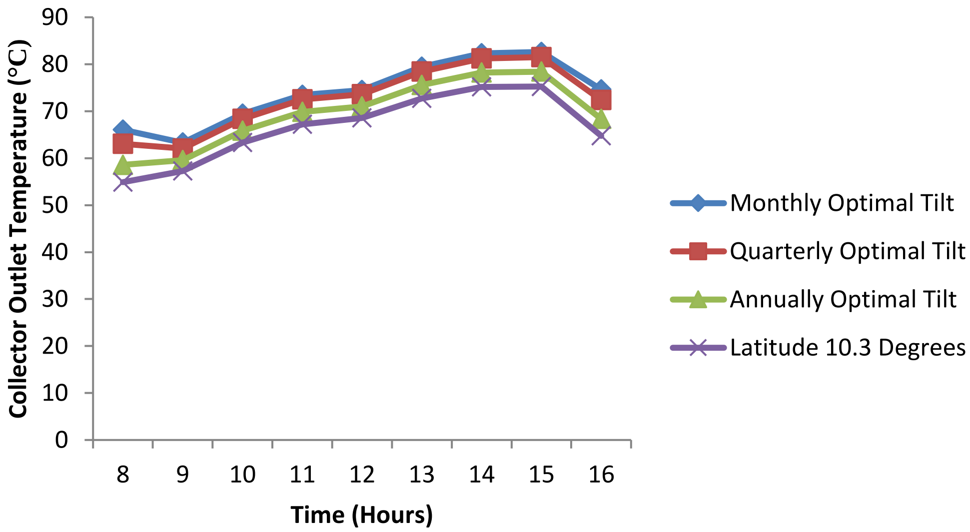

Figure 10. Comparison of tank inlet temperature on different optimal tilt angle scenario for August average recommended day.

Source: Own elaboration

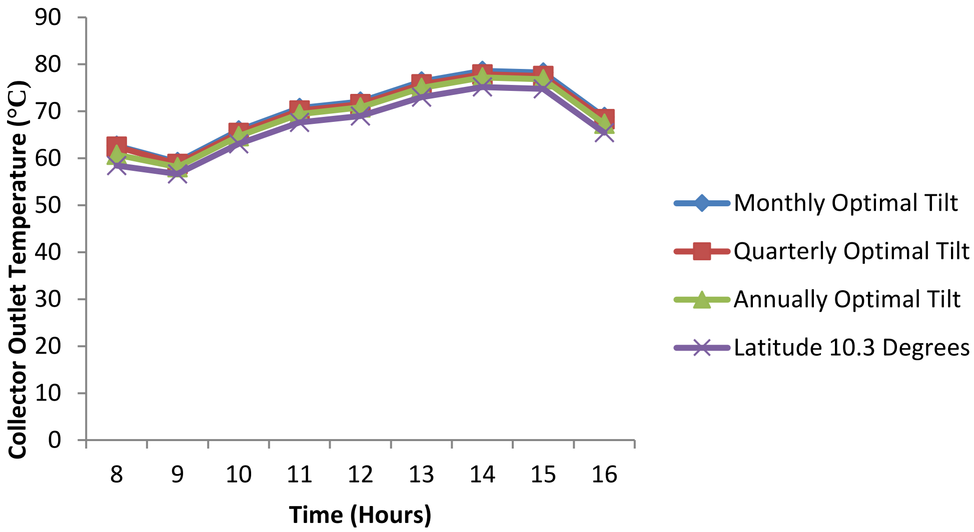

Figure 11. Comparison of tank inlet temperature on different optimal tilt angle scenario for September average recommended day.

Source: Own elaboration

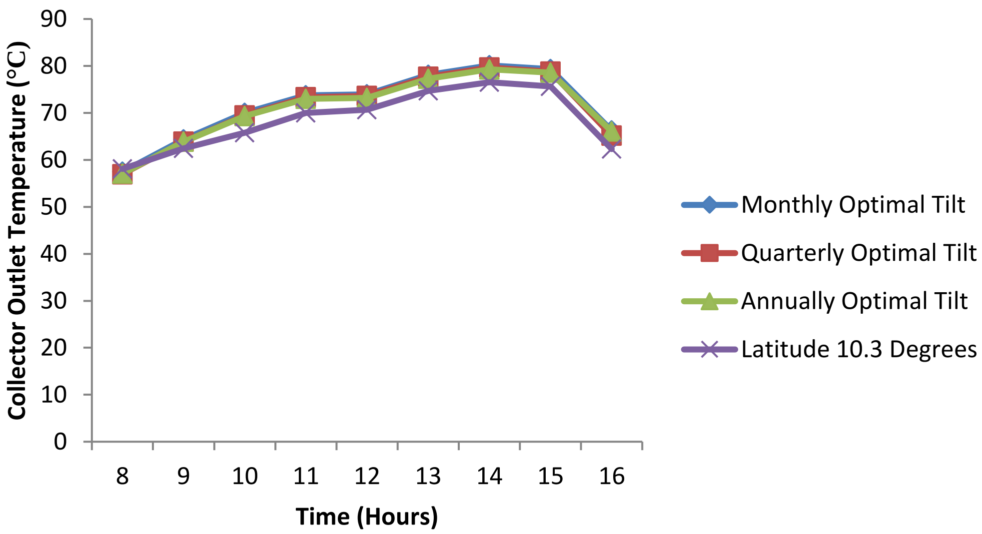

Figure 12. Comparison of tank inlet temperature on different optimal tilt angle scenario for October average recommended day

Source: Own elaboration

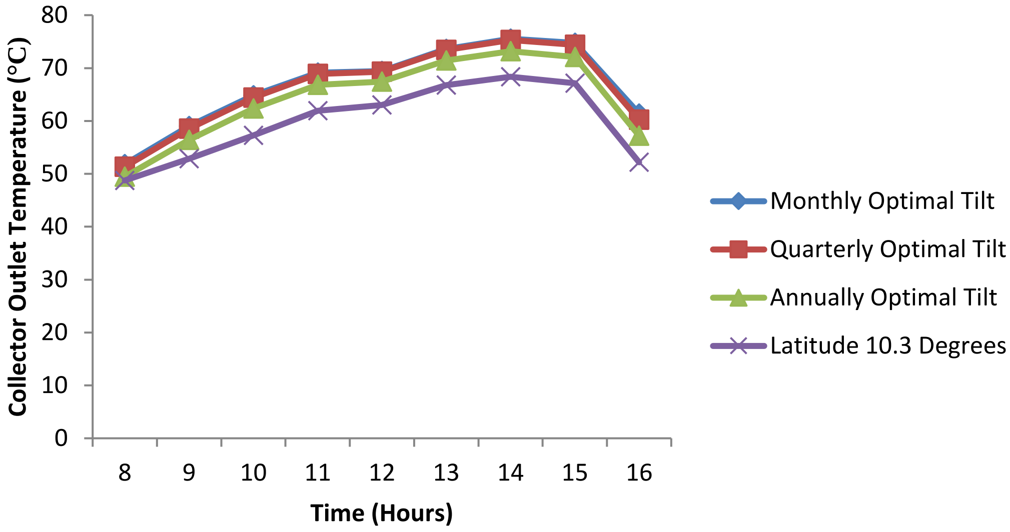

Figure 13. Comparison of tank inlet temperature on different optimal tilt angle scenario for November average recommended day.

Source: Own elaboration

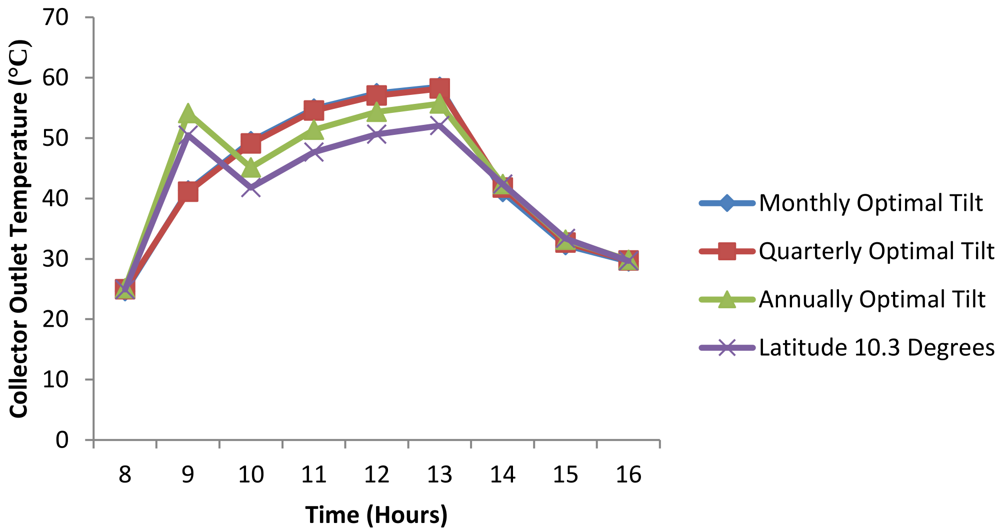

Figure 14. Comparison of tank inlet temperature on different optimal tilt angle scenario for December average recommended day.

Source: Own elaboration

Comparison of simulated and experimental result

Figures 15-17 present a comparison of the simulated and experimental results for the optimal monthly collector tilt angles from February to April. Slight differences were observed between the simulated and experimental collector outlet water temperatures. However, the experimental temperatures followed trends similar to the simulated values. This close agreement can be attributed to the optimized tilt angle, which minimized deviations in the solar radiation incident on the collector surface and thereby reduced the discrepancy between the simulated and experimental results.

Temperature fluctuations occurred at 10:00 and 13:00 in February, and at 10:00 in March, with only minor variations between the simulated and experimental values. Overall, the average hourly experimental collector outlet water temperatures were higher than the simulated values. The experimental peak collector outlet water temperatures occurred at 15:00 h, reaching 85°C in April-slightly higher than the simulated peak.

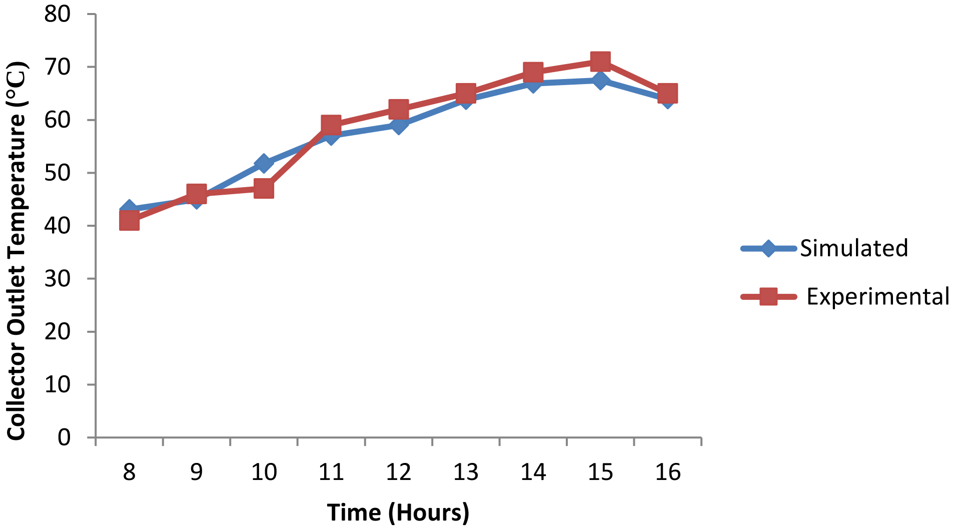

Figure 15. Comparison of simulated and average experimental tank inlet water temperatures for the monthly optimal tilt angle in February.

Source: Own elaboration

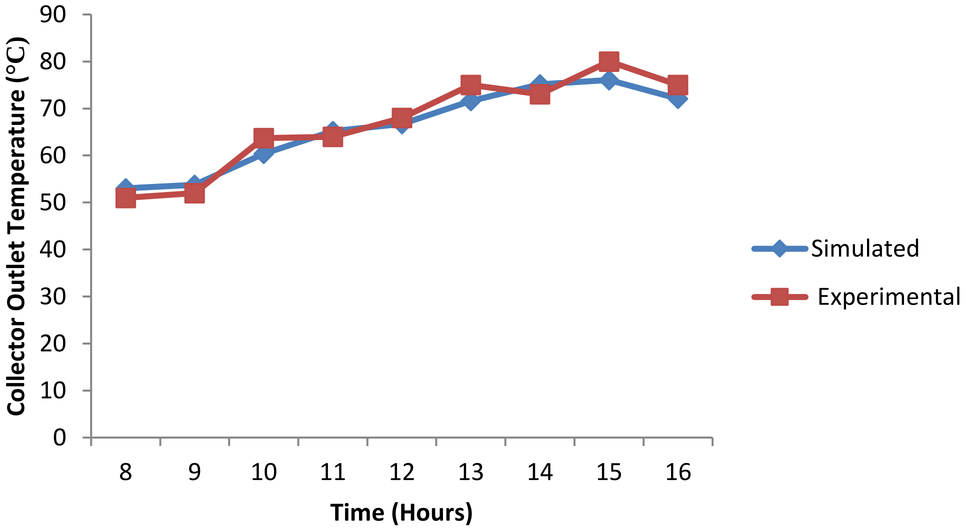

Figure 16. Comparison of simulated and average experimental tank inlet water temperatures for the monthly optimal tilt angle in March.

Source: Own elaboration

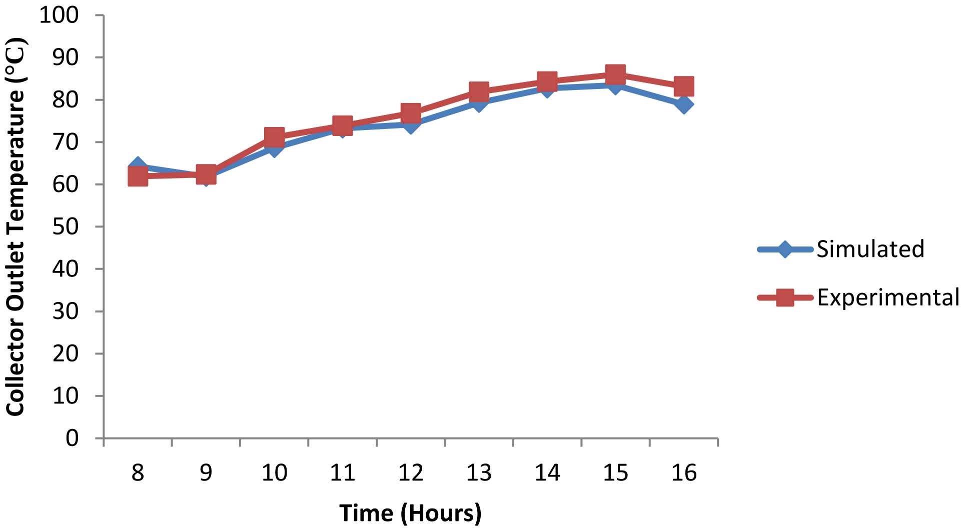

Figure 17. Comparison of simulated and average experimental collector outlet water temperatures for the monthly optimal tilt angle in April.

Source: Own elaboration

Model validation

The highest root mean square error (RMSE) was obtained in March, with a value of 2.71°C. The minimum Nash–Sutcliffe efficiency (NSE) occurred in April, corresponding to a predictive accuracy of 92%. The strong agreement between the simulated and experimental results demonstrates the ability of the flat-plate solar water heater model to capture the dynamic behaviour of the system under real operating conditions.

Economic analysis

The economic performance of the solar water heater was evaluated by comparing the cost of providing hot water using the solar system against electricity supplied by the Jos Electricity Distribution Company (JED). The analysis showed that the initial investment can be recovered within the estimated economic lifetime of 15 years when the system is utilized for a minimum of 210 and less than 150 clear sunny days per year for Band B and A respectively. Savings generated from only 150 or 180 days of annual operation fell below the total investment cost (see Table 6).

Table 6. Variation of annual thermal energy, cash flow, carbon (iv) oxide savings

Days	kWh	CF_i (Band A)	CF_i (Band B)	Savings (15 years), ₦ (Band A)	Savings (15 years) ₦ (Band B)
150	280.96	58,861.12	17,773.53	882,916.8	266,602.95
180	337.15	70,632.93	21,328.11	1,059,493.95	319,921.65
210	393.35	82,406.83	24,883.32	1,236.102.45	373,249.98
240	449.54	94,178.63	28,437.90	1,412.679.45	426,568.50
270	505.73	105,950.43	31,992.48	1,589,256.45	479,887.20
300	561.93	117,724.33	35,547.69	1,765,864.95	533,215.35

Source: Own elaboration

CONCLUSION

The flat-plate solar water heater developed in this study, incorporating optimal tilt adjustments, proved capable of delivering hot water at the required 50°C during normal working hours for pre-primary institutions throughout the year. Economically, the system demonstrated strong potential by recovering its initial investment well within its 15-year lifespan, provided it operates for a minimum of 210 clear sunny days annually.

Validation results revealed a strong correlation between the simulated and experimental data. The low values of Root Mean Square Error (RMSE) combined with a high Nash–Sutcliffe Efficiency (NSE) coefficient confirm that the model effectively captures the transient and dynamic performance of the solar water heater under real operating conditions.

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