



Development and performance evaluation of indigenous flat plate solar water heating systems under Kenyan climatic conditions

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Abstract: This work presents the performance of three solar water heaters equipped with 2 m² flat plate collectors. The experimental setup included a copper absorber plate manufactured in China (System C), along with two locally built flat plate collectors. One collector was made of aluminum material (System A), while the other was made of galvanized steel material (System B). The systems were tested over a period of three months. For systems A, B, and C; the average maximum outlet water temperatures were measured as 74.1 °C, 69.4 °C, and 78.7 °C, respectively. Systems A, B, and C had mean water outlet temperatures of 61.2 °C, 57.3 °C, and 63.5 °C, respectively. The efficiency of the aluminum-based flat plate collector was 32.8%, slightly below the copper-based flat plate collector, which reached an efficiency of 34%. On the other hand, the galvanized flat plate collector exhibited the lowest thermal efficiency of 28.8%. It can be inferred that even though the galvanized steel solar water heater had low thermal efficiency, it was 20% more cost-effective than systems constructed from copper and aluminum. These results would contribute to the widespread adoption of the inexpensive solar water heaters produced in the region as a reasonable alternative to conventional energy sources including biomass.

Keywords: Collector, Flat plate, Low-cost, Performance, Solar, Water heating

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Abbreviations	Descriptions
KU	Kenyatta University
KIRDI	Kenya Industrial Research and Development Institute
LPG	Liquefied petroleum gas
RE	Renewable Energy
SHS	Solar Heating System
TIM	Transparent insulating material
FPC	Flat-Plate Collector
FPSC	Flat-Plate Solar Collector

1. INTRODUCTION

The global energy demand is anticipated to increase by 30% by the year 2040 [1]. This rising demand is fueled by factors such as population growth, technological advancements, depletion of fossil fuels, and shifting consumer habits [2]. Consequently, the growing energy needs are expected to exacerbate the ongoing worldwide energy crisis, necessitating the exploration of reliable and sustainable energy alternatives.

Solar energy has emerged as a prominent replacement for conventional electricity and fuel sources. It provides a plentiful, environmentally-friendly, economically beneficial, clean, and carbon-neutral renewable energy option [3]. Solar power is particularly well-suited for meeting hot water requirements in both residential and industrial applications, especially in sunny tropical regions like Kenya. In Kenya, biomass dominates as the main energy source, representing approximately 68% of total energy consumption, especially among the urban poor, informal settlements, and rural communities [4]. Nearly 80% of the population depends on biomass, consuming up to 30 million tons annually [5]. Petroleum products and electricity constitute the remaining 22% and 9% of the energy mix, respectively [6]. Kenya's access rate to electricity stands at 73%, indicating that 27% of the population are yet to be connected to electricity [7]. Limited electricity access in remote communities and among marginalized groups reinforces biomass dependence, while urban areas primarily utilize commercial energy sources like kerosene, electricity, and liquefied petroleum gas (LPG). The cost of electricity remains elevated at around \$0.20 per kWh, significantly higher than the global average of \$0.13 per kWh [5]. In this context, solar water heating systems (SWHS) offer a promising alternative, as a non-complicated, less expensive, and efficient method of utilizing solar energy to supply hot water for households in any climate [8], potentially meeting up to 85% of household hot water needs. However, modern solar systems often remain financially inaccessible to many families, particularly those in middle-income brackets and economically disadvantaged rural regions. Solar water heating systems display improved energy conversion efficiencies, surpassing 70%, whereas electric energy systems typically achieve only about 17% efficiency [9]. According to the work of Timothy and colleagues, that positions solar energy as the most practical option for water heating in Kenya, especially considering the persistent dependence on biomass and the resulting environmental degradation from deforestation and vulnerability to climate change impacts [10]. The solar water heating (SWH) technology represents a cost-effective method of harnessing solar energy and is widely adopted in numerous countries around the globe [11]. It minimizes greenhouse gas emissions and fossil fuel reliance, making them important in global energy transitions [12]. However, their performance, cost-efficiency, and usefulness depend on design variables.

Researchers worldwide are diligently working to enhance the efficiency and design of solar thermal collectors, aiming to reduce costs and simplify maintenance. Among the various solar thermal water heating collectors, the flat-plate solar water heater (FPSWH) is frequently utilized due to its simple design, ease of use, low maintenance, and cost-effectiveness [3]. These collectors can achieve moderate water temperatures of up to 80°C, suitable for bathing, washing clothes, and cleaning utensils [13]. Additionally, they offer a relatively quick return on investment [14], with prior research indicating that solar water heating systems' financial sustainability depends on cost-effectiveness and payback periods. With proper design and care, these collectors frequently have a lifespan exceeding 20 years [14]. However, the performance of FPSWHs is limited by issues such as inadequate useful heat and high heat loss and the thermal efficiency depends on the solar collector's ability to absorb solar energy, necessitating in-depth research and the development of new ideas to acquire technological advancements that reduce production costs [15].

Modifications to solar collectors, including enhancing the absorptivity of solar radiation, cutting costs, and improving the durability of SWHs, have yielded promising outcomes in various studies. For instance, Sharma and coworkers [16] compared the performance of flat-plate collectors (FPC) with

circular and trapezoidal corrugated absorber plate designs, finding that the trapezoidal design exhibited superior thermal and exergy efficiency, with increases of 8.74% and 12.85%, respectively. Barbosa et. al., evaluated the effects of absorber tube configurations, discovering that series and parallel arrangements achieved maximum energy efficiencies of 37.8% and 40.9%, respectively [17]. Furthermore, Valizade et. al. demonstrated that applying full metal and semi-metal foam to both the upper and lower surfaces of the absorber plate enhances efficiency compared to systems without metal foam, with foam directly on the absorber plate improving energy absorption more effectively than when placed on the insulator [18]. Zhou and co-workers highlighted that Thermal Insulation Materials (TIM) can minimize heat loss from the front system, emphasizing that TIM transmittance should exceed 80% for collectors to operate efficiently [19]. Müller et. al. tested three types of absorber coatings—black chrome, highly selective sputtered PVD coatings, and solar paints—to evaluate their thermal performance and stagnation behavior in flat-plate solar collectors (FPSCs), finding that all coatings had absorbances above 90% and thermal emittances ranging from 5% to 90% [20]. Munuswamy et. al., studied the effects of finned absorber tubes and concluded that finned tubes were more effective than those without fins [15]. Alkhafaji and coworkers explored various types of finned tubes and found that wavy-finned tubes outperformed straight-finned ones, leading to 16.7% higher fluid temperatures and 16.2% higher tank temperatures compared to straight-finned tubes [21]. Kansara and coworkers improved the efficiency of the flat plate solar collector by using the internal fins and porous material [22]. Their results showed that the efficiency of the collector with fins and porous material is enhanced about 8.19% and 16.17% as compared with the conventional collectors. In light of rising copper prices, researchers are exploring alternative materials, such as aluminum and galvanized steel, as cost-effective substitutes for copper in flat-plate solar collectors. Research indicates that aluminum and galvanized steel serve as suitable alternatives, providing advantages in thermal performance and manufacturing costs. A work by Sakhaei and Valipour proved that aluminum absorber materials provide improved thermal conductivity, lower material expenses, and decreased weight compared to copper [23]. In a different work, Jaafar developed and evaluated a solar water flat-plate collector utilizing locally sourced materials, showcasing an aluminum absorber plate protected by a clear cover to gather emitted radiation [24]. In a recent work, Agyekum and co-workers conducted a detailed investigation across five locations in South Africa to examine the techno-economic and environmental effects of two distinct types of solar water heaters [25]. The findings indicated that, influenced by geographical conditions, FPC exhibited payback periods ranging from 3.2 to 4.4 years, whereas evacuated tube collectors (ETC) demonstrated payback periods between 3.5 and 4.3 years. Furthermore, the annual cost savings associated with the implementation of an FPC system were estimated to be between \$486 and \$625. In a separate study, Nshimyumuremyi et. al., explored the thermal efficiency and pricing of a solar water heater produced in Rwanda, revealing that the solar water heater manufactured by Tumba College of Technology is available for \$900, features a surface area of 2.77 m², and has a tank capacity of 200 lt [26]. It has also been estimated that a 100 lt/day system with 2 m² of collector area installed can save close to 140 lt diesel fuel in a year [27].

Combining thermal storage with FPCs can improve the effectiveness of solar water heating systems by reducing energy loss at the top, enhancing energy transfer to water, and storing absorbed heat energy for use during late evening hours [3]. Thermal performance methods primarily involve absorber designs, absorber tubes, and thermal energy storage. Furthermore, most of the research conducted suggests that the optimum collector area and the storage tank volume are major design components to be considered in order to ensure maximum system efficiency with minimal payback time [28]. Motivated by the literature review and recognizing the high cost of essential energy commodities in Kenya and other developing countries, this study aims to develop a novel, single glazed and cost-effective FSWHS using readily available materials, making them more affordable and accessible. Similar research has not been conducted and tested in Kenya, which currently relies on importing these systems. The goal is to explore strategies to lower the upfront costs of SWHS by employing commonly available materials, optimizing designs, and assessing economic impacts. The low-cost flat-plate solar water heaters with parallel flow will enhance the cost-effectiveness of SWHS and encourage wider adoption of solar energy as a sustainable alternative to conventional energy sources, thereby decreasing dependence on non-renewable energy and addressing energy-related challenges in Kenya.

2. MATERIALS AND METHODS

2.1. Study Area

The performance evaluation experiments were conducted between March and May 2015, at Kenyatta University (KU) in Kiambu County, Kenya, with geographical coordinates of 1°10'50.0"S, 36°55'41.0"E (latitude: -1.180568; longitude: 36.928042). The climate varied between cloudy and sunny during this period. At the Kenya Industrial Research and Development Institute (KIRDI) in Nairobi, two model systems for flat plate SWHS were designed and built using materials sourced locally.

2.2. Estimation of Hot Water Requirements and Storage Tank

The hot water needs of a typical household in Kenya, operating under an average isolation of 800 W/m², and the sunshine duration of 4 to 9 h/day were determined as per Onyango and Ongoma for the sizing and development of the systems [29]. The dimension of the system was determined by the hot water needs of consumers. Each system was designed to heat enough water to serve a family of five people per day, with the assumption that each person in a household requires at least 20 liters of hot water at temperatures of 50 °C per day to fulfill household hot water needs. Therefore, the quantity of warm water was determined using Eq. 1 from Ref. [30].

$$\text{Total Volume of water required} = \text{Average family size} \times \text{Volume of water required per person} \quad (1)$$

2.3. Estimation of Solar Energy Requirement

Assuming an ambient temperature (T_a) of 20 °C and a desired heating temperature (T_o) of 50 °C [14], the quantity of solar energy required to achieve the desired heating temperature for a specific volume of water can be expressed as per Eq. 2 [31].

$$Q_u = \dot{m} C_p (T_o - T_i) = \frac{12.6 \text{ MJ}}{\text{day}} \quad (2)$$

Where $\dot{m}$ (kg/s) is the mass flow rate of the water through the collector, C_p is the specific heat capacity of water, which is 4200 J/kg K, and T_o and T_i are the outlet and inlet temperature of water, respectively. The energy consumed from sun irradiation by the absorber plate is acquired by Eq. 3 [32].

$$Q_{\text{absorbed}} = A_c \alpha \tau I_{av} \quad (3)$$

The Eq. 3 considers the surface area of the collector plate (A_c), the light transmission of the glass (τ), the solar absorption of the absorber (α) and the mean radiation intensity (I_{av}) in units (W/m²). The thermal heat loss (Q_o) of the surface of the collector is directly proportional to the total heat transfer coefficient (U_L) Eq. 4 [32]:

$$Q_o = U_L A (T_o - T_a) \quad (4)$$

2.4. Solar Flat Plate Collector Sizing

The daily requirement for heated water and the solar irradiation available at the specific location were taken into consideration when determining the appropriate size of solar water collectors. Eq. 5 was used to calculate the minimum energy collection area (A_c) without taking losses into account [24].

$$A_c = \frac{m C_p (T_o - T_i)}{I_{Tav} \eta_t} \quad (5)$$

Assuming an average efficiency for solar flat-plate water collector of 40% [24] :

$$A_{c,40\%} = \frac{m C_p (T_o - T_i)}{0.4 I_{Tav}} \quad (6)$$

$$A_c = \frac{100 \cdot 4200 \cdot 30}{0.4 \cdot 800 \cdot 7 \cdot 3600} = 1.56 m^2 \quad (7)$$

The authors selected 2 m² for the collector, A_c as the minimal prerequisite. They opted for parallel pipework using 20 mm diameter tubes and 25 mm diameter conduits for the systems. The aim of this choice was to guarantee a consistent flow distribution in the parallel risers of the absorber and to increase the convective heat transfer between the damper plate and the water, as well as to expand the surface exposed to solar radiation [33]. The number of risers was established to optimize heat conveyance and efficiently warm up the water within the necessary period. The gap between the tubes was chosen within the range of 75 to 120 mm [28]. FPCs of 4 mm glass glazing were chosen because they boost the solar system's effectiveness [34]. Fig. 1 illustrates a three-dimensional view of the engineered flat-plate solar heating system. The system comprises of a collector, absorber plate, insulation materials, glass cover, cold and hot storage tanks and piping systems.

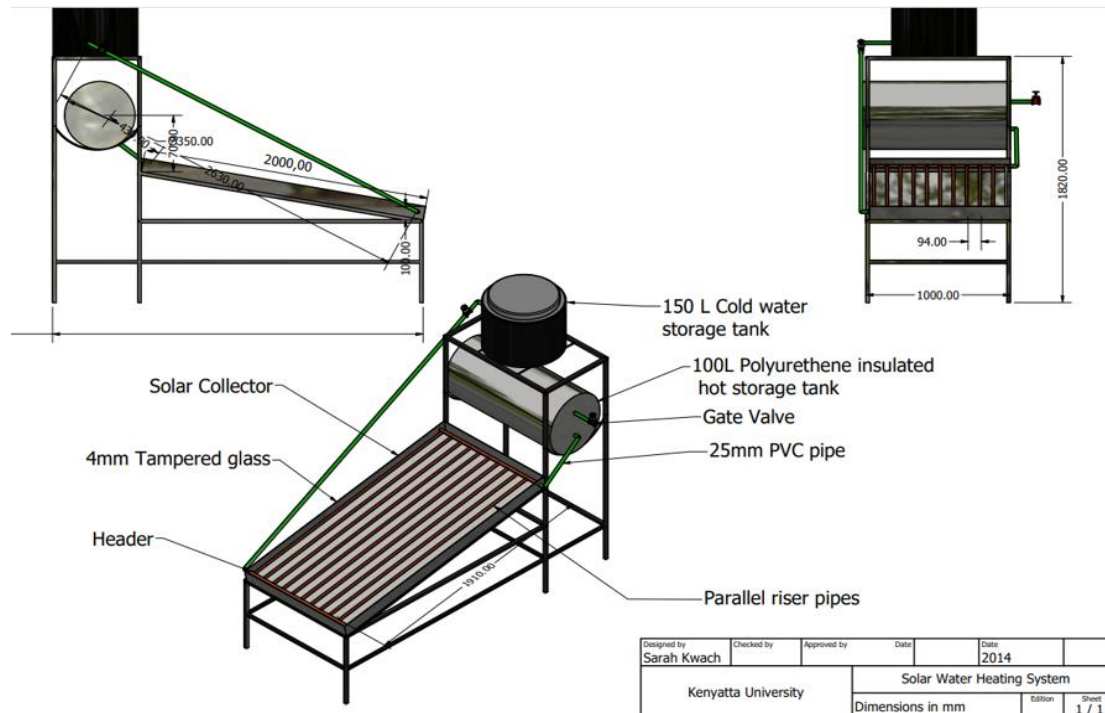


Figure 1. 3D designed drawings of the components of the flat plate solar water heating systems.

2.5. Selection of Construction Materials

Choosing the correct materials is essential to any engineering project's success. In the case of the SWH system, thorough assessments were performed to ensure that the chosen materials met the required performance parameters. Using locally accessible materials reduces costs and ensures the system is easily maintained and repaired if necessary. Numerous vital elements were considered when selecting the components for the experimental solar water heating system. These variables comprised thermal characteristics, durability, ease of handling, cost, availability in the local market, and economic considerations. Careful consideration was given to these factors to ensure that the materials selected were appropriate for the specific application and would function efficiently under the provided conditions.

System A chooses aluminum as the absorber plate and fin material due to its exceptional thermal conductivity, lightweight nature, durability, and ease of handling [20]. Moreover, aluminum is relatively inexpensive compared to materials like copper and has demonstrated high efficiency in solar water heating systems [23]. On the other hand, System B opted for galvanized steel as the fin material because of its cost-effectiveness, resistance to corrosion and humidity, and ease of handling. It is also readily available in the local market and has been successfully utilized in other solar water heating systems [22]. The transparent glazing is responsible for the majority of the heat loss in the solar panel. Consequently, the glazing material is essential for the solar flat plate collector's thermal efficiency. The glass cover behaves nearly like a black body for long-wave radiation. Thus, the project considered a low iron-tempered glass glazing with a 4 mm thickness; experimental results proved that the use of 4 mm glass glazing enhanced the performance by 7.6% [33].

2.6. Construction of FPSCs

The configuration of solar collectors primarily concentrated on optimizing energy absorption, reducing reflection and radiation losses, and effectively transferring heat energy from the collector plate to the fluid. Therefore, their primary purpose is transmitting heat to the riser tube fluid by capturing as much of the sun's radiant energy as possible. Two models of solar flat plate collectors with single glazing were built at KIRDI. Each has an effective glazing area of two square meters and an overall dimension of 2000 mm x 1000 mm (see in Fig. 1).

2.6.1. Construction of collector casing

FPC casing is supported to secure the various components together, protect the components from harsh weather conditions, and streamline installation on a supporting frame. In constructing the enclosure of solar collectors, a 0.5 mm thickness of mild steel metals was cut to a rectangular shape with a 2 m² area to hold one glass glazing [34]. A few cut parts were welded while different parts were connected with the assistance of screws. Two header holes of 29 mm diameter were then drilled in the sides of the frame to fit the tube inlet and outlet for prototypes A and B, respectively, as illustrated in Fig. 2.

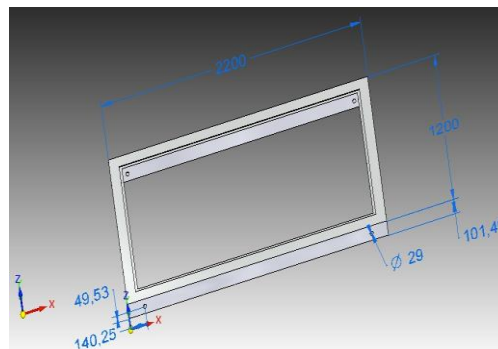


Figure 2. 3D drawing of solar collector casing.

Black mild steel was preferred because of its availability and low cost as compared to aluminum. Red oxide was applied to the mild steel, followed by a spray of gray paint to inhibit corrosion and enhance its visual appeal.

2.6.2. Collector absorber plate and tubes

The collector riser tube exchanges heat, and the absorber plate improves the system's heat-transfer surface [35]. For Systems A and B, two distinct absorber plates were constructed using various materials to achieve ideal heat transfer while remaining cost-effective. The collector plate in System A was cleverly constructed from a 0.5 mm aluminum sheet. This thin sheet was carefully trimmed and molded into a ridged design as illustrated in Fig. 3 This enabled it to securely house the water pipes and headers within its indentations. By doing this, it reached optimal connection with the pipes, enabling effective

heat exchange from the absorber plate to the water [36]. This considerate design played a critical role in optimizing the system's overall efficiency. On the contrary, System B's absorber plate was also constructed from 0.5 mm galvanized sheets. Both absorber plates were crafted to cover an expanse of 2 m², a standard measurement for most flat plate collectors.

The collector riser tube exchanges heat and the absorber plate improve the system's heat-transfer surface [37]. For systems A and B, two distinct absorber plates were constructed using various materials to achieve ideal heat transfer while remaining cost-effective. Numerous tubes constructed of aluminum and galvanized steel for the A and B systems were positioned on the absorber plate. The operating fluid traversed through the riser tubes, where it was heated. The risers were arranged parallel to one another on the collector plate [24]. The fluid riser tubes are connected at both ends by wide-diameter header tubes measuring 25 mm in diameter. These openings were slightly larger than the width of the riser pipes to facilitate welding. The riser tubes were measured and cut to a length of 1950 mm, with widths of 20 mm for both aluminum and galvanized pipes. Riser tubes were affixed to the absorber fins (see in Figs. 3(a-d)). The header and riser pipes were depicted in Fig. 3(c), where they were subsequently joined at both ends to form a complete heat exchanger. This configuration ensured efficient heat transfer to the circulating fluid [38]. To reduce the amount of radiation emitted by the collector plate and improve its ability to capture solar energy, the surfaces of the plate were coated in a black matte finish as illustrated in Fig. 3(d). This design guarantees optimal solar energy absorption and heat transfer. Given the high expense of copper, the project's developers opted for galvanized steel and aluminum instead [8].

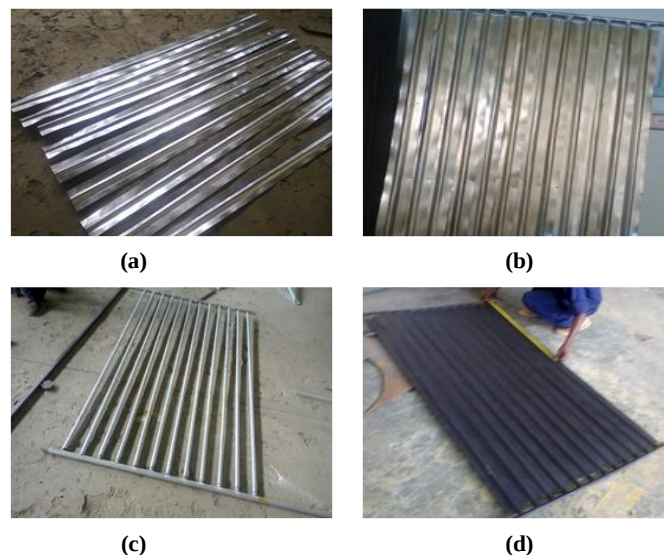


Figure 3. Photos of the assembled solar collector absorber components.

2.6.3. Insulation

The sides and lower part of the plate collector were well protected to diminish heat losses and enhance the thermal efficiency of the system [40]. By aiding in heating the tubes as well as the plate for the systems, a 50 mm thick layer of fiberglass wool was utilized to insulate the Panel A [41]. Fiberglass wool (see Fig. 4(a)) was utilized for its lightweight, simple installation, and effective thermal insulation.

In system B, a layer of 50 mm thick fiberglass insulation (see Fig. 4(a)) was utilized to insulate the internal partitions of the collector, and the front was covered with an aluminum foil sheet to improve heat absorption by the channel as the aluminum foil sheet is a proficient reflector (see Fig. 4(c)) [42]. The airspace between the glass panel and the collector plate was further widened to 50 mm, which also reduced heat loss [43]. To increase the structural rigidity of both setups, a Styrofoam layer with a 25 mm thickness (thermal conductivity = 0.04 W/m K) (see in Fig. 4(b)) was added along the edges of the collectors. Styrofoam was selected because it is relatively cheap, easily accessible, and has extremely

low thermal conductivity [18]. These insulation materials are recognized for being dimensionally and chemically steady at elevated temperatures, and resilient to weathering and moisture from condensation.

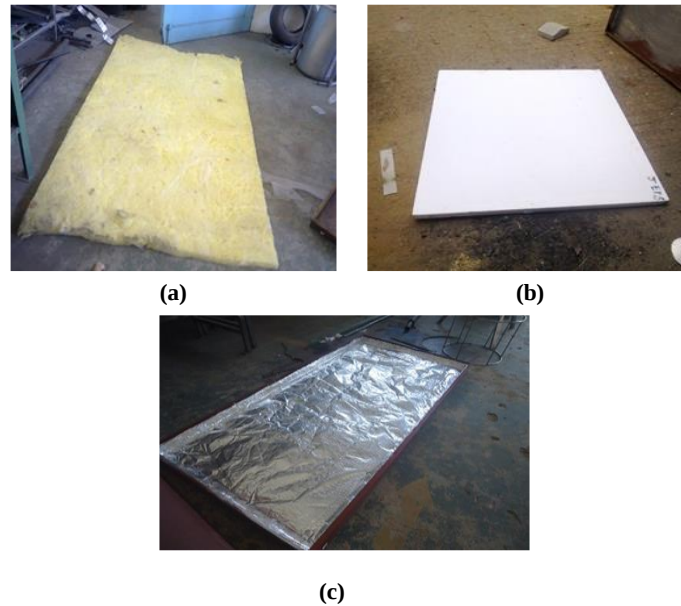


Figure 4. Photos of insulation materials used

2.6.4. Collector glazing

Glazing is the front cover of a solar collector. It performs three significant roles specifically: To minimize convective and radiant heat loss from the absorber, to transfer the incoming solar radiation to the absorber plate with minimal loss, and to protect the absorber plate from the outside environment [44]. For this reason, a 4 mm transparent low iron tampered glass with high transmittance to visible light and low transmittance to infrared radiation was chosen to cover the front surface of the collector [34]. The glass had a general component of 2000 mm x 1000 mm x 100 mm to limit the transmission of long-wave infrared radiation. The tampered glass was preferred to plastic due to its stability, ability to withstand significant hail without breaking, and overall durability.

The distance between the absorber Plate B and the bottom surface of the glass was set at 50 mm, which is within the recommended value for solar collectors. This distance provided a good insulating gap for the conduction-convection heat flow from the heated absorber plate to the glass lid, which in turn serves to enhance the effectiveness of the collector system. To allow for expansion of the glass at high temperatures, a rubber seal with a size of 220 mm x 20 mm was affixed around the glass circumference. After attaching the rubber gasket, the gaps were sealed using suitable sealing materials to prevent the leakage of hot air from the gap between the absorbing surface and the glass cover. The use of appropriate sealing materials helps to prevent the loss of heat energy from the collector system and ensures that the system operates efficiently.

2.6.5. Imported commercial type for System C

A benchmark model was selected based totally on experimental geometry from the literature. Copper sheets have been used as an absorber plate due to excessive thermal conductivity for over two decades [8]. Therefore, Chinese-made FPC was characterized by using copper absorber plates of 2000 mm length, 1000 mm width, and 100 mm thickness. The absorber plate of the collector was painted a matte black color and was covered with a transparent low iron-tampered glass of thickness 4 mm to capture the highest level of incoming radiation. To decrease the heat loss by conduction via the absorber plate, glass wool of thickness 50 mm was used to insulate the bottom of the collector [45]. The collector was acquired from a nearby solar vendor in Nairobi, Kenya.

2.6.6. Hot water storage tank

Insulation in a storage tank helps maintain the temperature of the water steady and minimizes heat dissipation. In order to prevent thermal energy losses and keep heated water at a high temperature, particularly during times of low solar radiation, insulating materials with poor heat conductivity were utilized [39]. Water was selected for its high specific heat capacity, making it a convenient heat storage medium, and the specially designed hot storage container was well insulated to keep hot water for household use for an extended period of time [39]. To accommodate the tank's inner and outer compartments, the storage container had two layers of 0.002 mm-thick galvanized metal sheet. Polyurethane insulation with a thickness of 50 mm was used to fill the tank's 50-millimeter gap between its internal and external walls. To prevent backflow, the storage tank was set at the ideal height of 70 meters above the collector. The solar water-heating device's overall design was fine-tuned for maximum efficiency and durability, ensuring its long-term reliability and cost-effectiveness. The SWH's design is depicted in Fig. 5.

2.7. Experimental Setup

Three experimental systems were set up, using either corrugated galvanized sheet or aluminium as the absorber plate. The designed systems were tested simultaneously under field weather conditions and compared against the imported solar water heating system. This study used two experimental solar water heaters with improved FPC. The third solar heating system was assembled with a copper absorber plate imported from China but purchased from a nearby store in Nairobi. This specific configuration served as the control mechanism.



Figure 5. Photo of the experimental setup of solar water heating systems (A, B and control system C)

The experimental systems were specifically engineered to manage a continuous water flow with an average design low temperature of 50°C for domestic water heating. The 25° tilt angle was chosen as it strikes a balance between capturing sufficient sunlight throughout the seasons. This angle allows for efficient solar collection without requiring complex and costly continuous sun tracking. In a recent paper, Al-Mamun and coworkers have reported that increase in angle from 15° to 25° improved the thermal performance of the collector from 27% to 30% [31]. The collector stands were designed to ensure the collectors were positioned at the same height and angle. This helped eliminate any potential bias from differences in the angle or orientation of the collectors. The stands were also constructed to be sturdy and durable to withstand various weather conditions. Moreover, the stands were designed to ensure that the collectors were at the same height and angle. This helped to eliminate any potential bias due to differences in the angle or orientation of the collectors. The stands were also constructed to be sturdy and durable to withstand various weather conditions.

2.8. Instrumentation and Data Collection Procedure

The arrangement for instrumentation and data collection is depicted in Fig. 6. It consists of a data logger model Agilent 34970A data acquisition unit. The test systems were evaluated together with the Chinese

commercial SWHS, positioned with the collectors in the east-west orientation to avoid shading as the sun transitions from east to west. Tests were carried out at the Kenyatta University location for a duration of three months, spanning from March, April, to May 2015, between 09.05 hours and 17.05 hours. At the beginning, the data logger was switched on 10 minutes before the commencement of the experiment. The thermal efficiency and heat gained by the water were calculated, and the results are discussed. All measurements, including solar radiation, wind speed, and temperature, were monitored and recorded at 60 min intervals via a Chinese data logger model Agilent 34970A data acquisition unit, solar collector, anemometer, thermocouples, thermometer and radiometer. The data was then processed via computer, as shown in Fig. 6. The monitoring and recording of these parameters enabled the precise evaluation of the efficiency of the SWHS.

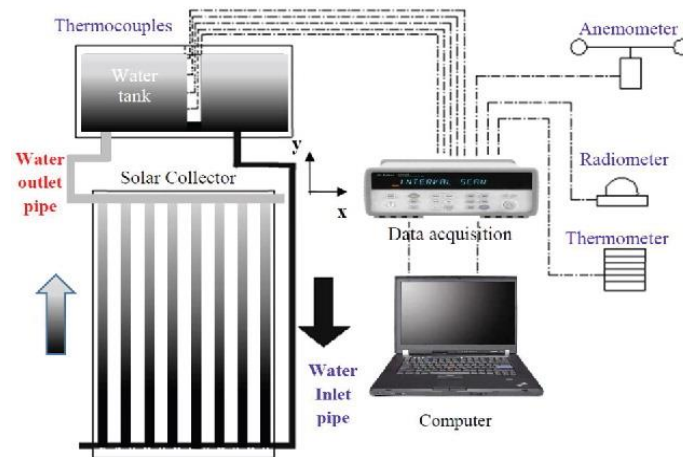


Figure 6. Side view of the experimental solar water heating system.

2.8.1. Temperature, solar radiation and wind speed measurements

The following data was collected from the three experimental solar water-heating systems:

- i. Water inlet and outlet temperature and ambient temperatures on hourly basis using with thermal couple connected via a datalogger from 09.00 hours to 17.00 hours.
- ii. Solar radiation was measured using a solarimeter Australian Kipp and Zenon pyranometer (CN27-277)
- iii. Wind speed was measured using a Velocicalc portable air velocity meter model 8357 (USA) with a sensitivity of 0.05m/s manufactured by TSI, USA connected via a data logger.

Temperature measurements were performed by using copper-nickel thermocouple wires, which have a temperature range of -185 °C to 300 °C and a sensitivity of 0.1 °C. The thermocouples were placed at four different positions on the collectors to measure the temperature at the inlet, absorber plate, and outlet side of the solar collector. To ensure precise measurement, the thermocouple sensors were affixed using heat-resistant adhesive. Solar radiation was also measured using an Australian Kipp and Zenon pyranometer (CN27-277) with a sensitivity of 91.68 W/m² per mV, installed on the rooftop of the Kenyatta University Engineering building.

2.8.2. Experimental Testing Conditions

The systems were tested over three months (from March, April, to May) in the year 2015. During this period, the weather was varying between cloudy and sunny, with ambient temperatures ranging from 24. °C to 33. °C. The reason for spreading these experiments was unpredictable weather conditions during the testing period. About 60 experiments were carried out with loaded solar water heating systems, from which we selected a clear sky condition to avoid fluctuations associated with unpredictable cloudy rainy conditions.

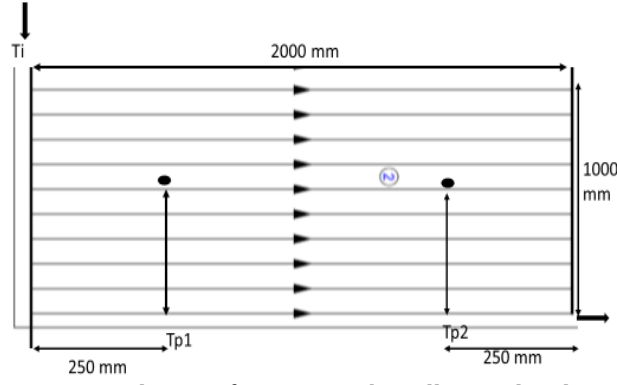


Figure 7. Distribution of sensors on the collector absorber plate.

2.9. Evaluation of Thermal Efficiency of a FPC

The performance evaluation of the FPS collectors was conducted in compliance with ISO 9806-1.2, ASHRAE Standard 93:1986, and Solar Water Heating for Domestic Hot Water Kenya (Standard KS 1860:2008). These standards assess the performance by measuring the instantaneous efficiency values under various combinations of solar radiation, ambient temperature, and inlet fluid temperature. To obtain these values, experimental measurements were taken for both the incident solar radiation rate and the energy absorption rate by the working fluid. The experiments were performed at a constant flow rate of 0.1 kg/s for all three systems during daylight hours from 9.05 to 17.05. The useful energy gain of the working fluid under steady-state conditions was calculated using Eq. (8) [31].

$$Q_u = mC_p (T_o - T_i) \quad (8)$$

The efficiency (η) of the collector is determined as the proportion of valuable heat gain of the operational fluid to the energy striking the solar collector surface, which can be computed using Eq. (9) [31].

$$\eta = \frac{Q_u}{A_c I_T} = \frac{mC_p(T_o - T_i)}{A_c I_T}, \quad (9)$$

where Q_u is the useful heat gain of water, W; m is the mass flow rate, kg/s; C_p is the thermal capacity of water, J/kg K; T_o is the outlet temperature of the solar collector, °C; T_i is the inlet temperature of the solar collector, °C; T_a is the ambient air temperature, °C; A is the surface area of the solar collector, m²; and I is the incident solar radiation, W/m²

The actual useful heat gain is usually associated with the maximum heat acquisition of the solar collector if the entire collector surface is at the inlet water temperature. This amount is known as the heat removal factor F_R stated in Eq.10 [46].

$$F_R = \frac{mC_p(T_o - T_i)}{A_c \{ \alpha \tau I_T - U_L (T_i - T_a) \}} \quad (10)$$

Finally, equation for efficiency of flat plate solar collector can be given by so-called Hottel-Whillier-Bliss equation [33].

$$Q_u = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{I_T}, \quad (11)$$

where F_R is collector heat removal factor, U_L is total heat transfer coefficient, $(\tau\alpha)$ is the effective transmittance-absorbance value for the solar collector, T_i is fluid inlet temperature and T_a is ambient air temperature and I_T is the insolation in plane of the collector. Therefore, to evaluate the thermal

efficiency of flat plate solar collectors, it is essential to calculate efficiency (η) as a function of $(T_f - T_a)/I_T$.

2.10. Economic Evaluation of the SWHS

To assess the economic viability of the planned collectors, a simplified analysis was performed. The life cycle cost (LCC) is a quantitative approach that determines the overall expenses of a system across its entire lifespan, encompassing all the expenditures related to the system's development, functioning, and maintenance.

2.10.1. Simple payback period

The payback period is the time (in years) required to recover the initial investment. The payback time of SWH can be calculated using equation 12 [2].

$$\text{Payback period (in years)} = \frac{\text{Capital investment}}{\text{Annual net savings}} \quad (12)$$

$$\text{Annual savings} = 365 \text{ CE } Q_{\text{load}} \quad (13)$$

$$Q_{\text{Load}} = Q_w C_p (T_o - T_i), \quad (14)$$

where, CE is the cost of electricity per kWh, Q_{load} is the quantity of electricity needed per day, $(T_o - T_i)$ is the difference of final and initial temperature of heated water and Q_w is the daily quantity of water needed.

3. RESULTS AND DISCUSSION

3.1. Incident Solar Radiation and Ambient Temperature Distribution

Fig. 8 depicts the solar irradiance and temperature pattern throughout the research period. The surrounding temperatures varied from 24°C to 34°C. As shown in Fig. 8, the ambient temperature gradually increased throughout the day due to the heat radiated by the sun and the movement of the wind [40]. On the clearest days, the average solar intensity observed rose from 10.05 hours to 12.05 hours, reaching a peak value of 994.1 W/m² at 12.05 hours. However, the solar radiation decreased from 747.7 W/m² at 14.50 hours to 385.6 W/m² at 17.05 hours. This variation in solar radiation throughout the day is a result of the sun's position relative to the Earth's surface. The average recorded solar radiation and ambient temperatures were 711.9 W/m² and 29.8°C, respectively. These findings align favourably with the research conducted by Ali and co-workers, which indicated that the ambient temperature ranged from 28°C to 37°C, while the sunlight intensity ranged from 350 W/m² to 850 W/m² [47].

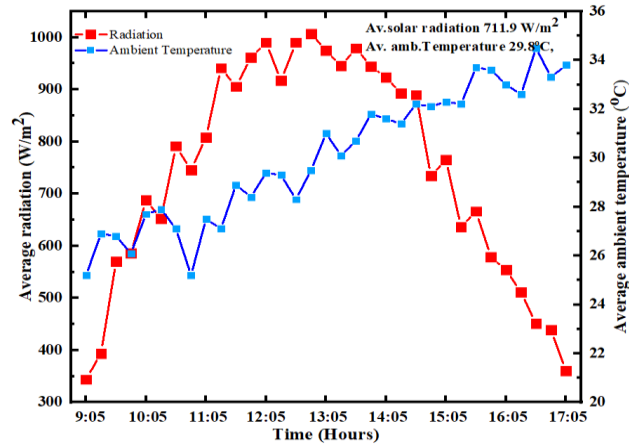


Figure 8. Solar radiation and ambient temperature distribution.

3.2. Temperature profiles

3.2.1. Temperature variation of inlet and ambient temperature

Fig. 9 illustrates the influence of inlet temperature on the collector efficiency. The figure shows that the water entering the inlet of the flat plate collector had a marginally elevated temperature compared to the surrounding environment.

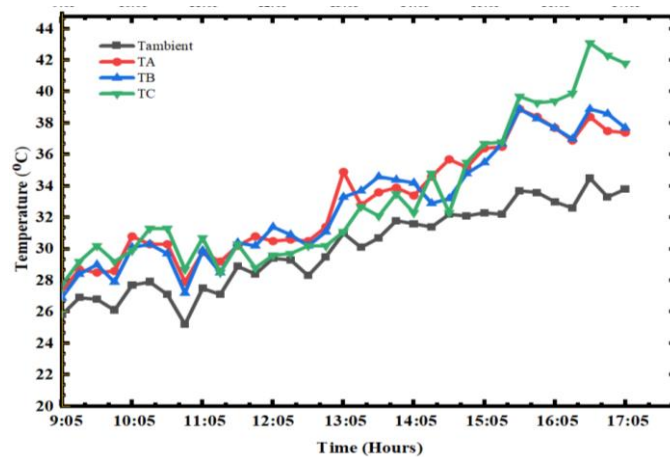


Figure 9. Inlet and ambient temperature profiles of Systems A, B and C.

This is because the inlet tube is exposed to the sun. The water passing through the copper and aluminum riser pipes heated up faster than the galvanized collector, as these materials absorb heat faster from the hot absorber plate. The heat is absorbed by the water inside the tube, but because water has a substantial capacity to store heat before its temperature increases, the increase could be attributed to an enhancement in the overall heat transfer coefficient [47]. Consequently, the temperature slightly rose from 27.3°C to 37.4°C, 26.9°C to 37.7°C, and 27°C to 41°C for Systems A, B, and C, respectively. The pattern of variation in inlet temperature aligns with the findings reported by Islam and coworkers [48] and Djimeli [49].

3.2.2. Water inlet and outlet temperature profiles

The graph in Fig. 10 illustrates the relationship between solar radiation and the temperatures of the water outlet, inlet, and ambient conditions in an aluminum pipe collector over the course of a clear day. The water circulates through a closed system storage tank.

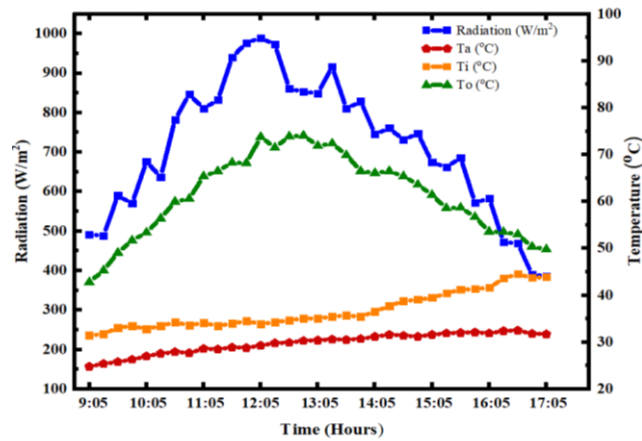


Figure 10. Effect of daytime on water outlet, inlet, and ambient temperature and solar radiation for aluminum pipe collector on a clear day.

The graph shows that the water inlet temperature increased slightly and almost linearly, as the inlet tube is exposed to the sun. As the water flows through the riser tubes, it gets heated by the collector's operation. The absorber plates absorb heat in all the systems. The glazing glass is opaque to infrared rays and transparent to solar light in the visible range. As the incident radiation increases until midday, the outlet water temperature for all three systems (A, B, and C) rises to a maximum and then decreases due to decreases in incident solar radiation as the time goes closer to the evening. The minimum average outlet temperatures were recorded at 9.05 hours for systems A, B, and C, respectively. During the peak solar radiation between 12.00 and 14.20 hours, the average maximum recorded outlet water temperatures were highest for the copper absorber (system C), followed by the aluminum absorber (System A), and the galvanized steel absorber (System B). The average maximum ambient temperature recorded was 33.7°C. The average outlet water temperatures were significantly higher than the ambient temperature around 12.05 and 12.50 hours for Systems A, B, and C, respectively, due to proper insulation of the systems. Due to changes in solar radiation, the outlet temperature decreased from 14.20 hours until 17.05 hours for all three cases. The variation of the outlet temperature with time was higher than the inlet temperature with time. Consequently, System A had an average water outlet temperature of 61.2 °C, System B had 57.3°C and System C had 63.51°C. This result corresponds to research conducted by Duraivel and coworkers, who emphasized the outlet temperature rises directly with radiation as noon approaches and the systems had maximum outlet water temperatures of 54.4 °C and 74.6 °C, respectively [33]. The results show that the copper absorber material had the highest temperature difference between water inlet and outlet, indicating the highest heat transfer and minimal heat loss due to proper insulation. The aluminum material was the second, and the galvanized material was the third. These findings are consistent with previous research, and the slight differences can be attributed to differences in location, solar intensity, and collector surface area. Overall, the designed solar water heating systems (Systems A and B) are effective in providing hot water with outlet temperatures significantly higher than the required 50 °C for domestic use.

3.2.3. Temperature distribution on solar absorber plate

From the inlet side to the outlet side, the collector working fluid temperature increases as the heating of the fluid gets heated up. This is because as the sun strikes the solar collector, the plate absorbs a large portion of the incoming energy and transfers it to the circulating fluid going through internal passageways or rise tubes [48]. The water temperature increases as it moves from the inlet to the outlet through the tube.

Table 1 illustrates the temperature distribution on the solar absorber plate for the three systems. It was observed that the mean absorber plate temperature was lowest at the inlet and highest at the outlet. For instance, the average temperature for the absorber at T_{p1} was lowest for System B (51.3°C), followed by System A (62.5°C), and System C (67.0°C), while the average temperature for the absorber at T_{p2} was

lowest for System B (52.9°C), followed by System A (65.0°C), and System C (69.4°C). This shows that the temperature of the absorber plates increases gradually from the bottom to the top of the collector. The high registered temperature is because absorber plates for aluminum and copper absorber plates absorb heat energy faster than galvanized absorber plates. This is due to their higher thermal conductivity and high absorptivity values as compared to galvanized. Furthermore, the insulation placed at the side and base of the collector's prevented loss of heat while the radiation emitted by the absorber plate of the collectors was not able to escape through the tempered glass used, thus increasing the absorber plate temperatures.

Table 1. Summary of different absorbers.

Item no	Absorber Plate	T_{p1} (°C)	T_{p2} (°C)
1	Collector A	62.5	65
2	Collector B	51.3	52.9
3	Collector C	67	69.4

It is also worth noting that low average plate temperatures were recorded at 9.05 hours as 48.1, 46.5, 50.8°C for Systems A, B and C respectively and the average maximum values were attained at 13.30 hours when system A, B and C recorded 84.1 °C, 77.1 °C and 84.8 °C, respectively. The copper plate experienced the highest temperature due to its high conductivity rate and efficient heat exchange from the absorber plate to the water inside the riser tube [48]. The measured absorber temperature profile near the riser tubes, both at the bottom and at top headers, closely matched the theoretical models [50].

3.2.4. Comparison between solar absorber plate and outlet water temperature

Fig. 11 depicts the fluctuation of collector water temperature for the three solar water-heating systems. It is noted in Fig. 11, that the maximum outlet water temperature of 81.2 °C was attained at 13.05 hours for the aluminium absorber plate (System A), galvanised plate reached a maximum of outlet temperature of 77.4 °C at 12.50 hours while the maximum outlet temperature for a copper plate was highest at 88.6 from 12.35 hours because it has the highest thermal conductivity rate as compared to aluminium and galvanised steel. Maximum values were realised during this period because solar radiation is high. There was a steady variation of temperature for all the systems during the morning time from 10.35 to 11.35 hours. The average outlet temperature from the copper absorber plate is higher than the absorber plate for Systems A and B. The highest outlet water temperature of the copper absorber plate is 71° C when compared with the aluminium absorber plate and galvanised steel, which had 66.8 °C and 64.1 °C respectively.

From Fig. 11, it can be revealed that during the study the temperature variation directly affected the variation of the water outlets [50]. For instance, the increased solar radiation absorbed by the plate results in elevated water outlet temperature. Conversely, diminishing solar radiation intensity and dissipation of heat from solar collector to the surroundings results in the decrease of water temperature.

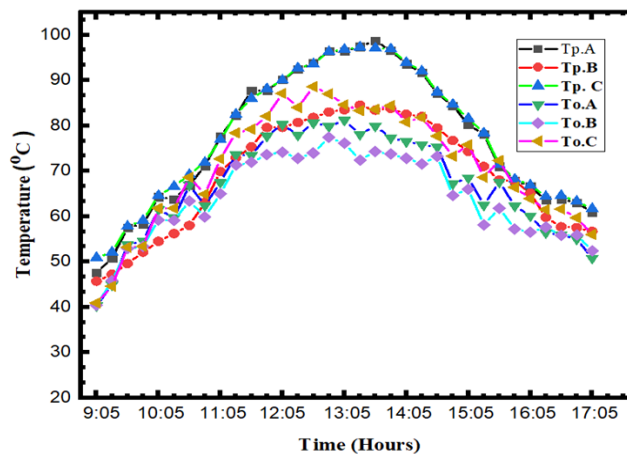


Figure 11. Variation of temperatures in absorber plate and hot water storage tank.

3.3. Thermal Performance of the Solar Water Heaters

Fig. 12 shows the variation in collector efficiency for the three Systems A, B, and C. It is noticed that the efficiency was low during the first hours of each day because of low solar radiation and then begins to increase by the time of the day when the incident solar ray gets more direct and above the collector.

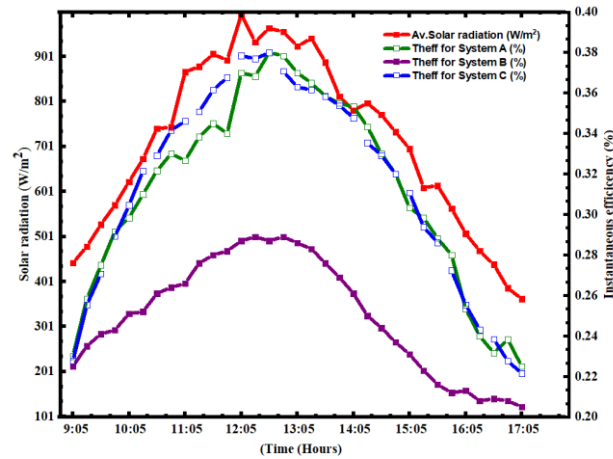


Figure 12. Comparison of average collector instantaneous efficiency with local time for the different experimental collectors for clear sky condition during continuous flow operation.

The pinnacle mean collector proficiency was noticed between 12:05 hours and 13:35 hours due to the highest level of solar radiation at that moment, leading to enhanced heat absorption by the collector. The results show that the imported Chinese water heating system FPC demonstrated the highest thermal efficiency, coming in at 34.7%. The locally made aluminum FPC water heating system showed a thermal efficiency of 32.8%, whereas the galvanized FPC system demonstrated the least thermal efficiency of 28.9%. The results are consistent with the findings of Duraivel et. al., [33]. They also found that the galvanised-based FPC water heating system showed a rapid return on investment and notable heat efficiency when compared to the other systems examined. In conclusion, it can be determined that Systems A and C outperformed System B, a solar collector made of galvanized steel.

3.3.1. Flat plate collector efficiency and characterisation

Fig. 13 illustrates the temperature trends of the solar thermal systems recorded during the outdoor trial on sunny days of the experiment. The significant decrease in thermal efficiency with the increase in inlet water temperature is due to the losses associated with the rise in temperature difference between the water in the riser pipes and the surrounding temperature ($T_i - T_a$). From the generated equation of the lines of best fit, the gradients of the efficiency curves were $5.62 \text{ W/m}^2 \text{ } ^\circ\text{C}$ for the aluminum collector (System A), $10.21 \text{ W/m}^2 \text{ } ^\circ\text{C}$ for galvanized steel collector (System B), and $6.06 \text{ W/m}^2 \text{ } ^\circ\text{C}$ for the convectional copper collector (System C). The slope of the efficiency curve is equal to the collector heat removal - loss efficient product (FRUL) and the intercept of the line on the efficiency axis is the heat removal factor-transmittance absorbance product $FR(\tau\alpha)$ (Table 2). The collector's efficiency in this study is zero at a temperature difference of 0.022 and 0.011 for Systems A and B, respectively.

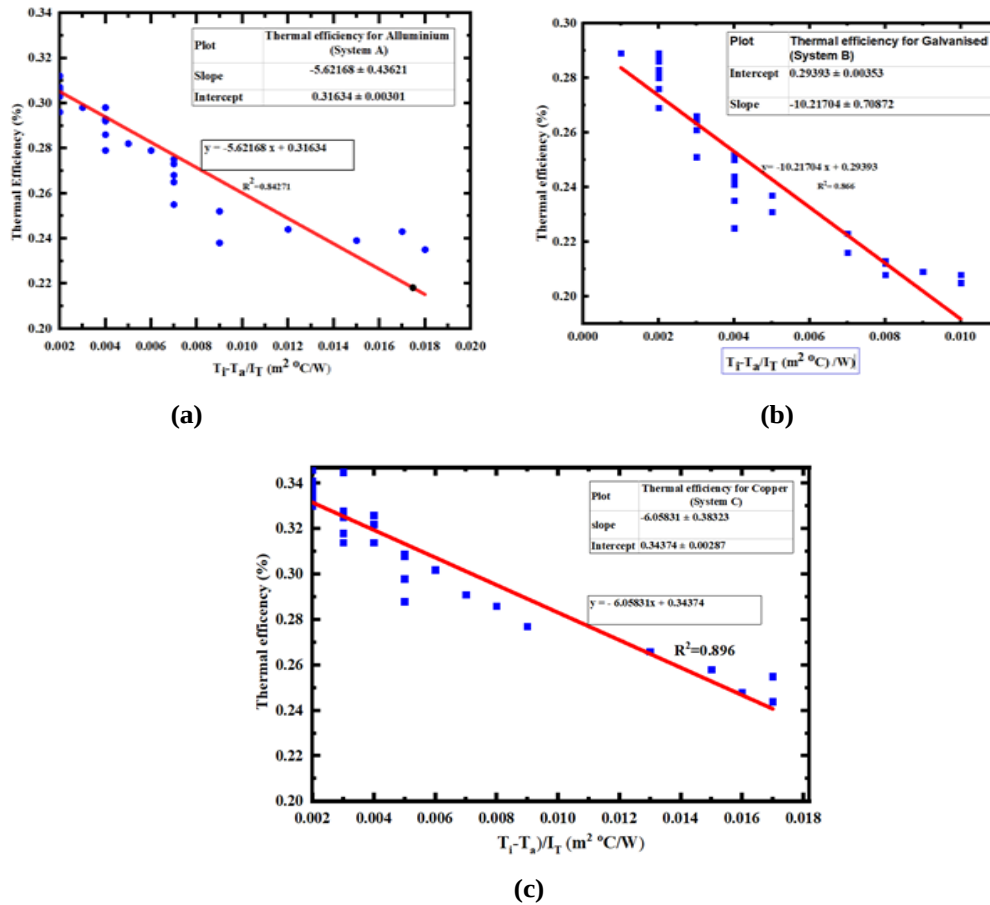


Figure 13. Thermal efficiency curve for the three collectors.

Table 2. Collector characteristic parameter

Item No.	System	$F_R(\tau\alpha)$	$T\alpha$	F_R	U_L
1	A	5.62	0.819	0.387057	15.19155
2	B	10.21	0.819	0.2442	41.37998
3	C	6.058	0.819	0.413431	14.66218

These findings align with numerous studies in the literature, such as the research results of Agyekum, et. al., [25].

3.4. Economic Evaluation of the Solar Water Heating Systems

A comprehensive lifecycle cost analysis was conducted on the designed flat-plate collector systems. The capital and installation expenses for the systems are summarized in Table 3 and Fig. 14, with System A costing Ksh. 54,160.0, System B costing Ksh. 45,996.80, and System C costing Ksh. 68,664.0.

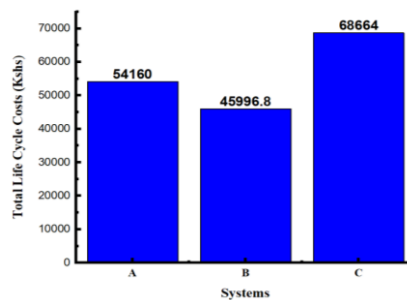


Figure 14. Comparison of systems of life cycle cost.

Research indicates that domestic solar water heaters with capacities ranging from 100 to 300 litres in Kenya cost between Ksh 70,000 and Ksh 300,000 (EED, 2017). In contrast, the prototype solar water systems developed in this project have lower life-cycle costs: system A (Ksh. 54,160), system B (Ksh. 45,996.80), and system C (Ksh. 68,664), as shown in Table 3 and Fig. 14. The life-cycle cost analysis revealed that the galvanized sheet-based flat plate collector (FPC) water heating system had the lowest life-cycle cost, despite having marginally lower thermal efficiency than the copper and aluminium-based FPC systems. This can be attributed to the galvanized system's reduced initial cost, leading to a lower total cost over its lifespan, as well as its local availability. Notably, the costs of the designed systems are below the \$800 to \$10,000 price range documented in the literature [26], aligning with the findings of Benli [51]. In a country like Kenya, where cost is a significant factor, galvanized sheet-based FPC solar water heating systems may represent a more practical and cost-effective option compared to aluminium-based FPC systems.

Table 3. Comparison of systems of Life cycle cost

Item No.	Experimental set up	System A (KES)	System B (KES)	System C (KES)
1	Three Storage tanks	20000.00	20000.00	20000.00
2	PVC piping	1500.00	1500.00	1500.00
3	Three Valves	1700.00	1700.00	1700.00
4	Mild steel Collector housing (2 m ²)	1750.00	8000.00	8000.00
5	4mm Low iron glass (2 m ²)	3500.00	3500.00	3500.00
6	25mm galvanized pipe riser	-	1500.00	-
7	25mm aluminium pipe riser	2500.00	-	-
8	Copper heat exchanger (Absorber and sheet)	-	-	4500 plus 3800
9	Galvanized steel sheet for the absorber plate	-	2000.00	-
10	aluminum sheet for the absorber plate	3400.00	-	-
11	Fibre glass piece	500.00	500.00	500.00
12	Styrofoam 1inch	250.00	250.00	250.00
13.	Aluminium Foil		300.00	
14	Installation accessories (10% of the total capital)	3910.00	3490.00	4345.00
Total capital cost		43000.00	38390.00	43450.00
Other cost Operation and maintenance cost (2% of capital)		860.00	767.80	869.00
Replacement cost (10% of capital cost)		4300.00	3839.00	4645.00
Total life Cycle Cost (LCC)		54160.00	45996.80	68664.80

3.4.1. Cost and payback period

The payback period calculated in economic analysis estimates when an energy investment will pay off. Payback period calculation is influenced by several critical factors, including the technology employed, the materials used for the solar collectors, and the hot water consumption patterns of the user. Comparing the SWH to electricity yields annual net savings.

Prototypes of solar water heaters were developed using locally sourced commercial materials, and their costs were evaluated against those of electric water heating systems. Table 3 shows capital cost estimation for the three systems. Each system is designed with a 100-liter tank capacity and a collector area of 2 m², which is adequate for a household of five. According to the Kenya Power and Lighting Company, the prevailing electricity tariff in Kenya is Ksh. 15.8 per kWh (KPLC, 2023). The payback periods for these solar water heater systems were derived from Eq. 12, and the findings are detailed in Table 4.

Table 4. Payback period values

Item no	Specification	System A	System B	System C
1	Quantity of water needed per day (kJ)	18732.00	10458.00	12.810
2	Quantity of water needed per day (kWh)	5203.00	2905.00	358.00
3	Annual savings cost (Kshs)	24215.01	13519.14	16559.60
4	LCC (Kshs)	54160.00	45996.80	68664.00
5	Payback period (years)	2.00	3.00	3.20

Table 4 outlines the payback periods for the flat plate collectors, showing that System A has a payback period of 2 years, System B has a payback period of 3 years, and System C has a payback period of 3.2 years. The analysis reveals that Collector C, made from the more expensive copper material, has the highest cost and the longest payback period. In contrast, the collector with the shortest payback period is constructed from galvanized steel, which was installed at a lower cost compared to aluminium and copper. Consequently, higher life cycle costs are associated with extended payback periods. Aluminium had the shortest payback period and could be a better choice because the system pays for itself more quickly and continues to provide savings throughout its operating life. The results indicate that the payback periods for these systems align with the repayment timelines of 2.5 to 3.5 years reported in various literature source [2].

4. CONCLUSION AND RECOMMENDATIONS

This study examined the thermal efficiency of three domestically produced flat-plate solar water-heating systems in Nairobi, Kenya, using real-world weather conditions. The findings revealed that under optimal weather conditions, characterized by a clear sunny day with an average solar radiation of 711.9 W/m^2 and an ambient temperature of 29.8°C , the storage tank water temperature reached its highest at 74.1°C for Aluminum (System A), 69.4°C for galvanized steel (System B), and 78.7°C for copper (System C). The absorber temperature peaked at 84.1°C , 77.1°C and 84.8°C for Systems A, B and C, respectively.

The study unveiled intriguing discoveries. The aluminum-based FPC water heating system demonstrated a thermal efficiency of 32.8%, inferior to the copper-based FPC water heating system, which achieved an efficiency of 34%. Conversely, the galvanized FPC system exhibited the lowest thermal efficiency, measuring at 28.9%. However, this still represented a noteworthy enhancement compared to conventional water heating techniques. Although the galvanized steel solar water heater has a low thermal efficiency, it was 20% less expensive than systems made of copper and aluminum. Finally, authors concluded that the FPC system based on copper-exhibited superior performance compared to both aluminum and galvanized systems.

The findings indicate that locally manufactured galvanized FPC water heating systems in Kenya possess significant capacity to provide domestic hot water over 50°C . Therefore, the adoption of domestically manufactured galvanized FPC systems should be encouraged for widespread utilization in heating residential water. This initiative would contribute to the establishment of new businesses and help mitigate the degradation of the environment in Kenya. The authors of this study propose an increase in the thickness of the backside insulation to 80 mm (fibre wool) instead of the current 50 mm. This adjustment will enhance the system's performance by effectively reducing heat losses.

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