Universal Research Reports
ISSN: 2348-5612 | Vol. 12 | Issue 3 | Jul - Sep 25 | Peer Reviewed & Refereed

Design and Testing of a Low-Cost Solar Water Heater Using Recycled Materials

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DOI: http://doi.org/10.36676/urr.v12.i3.1568
Accepted: 13/07/2025 Published: 20/07/2025 * Corresponding author

1. Introduction

Solar energy is an abundant, renewable, and environmentally benign source of electricity that has been used for a variety of purposes throughout human history. Among its various applications, solar water heating is one of the most practical and cost-effective ways to transform solar radiation into usable thermal energy. Solar water heaters (SWHs) absorb sunlight and turn it into heat for a variety of home, industrial, and agricultural purposes, including bathing, washing, cleaning, and space heating. Solar water heaters, as opposed to traditional water heaters that use electricity or fossil fuels, save energy, reduce reliance on non-renewable resources, and reduce environmental pollution.

The essential idea of solar water heating is the conversion of solar energy into thermal energy via collectors. These collectors capture solar energy and convert it to a fluid, often water or a heat transfer medium, which circulates through pipes or tubes. The hot fluid is kept in an insulated tank for subsequent use. Depending on the design, climatic conditions, and economic variables, SWHs can be passive or active. Passive systems rely on natural convection and do not require pumps or controllers, whereas active systems employ pumps and controls to circulate fluids and regulate temperatures.

Despite the scientific maturity of solar water heating, various challenges prevent widespread adoption, particularly in rural and low-income regions. High initial costs, difficult installation processes, and a lack of knowledge are major deterrents. In this context, creating a low-cost solar water heater out of recycled materials is a sustainable solution that adheres to circular economy principles, encourages waste reduction, and provides clean energy to underserved populations.

The concept of using solar energy for water heating extends back to ancient cultures. The Greeks and Romans were known to build their bathhouses to optimize sunshine exposure, and early attempts with solar heating were documented in the 18th and 19th centuries. Clarence Kemp received the first known patent for a solar water heater in 1891 in the United States. His contraption, known as the "Climax," combined a water tank with a collection box and was most popular in California because to its sunny environment. Solar water heaters were popular in high-solar-insolation areas in the early twentieth century. However, the introduction of inexpensive electricity and fossil fuels in the mid-twentieth century caused a fall in their use. Only during the 1970s oil crisis did solar energy, particularly solar water heating, gain traction as governments began to look for other energy sources.

Solar water heater materials, design, and efficiency have improved significantly over the last several decades. Modern systems include flat-plate collectors, evacuated tube collectors, selective surface coatings, and computerized controls to improve performance. Government subsidies and international development initiatives have contributed to the increased use of solar thermal systems in developing countries such as India, China, and Kenya. Nonetheless, many commercially marketed SWHs are out of reach for economically disadvantaged groups because to their high cost and maintenance needs. There is a growing corpus of work on the design, modeling, simulation, and performance evaluation of solar water heating systems. The majority of academic research and commercial advances focus on increasing thermal efficiency, lowering heat loss, and enhancing collector design with new materials

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and technology. Researchers investigated numerous collector types, including flat-plate, evacuated tubes, and parabolic troughs, and assessed their performance under a variety of climatic and geographical situations.

While technical progress in high-end systems continues, less emphasis has been placed on the creation of ultra-low-cost systems that may be locally manufactured from waste or repurposed materials. Existing studies are frequently limited in scope, region-specific, or do not include empirical testing and validation. For example, while some researchers have proved the viability of employing materials such as plastic bottles, aluminum cans, and discarded glass panels in solar heater prototypes, thorough design techniques and long-term performance assessments are limited. Furthermore, few research seeks to strike a balance between price, sustainability, and usefulness. The convergence of solar thermal technology with sustainability principles, particularly the utilization of recycled or upcycled materials, is an area that has received little attention. There is a significant gap in reproducible designs that local communities or vocational students may implement using locally accessible materials and with no technical expertise.

Another important gap exists in thermal performance testing and real-world validation of these low-cost devices under a variety of climatic circumstances. Most experimental setups are limited to controlled laboratory surroundings, making it impossible to judge their true value in home or field settings. Scaling and policy endorsement of such systems become difficult in the absence of reliable performance data.

Figure: PET Solar Heating System (Source: https://criticalconcrete.com/pet-solar-heating-system/)

The study's logic is based on two goals: environmental sustainability and socioeconomic inclusiveness. With growing worries about climate change, the depletion of non-renewable resources, and rising energy needs, particularly in developing countries, there is an urgent need to shift to clean and inexpensive energy alternatives. Solar water heaters are a well-established and mature technology, but their price and accessibility remain significant barriers to widespread rural adoption. This work intends to provide a practical answer to environmental and social concerns by creating and testing a low-cost solar water heater made from recycled materials. The reuse of wasted materials decreases waste and environmental deterioration while also lowering production costs. This enables the creation of a scalable, do-it-yourself (DIY) model that schools, non-governmental organizations (NGOs), and self-help groups may readily copy.

In rural and peri-urban settings, where energy supply is frequently unpredictable and biomass-based water heating adds to indoor air pollution and deforestation, a solar-powered solution can considerably enhance quality of life. Women and children, who are largely responsible for household duties in many civilizations, will benefit immensely from having access to warm water without the need for firewood or kerosene. Furthermore, vocational training programs may incorporate the creation of such systems

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into their curriculum, encouraging young people to improve their skills and be environmentally responsible.

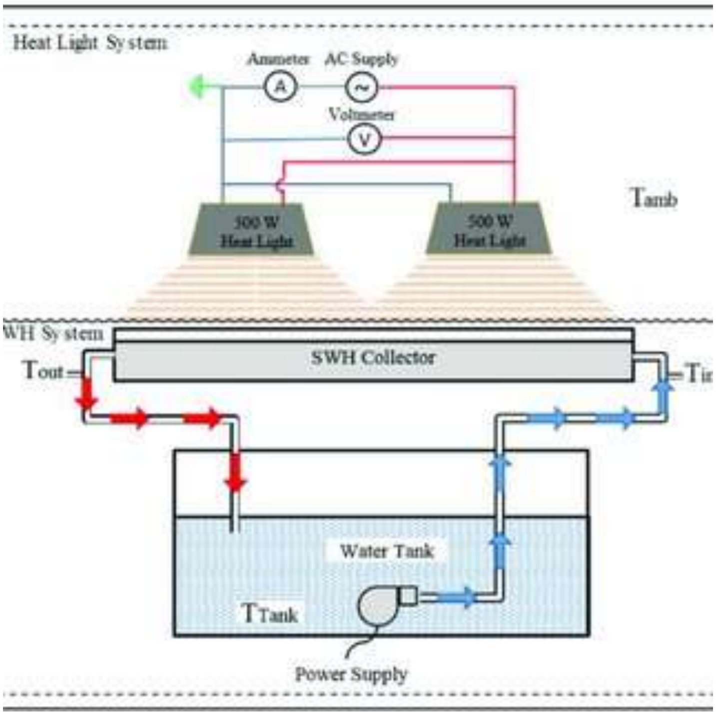
The utilization of recycled materials improves the study's sustainability quotient. Used PET bottles, aluminum cans, discarded window glass, rusty steel drums, and PVC pipes are not only prevalent in urban waste streams, but also have excellent physical qualities that make them ideal for solar thermal applications. By recycling these things, the study helps to foster a circular economy and innovative material reuse. Furthermore, the study's experimental testing component will assess important performance indicators such water heating capacity, temperature retention, cost-effectiveness, and material durability. This will provide significant insights about the system's practicality and scalability in a variety of scenarios.

The study also has an educational component. It can assist promote awareness of renewable energy technology, environmental conservation, and do-it-yourself engineering solutions. The initiative can enable local communities to embrace and adapt technology to their own requirements by providing thorough documentation and open-access distribution of the design. This study is consistent with the worldwide Sustainable Development Goals (SDGs), including SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action). The research helps to promote energy fairness and environmental conservation by closing the gap between modern solar technology and grassroots applications.

2. Objectives

- To design and develop a functional, low-cost solar water heater using readily available recycled materials.
- To evaluate the thermal performance and efficiency of the fabricated system under real-world environmental conditions.
- To assess the economic feasibility and environmental benefits of using recycled components in solar water heating applications.

3. Designing a Low-Cost Solar Water Heater Using Recycled Materials



In the search for sustainable energy solutions, designing and developing low-cost solar water heaters using recycled materials is a potential option for meeting home hot water demands in low-income and off-grid areas.

3.1. Conceptual Framework and Design Methodology

Understanding the essential components and operating principles of a simple solar thermal system is the first step toward designing a low-cost solar water heater. A conventional solar water heater comprises of a solar collector, a fluid circulation mechanism, a storage tank, and thermal insulation. For this study, the method entails using recycled materials for each of these components in order to cut costs while preserving functional

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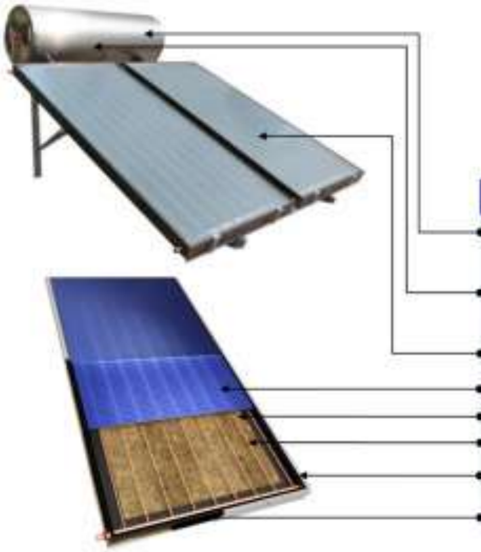
performance. Polyethylene terephthalate (PET) bottles, aluminum cans, discarded windowpanes, and old PVC pipes are utilized to build the system. The collector is designed to optimize solar radiation absorption by painting dark-colored metal cans black to increase heat absorption, while translucent PET or glass sheets serve as coverings to trap heat via the greenhouse effect.

Figure: Schematic Diagram for Thermal Performance Test Rig. (Source: Din and Azlan, 2018)

Water movement inside the system is based on thermosiphon principles, which eliminates the need for electric pumps and controllers. As the water in the collector heats up, it gets lighter and rises into the storage tank, while cooler water falls to replace it, guaranteeing continuous circulation. The hot water is stored in a tank made of reused steel drums or insulated plastic containers. To optimize sun exposure, put the collector at an appropriate tilt angle (usually equal to the location's latitude) and face it towards the equator. Insulating materials, such as discarded Styrofoam or mineral wool, are utilized to reduce heat loss from both the collector and the storage tank.

3.2. Material Selection and Fabrication Process

The selection of materials is critical to the project's sustainability and cost objectives. Recycled materials not only save production costs, but also help to protect the environment by minimizing landfill trash. Aluminum beverage cans, for example, are good thermal conductors and commonly accessible. When sprayed with non-reflective black paint, they effectively absorb solar energy. Cut, flatten, and combine these cans to form an absorber plate or a series of vertical tubes through which water can flow. Transparent covers, which are critical for capturing solar energy, are produced from discarded glass panels or PET sheets acquired from old packaging materials, providing heat insulation while allowing sunlight to enter the collector.



Part	Material	Recycle	CE design aspects
Storage tank	Stainless steel	Yes	Use recycled materials.
Heat exchanger	Copper or Steel	Yes	Important part of the environmental impacts are associated to copper. Potential replacement with steel.
Glazing	Glass	Yes	Use of Transparent Insulating Materials.
Absorber plate	Aluminium	Yes	Use recycled materials.
Insulation	Poly-Urethane or Rockwool	Yes	Use thinner layers and recycled materials.
Tubes	Copper	Yes	Replace copper with steel.
Collector frame	Aluminium profiles for the sides	Yes	Increase the recycled aluminium percentage
Casing	Galvanized steel sheet for the bock	Yes	Use thinner layers and recycled materials.

Figure: Recycled Material and Fabrication (Source: Milousi and Souliotis, 2023)

The solar collector's frame and housing are made of repurposed wood, scrap metal, or plastic, which ensures structural stability. PVC pipes reclaimed from construction debris use as water circulation channels. The insulating layer, which is essential for reducing heat loss, is made from recycled materials such as discarded foam packaging or shredded thermocol. To achieve maximum solar gain, the complete system is installed on a metal or wooden pedestal at an optimum angle. The manufacturing technique stresses simplicity, enabling for local duplication using simple equipment and no technical knowledge. Each component is modularly constructed, allowing for easy repair or replacement and increasing the system's operating life.

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3.3. Functional Evaluation and Performance Considerations

Functional testing follows prototype building to examine critical performance indicators such as thermal efficiency, temperature increase, heat retention, and durability under varied climatic conditions. During the day, the system's heating capability is evaluated by measuring the water temperature at the intake and outflow, the ambient temperature, and the amount of solar radiation. On clear sunny days, the prototype can boost water temperature by 25-35°C over ambient, which is suitable for most domestic applications like bathing and washing. The thermosiphon mechanism successfully enables passive water circulation without the requirement for external energy input, demonstrating the system's potential for off-grid application.

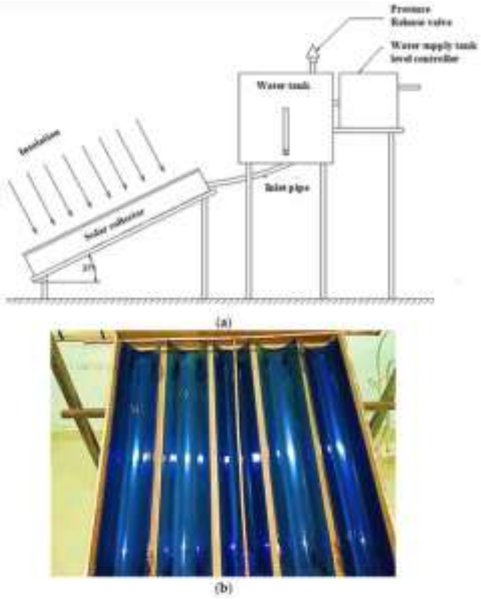

Figure: (a) The layout of a solar water heating system using aluminium cans (Source: Barik et al 2022)

Long-term performance is further assessed by measuring heat retention in the evenings and on overcast days, when thermal insulation quality is crucial. The insulated storage tank keeps water temperatures above freezing for several hours after dark, allowing for use in the early morning hours. Additional factors include material durability under prolonged sun exposure, leak resistance, and simplicity of maintenance. While the system may not be as efficient as commercial SWHs with sophisticated coatings or evacuated tube collectors, it is a more cost-effective and ecologically responsible option. The prototype's unit cost is less than ₹1000, making it affordable for rural and low-income urban populations alike.

The design and construction of a functioning, low-cost solar water heater using easily accessible recycled materials exemplifies the ideas of sustainable engineering, grassroots creativity, and circular economy. The idea, which uses thermosiphon principles and reused objects, fills a critical gap in clean energy availability for underserved regions. While there is room for performance improvement, the system shows promise in terms of thermal efficiency, usability, and environmental effect. Future research should focus on improving insulation techniques, including hybrid heating modes for winter usage, and creating standardized DIY kits to promote wider distribution and community acceptance.

4. Performance and Efficiency of a Low-Cost Solar Water Heater Fabricated from Recycled Materials

Assessing the real-world thermal performance and efficiency of a recycled solar water heating system is crucial for determining its feasibility, economic viability, and environmental advantages.

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4.1. Parameters and Methodology for Thermal Performance Testing

Thermal performance evaluation necessitates the careful monitoring of certain factors that impact the heating capacity and overall efficiency of the system. The essential factors evaluated are intake and exit water temperatures, ambient temperature, sun irradiation, heat gain, thermal losses, and system efficiency. Data is taken at several times of day to capture changes caused by sun intensity and weather disturbances. Temperature sensors are installed at important areas, such as the collector, intake pipe, output pipe, and storage tank, to obtain precise readings. Solar radiation is measured with a pyranometer or approximated using meteorological data from the test site. The experiment design replicates residential use circumstances by providing passive water circulation and continuous sunshine exposure.

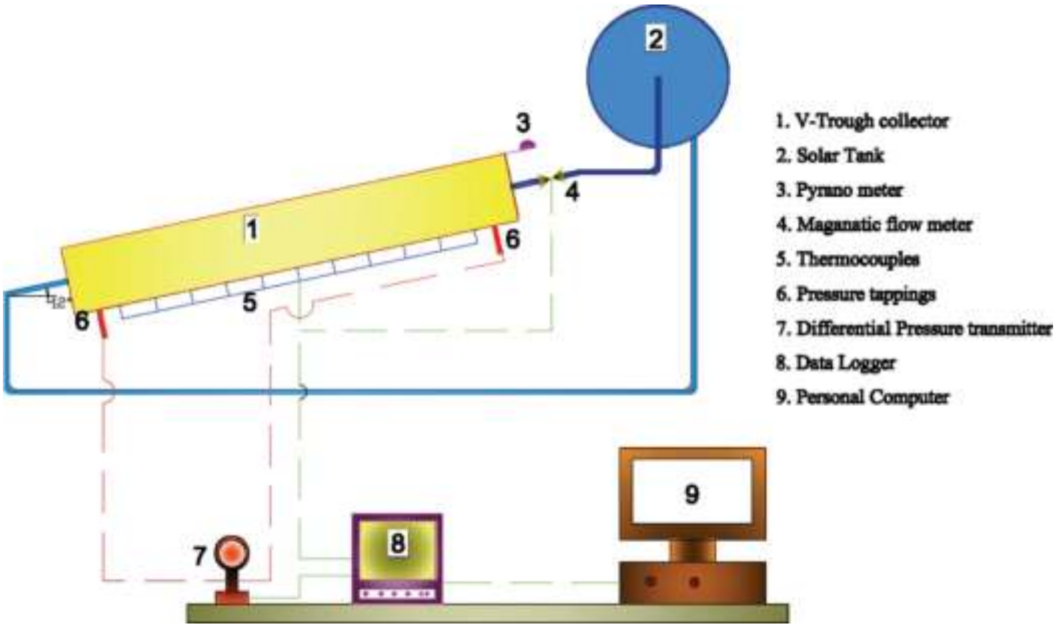

Figure: Thermal performance prediction of a V-trough solar water heater with a modified twisted tape (Source: Saravanan et al 2024)

Efficiency is determined as the usable thermal energy obtained by the water divided by the total solar energy incident on the collector surface. A basic energy balance equation is used, in which usable heat gain is calculated by multiplying the temperature difference between the entrance and outflow by the water mass and specific heat capacity. Divide this gain by the solar input and adjust for collector area and time to get the efficiency percentage. Tests are carried out in clear, partly cloudy, and overcast situations to evaluate system response to environmental variability. This method guarantees a thorough examination of the heater's ability to produce consistent performance in real-world environments, providing crucial insights into its dependability and robustness for home usage.

4.2. Observations and Results under Real-World Conditions

Thermal performance statistics obtained over many days show that the system can raise water temperatures by 25-35°C over ambient temperature on clear, bright days. During peak sun exposure (usually between 11:00 AM and 2:00 PM), the output temperature ranged between 55°C and 62°C, which is enough for most home hot water requirements. The inflow water, which was typically at room temperature in the morning, was progressively heated by passive circulation in the collector. The water in the storage tank remained useable far into the evening owing to recycled foam insulation and multiple coatings. Even on partially overcast days, the system maintained a temperature rise of 18-25°C, demonstrating operational durability.

Thermal efficiency varied between 35% and 52%, depending on sunshine availability and ambient temperature. These results, while small when compared to high-end commercial evacuated tube

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systems, are surprisingly effective given the low cost and recyclable nature of the materials utilized. Overcast days resulted in much lower performance, with output temperatures increasing just 10-15°C above ambient. Heat loss was greater during strong wind conditions or after dark, emphasizing the significance of insulation around the storage unit. Nonetheless, total efficiency remained within acceptable limits for home utility in temperate to tropical climates, particularly in areas where electricity or LPG-based water heating is unavailable or prohibitively expensive.

4.3. Implications and Scope for Optimization

The findings demonstrate that low-cost solar water heaters made from recyclable materials may operate efficiently in real-world situations, providing a cheap alternative to traditional systems. The system's capacity to provide hot water with a moderate temperature rise and retention throughout the day meets the demands of homes in off-grid or low-income communities. The thermosiphon-driven circulation is reliable even without mechanical help, decreasing the requirement for external power and maintenance. Furthermore, the effective reuse of waste materials such as aluminum cans, PET sheets, and foam insulation promotes the ideals of sustainable design and circular economy. These findings support the practicality of decentralized solar heating solutions developed at the community level.

Minor design changes, however, might improve the system's performance even further. Thermal efficiency may be increased by increasing absorber surface area, improving sealing mechanisms, and adopting sophisticated recyclable materials like double-glazed window panels or selective surface coatings. Integrating low-cost thermal storage materials, such as phase transition compounds, may increase heat retention overnight. Long-term UV radiation and moisture exposure can have an impact on material durability, necessitating regular inspections or material treatment enhancements. While the existing system meets basic family water heating needs, future iterations may focus on higher efficiency-to-cost ratios and more climate flexibility, enabling widespread community acceptance and legislative backing.

In short, the thermal assessment of the constructed solar water heating system yields promising findings in terms of efficiency, functionality, and sustainability. The capacity to regularly supply warm water using freely accessible sunshine and reused materials demonstrates the promise of such systems in energy-constrained areas. The efficiency attained under real-world situations supports the viability of scaling these models for community-level use, instructional displays, or grassroots energy projects. By documenting and confirming performance using empirical analysis, this study helps to bridge the gap between sustainable innovation and practical, on-the-ground energy solutions.

5. Assessment of Economic Feasibility and Environmental Benefits

Evaluating the economic and environmental implications of using recycled materials into solar water heating systems is critical for promoting sustainable, low-cost energy solutions that are affordable to marginalized areas.

5.1. Cost Structure and Economic Viability

The economic viability of a SWH built using recycled materials is essentially established by comparing its overall construction and operating costs to those of commercially available systems. Traditional SWHs frequently incur manufacturing, specialty component, and shipping costs, which raise their market price, making them unaffordable for many rural and low-income consumers. In contrast, a system constructed from recycled materials such as aluminum cans, PET sheets, old glass panes, PVC pipes, and foam insulation greatly minimizes capital expenditure. Domestic prototypes often cost less than ₹1000 and include basic tools, paint, connections, and storage units, making them ideal for resource-constrained organizations.

In addition to cheap initial expenditures, the system features little operating and maintenance costs. The design is based on passive thermosiphon principles, thus there is no need for power or mechanical

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pumps, and there is less wear and tear. Minor replacements or cleaning are examples of routine maintenance that may be performed without the need for professional competence. Over an anticipated lifespan of 5 to 7 years, the overall cost per liter of heated water is significantly cheaper than electric or gas-powered systems. Return on investment (ROI) is quick, especially in places with strong solar insolation and limited availability to conventional electricity. Furthermore, the system's low-cost DIY character fosters local enterprise growth by allowing micro-entrepreneurs or community organizations to produce and sell units, resulting in decentralized economic opportunities.

5.2. Environmental Impact and Sustainability Advantages

The environmental benefits of employing recycled materials in solar thermal systems go beyond energy savings and include broader ecological protection. The technique diverts trash from landfills, reduces the demand for virgin raw materials, and lowers greenhouse gas (GHG) emissions associated with traditional industrial processes. Aluminum cans, for example, are one of the most energy-intensive commodities to manufacture from raw bauxite, but recycling them as thermal absorbers in a solar collector avoids the need for melting and reshaping, saving energy and reducing carbon emissions. Similarly, PET plastic, which is frequently a problem in water bodies and urban environments, finds a new life as transparent heater covers, minimizing plastic pollution and furthering a circular economy.

Furthermore, the usage of such solar systems directly replaces fossil fuel consumption for water heating. Many regions of rural India and Sub-Saharan Africa continue to heat water using firewood, kerosene, or liquefied petroleum gas (LPG), all of which contribute to deforestation, indoor air pollution, and GHG emissions. Transitioning to solar-powered heating systems, particularly those that employ recycled materials, increases environmental benefits by addressing both energy source and material lifetime implications. Using a simple SWH instead of firewood or LPG can reduce CO_2 emissions by 0.5-1.5 tons per year. When such systems are implemented throughout communities, the cumulative environmental benefit is significant, supporting national and global sustainability goals.

5.3. Social Acceptance and Policy Integration Potential

The effective implementation of any ecologically and economically advantageous technology is also dependent on community acceptance and incorporation into larger regulatory frameworks. One significant benefit of recycled-material-based SWHs is their compatibility with local knowledge networks and resource availability. Because the materials are frequently acquired locally, communities are more likely to use, understand, and maintain the technology. This instils a sense of ownership and enhances the chance of continued use. The system's simplicity also enables local craftsmen, vocational trainees, and self-help organizations to participate in manufacturing, therefore sharing technical knowledge and promoting green skill development.

Integrating these devices into rural energy or waste management plans might have a double-edged policy advantage. Municipalities and development organizations, for example, can support such efforts as part of the Swachh Bharat or decentralized renewable energy programs. Local governments may help to promote livelihoods, decrease trash, and improve access to clean energy by formalizing the collection and repurposing of certain waste streams (e.g., aluminum, PET, glass) for solar applications. Additionally, attaching such low-tech systems to incentives, such as subsidies for solar units built from recyclable materials, might increase their acceptance. Incorporating these ideas into state-level sustainability policies may help improve compliance with national climate obligations under the Paris Agreement and the SDGs, notably those pertaining to clean energy (SDG 7), responsible consumption (SDG 12), and climate action (SDG 13).

Finally, evaluating the economic and environmental benefits of employing recycled materials in solar water heating systems demonstrates a compelling argument for encouraging their development and implementation. These systems provide a low-cost, energy-efficient, and environmentally friendly

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alternative to traditional water heaters, particularly in areas where pricing and availability remain significant difficulties. Their simplicity and versatility make them suitable for community-level deployment, and their capacity to cut carbon emissions and encourage garbage reuse aligns with national sustainability goals. With intentional policy integration and community engagement, such innovations can make a significant contribution to an equitable and green energy transition.

6. Conclusion

This work indicates that designing, fabricating, and testing a low-cost solar water heater out of recycled materials is not only feasible, but also extremely important in solving the combined concerns of energy poverty and environmental deterioration. By combining thermosiphon principles with locally accessible waste materials such as aluminum cans, PET sheets, discarded glass, and PVC pipes, the system successfully delivers warm water with moderate temperature increases suitable for residential applications. Its cheap cost, simplicity, and self-sustaining operation make it ideal for use in rural and low-income urban areas where access to traditional energy solutions is restricted.

The empirical examination of thermal performance showed that the system keeps water temperatures 25-35°C above ambient on bright days, with an efficiency range of 35-52%. Furthermore, its low capital cost, inexpensive maintenance, and speedy return on investment when compared to commercial alternatives show its economic viability. The environmental advantages are as compelling: reducing reliance on fossil fuels, eliminating plastic and metal waste piling, and lowering greenhouse gas emissions. The initiative also supports skill development and grassroots creativity, enabling communities to take control of their energy requirements through local manufacture and maintenance.

Looking ahead, the future road entails increasing design efficiency through material optimization, improved insulation, and better thermal storage options, which may include phase change materials. Pilot-scale installations in various climatic locations would aid in determining adaptation and long-term performance. Integration with government initiatives aimed at renewable energy, rural livelihoods, and trash management can help to increase adoption. Furthermore, producing standardized fabrication guides, training modules, and awareness campaigns would be critical for widespread replication of this methodology. This approach allows this invention to go from a stand-alone solution to a community-driven, sustainable technology that makes a significant contribution to clean energy access, climate resilience, and circular economy practices.

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