Evaluating solar still grey water purification efficiency using a Fresnel lens embedded system

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Abstract
The world faces serious challenges regarding the accumulation of untreated greywater and the growing shortage of clean drinking water. Untreated greywater poses serious risks to the public while also causing damage to the environment. Traditional solar stills face limitations of low yields when treating water. This research focuses on the design and evaluation of an acrylic solar still, incorporating a third-order Fresnel lens to concentrate solar energy and enhance the evaporation rate. IoT-based monitoring systems using a DHT11 sensor and Arduino Nano enabled real-time assessment of temp and relative humidity, monitoring the system's performance. Domestic kitchen and handwashing greywater was processed, achieving a calculated concentration ratio of roughly 700x and focal irradiance of approximately 350,000 W/m². 1.5 L/h was achieved during testing, resulting in a calculated yield of 31.25 L/m²/day, more than five times the output of passive stills. The water produced was distilled to the point of being visually and odorlessly free of impurities. The developed system is easily scalable and affordable, providing an effective solution to greywater treatment for off-grid and low-resource communities.

Keywords: *Solarstill, Fresnel lens, grey water filtration, sensor integration.*

1. **Introduction**

The worldwide shortage of clean drinking water is one of the gravest issues facing contemporary society. The World Health Organisation reported that by 2022, over 2.2 billion people around 26% of the planet's population lacked reliable, safe drinking water. The World Bank anticipates that, should trends continue, 2.4 billion people living in urban centres could confront water shortages by 2050, underlining the deepening nature of the problem[1,2]. The consequences extend far beyond thirst: inadequate drinking water fuels the resurgence of waterborne diseases, jeopardises food production, stifles economic development, and can provoke civil unrest and population displacement, particularly in fragile areas where infrastructure and governance are already strained.

In many coastal and arid regions, seawater desalination remains a common response to drinking water shortages. Although these systems are technologically reliable, their high energy demands and capital costs limit their viability in low-income or rural areas[3]. At the same time, household-level practices are wasting a large part of the water footprint. Up to three-quarters of the total wastewater produced in typical dwellings comes from grey water, which includes flows from baths, sinks, and washing machines[4]. Although it represents a sizeable share of the total, grey water is frequently routed directly to drains without treatment, compounding the over-extraction of already scarce freshwater supplies. Research shows, however, that grey water can be safely treated and reused, mostly for irrigation, leading to a reduction of household freshwater demand that can exceed 17 gallons a day[5].

Various approaches to treating and reusing domestic greywater have been investigated. Membrane bioreactors are noted for their compact design and impressive purification rates, but their complexity, high maintenance burden, and substantial upfront costs typically restrict their appeal to larger, commercial-scale installations rather than the average home[6]. Alternatively, sand filters and low-tech biological systems ease accessibility and affordability but may struggle to achieve adequate removal of select chemicals and pathogens, resulting in effluent that sometimes falls short of stringent health standards[7]. Solar stills leverage solar energy for evaporation and condensation and thus demand minimal maintenance; however, traditional basin designs often produce less than 2 litres of distilled product per square meter of collector area each day and rarely achieve thermal efficiencies above 30%, limiting their practical contribution to household water balance[8].

More recent studies have been directed at improving the performance of solar stills by implementing concentrated solar techniques to address the issues of the slow water output. One way to intensify the efficiency of solar stills is the use of fresnel lenses. They can focus sunlight to a smaller area, greatly increasing the internal temperature and the rate of evaporation. Some studies have already confirmed that the use of Fresnel lenses on solar stills can enhance the output of distillate by 41.8% compared to the conventional designs[9]. Such systems can create several hotspots, thereby further enhancing evaporation and purification.

This research is aimed at designing and testing solar still systems made of transparent and durable acrylic, enhanced with a novel third order Fresnel lens for concentrated solar augmentation. Temperatures can be optimized with the embedded temperature sensors for better evaporation efficiency. The still is fed with grey water from household chores, where with the increasing concentrated solar energy the water temperature rises, vaporizing water and leaving behind dissolved and suspended impurities. The vapor is further purified and condensed on the cool walls of the stills to be collected for further use, targeted aimed.

The impact of this research is particularly relevant to people and the region’s water industry. It can help households alleviate domestic water use at the expense of the environment by 75% through effective treatment and reuse of grey water. This system is especially designed for off-the-grid or disaster-affected communities and is affordable and scalable. Communities lacking adequate resources have low-cost construction material and no grid electricity dependency. Moreover, this system can improve the health of communities and home gardeners, contribute to the food self-sufficiency of households, and enable enhanced urban and rural water resource resilience. Such systems also augment the other systems in place at a wastewater treatment facility. Advanced treatment is a step that will support the water infrastructure. The research concentrating on the renewable energy systems industry regarding the use of solar energy helps solve a critical concern, namely water supply scarcity in conjunction with the problem of neglecting the management of grey water.

2. **Literature Review**

Khalaf et al. [13] look into the ongoing problem of low yield of freshwater and high cost of water with small scale solar stills. They pulled together advances in material science, thermal management, as well as hybrids and active add-ons, and looked into what changes reliably increased still productivity as opposed to only functioning in lab conditions. A structured review of design cost integration across passive, active and hybrid stills was also part of the methods used. They underscored that most of the benefits revolve around the optical/thermal concentration, effective condensation heat removal, cost-efficient design, and most importantly an uncovered need for outdoor testing and detailed cost analysis for integrated concentrator stills.

Elminshawy et al [14] addressed the productivity problem in conventional basins with a designed floating solar still incorporating a Fresnel lens and a submerged condenser. They conducted an experiment with the modified unit and a conventional still to compare the performance. Their findings confirmed significantly increased water production and remarkable energy and exergy efficiency (as high as 79.38% and 26.94% respectively) attributed to concentrated heating and condensation. They considered the embedment of floating concentrators as a base and proposed focus on design/controls, validation, and alignment for the seasonal field as the gaps.

Almajali et al. [15] discussed the latest developments attempts aimed at breaking the productivity barrier of passive stills. They assessed the performance and cost of active and passive approaches (nanofluids, wicks, PCMs, concentrators, TEC/ PV-thermal assists). They concluded that single-knob tweaks and coupled thermal-optical strategies diverged markedly. The authors pointed out a gap in long-duration durability data (fouling, scaling, polymer aging) and in techno-eco comparisons that integrated O&M and cleaning for concentrator-aided systems.

To resolve limited heat absorption and slow evaporation, Günay, Gümüş, and Şahin [16) analyzed the effect of mono and hybrid nanofluids on still performance. Their review created an inventory of experimental and analytical studies and stated the range of improvement in daily productivity and thermal efficiency that could be achieved with appropriate design of the particle type, size, and concentration. The authors raised the safety and repeatability concerns and emphasized the need for standardized test protocols and lifecycle assessments prior to the implementation in fielded units.

Rashid et al. [17) reviewed technologies incorporating Fresnel lenses for solar energy applications such as desalination as a means to solve low-flux issues in passive stills. They reported several instances where Fresnel lenses increased distillate production and improved daily efficiency in comparison to non-concentrating stills vis-à-vis daily efficiency. They also noted sensitivity to alignment, optical losses, and maintenance as compelling issues. Affordable enabling tracking/cleaning mechanisms and durable outdoor validations remained unfilled. Wiener et al. [18] used textile-coated polyurethane rollers as wicks together with a cooled condensation plate to work on limited evaporation area. Their prototype had maximum instantaneous efficiency of approximately 62.16%, exergy of 7.67%, daily productivity of 1.14 L m-2, and a cost of 0.023 USD/L. The approach, however, did not focus on the incorporation of optical concentration and sensor based control to increase manage flux and control transient conditions.

With the use of cloud-connected sensors and IoT, cloud-connected sensors/actuators were incorporated into a hybrid-powered desalination testbed to resolve the issue of monitoring and control as described by Odeh et al. [19]. This group described the architecture, dashboards, and even the experiments performed which showcased temperature and pH logging. This demonstrated how the processes could be managed and how the testbed could be evaluated under different weather conditions. They demonstrated proof of concept for remote supervision but pointed out the gaps that still need to be filled, such as low power, field rugged, S&C communications for stand-alone stills and the need for IoT to be incorporated alongside optical tracking for concentrator systems. Focusing on the urban slum context, Yusof et al. [20] looked into the urban greywater reuse, focusing on double slope passive stills with low production cost per liter: analyzing the quality and the yield. Their experiments showed that greywater distillation could be achieved and CPL quantified optically. However, without optical concentration, the daily output was limited, and household-level reuse was constrained by throughput and scalability.

Hussein et al. [21] analyzed hybrid nanofluids within the context of solar-still energy systems, focusing on addressing limitations of weak solar absorption as well as poor thermal transport. For studies conducted between 2020 and 2024, they documented substantial productivity improvements resulting from the precisely designed hybrid nanofluids and outlined rules concerning their concentration, stability, and operational parameters. Gaps concerning long-term stability, environmental and health implications, and standardisation of methodology, particularly in cross-study comparisons, were highlighted.

In pursuit of higher throughput, Akeel et al. [22] added Fresnel lenses to a parabolic trough in order to increase the temperature of the basin. While reporting on productivity improvements in comparison to a conventional still in the domain of concentrated and preheated inputs in their AIP experimental paper, they did not address issues of alignment in relation to real-time tracking, cost, and enduring outdoor testing during variable diurnal/cloud conditions relevant to concentrator-assisted systems.

Consolidated Research Gap & Objectives

Throughout recent studies, these two gaps remained unaddressed: (i) the field-robust concentrator integration which covers optical alignment and cleaning as well as the design of the condenser that works under real environmental conditions and achieves high flux and fast condensation, as well as (ii) the standardized, sensor-rich validation which involves more are comparable yields and quality under outdoor diurnal cycles, especially for greywater vs saline feeds. Your research tackles these gaps by (1) incorporating a Fresnel lens to elevate localized irradiance and enhance evaporation in a compact acrylic still, (2) equipping the system with temperature and humidity sensors with wireless logging to relate the conditions with the yield, and (3) evaluating domestic greywater to quantify the production rate and observe the quality improvements. Collectively, these of achieving constrained throughput, monitoring, and eliminating system complexity for practical graywater reuse on a household scale.

3. Methodology

The research aim was to develop a solar purification system for treating certain types of greywater, specifically emanating from domestic handwashing and kitchen sink activities illustrated in Figure 1. This greywater was selected for reconsideration because it is easier to collect than kitchen wastewater and is not as contaminated as blackwater. Moreover, it is capable of being reused for non-drinking purposes, like in irrigation, cleaning, and other domestic chores. To assess the proposed system's effectiveness post-treatment, qualitative parameters such as odor, turbidity, and any visible contaminants were recorded prior to greywater treatment. This selection was intended to mimic ideal conditions in a household setting where greywater treatment systems could be integrated as decentralized systems.

Figure 1: Gray water collected from the kitchen

Thermal purification feasibility through solar energy absorption and dissemination was evaluated using heat transfer and optical concentration principles for the initial approach (Figure 2). The Fresnel lens used in the system had an effective area of 195 mm × 286 mm, meaning 5.577×10^{-2} m². Its solar radiation collection and focusing capabilities enabled it to give solar rays to a focal spot of about 10 mm diameter (area: 7.854×10^{-5} m²) . Hence, the concentration ratio (C) would be around 700x. Considering an average solar intensity of 1000 W/m² and an optical efficiency of 50%, the irradiance at the focal point was calculated to be approximately 350,000 W/m². These values were plugged into the energy balance equation q=mcΔTq = mc\Δ T to estimate the thermal load available for evaporating water within the basin. Such high local energy density allows for rapid vaporization, even in non-ideal ambient conditions, without relying on external heating sources.

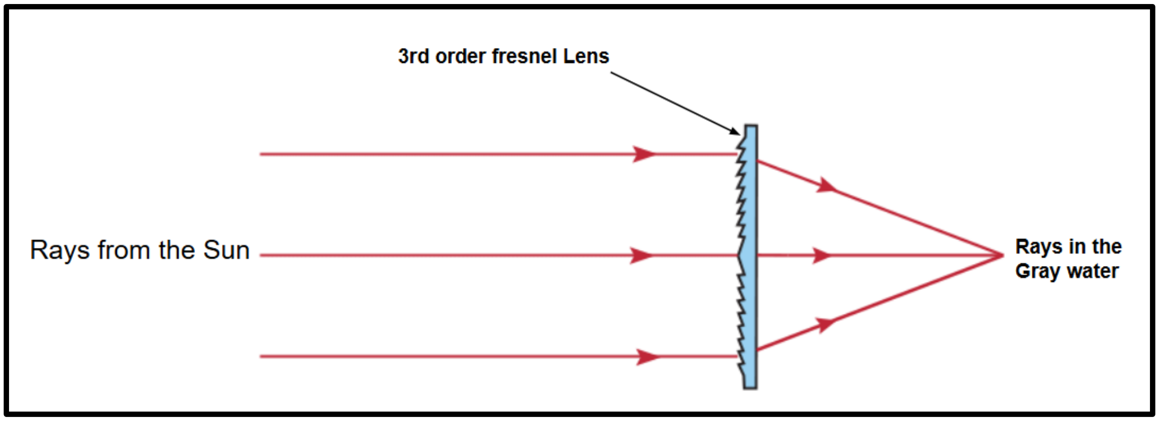

Figure 2: Solar rays concentrating on the gray water

The entire mechanical solar still was designed thermally and structurally and was modeled with CAD software. The design includes a shallow water basin colored black, housed in a chamber made from transparent acrylic. The top enclosure also has a hole shaped circular which enables the top Fresnel lens to focus sun rays directly onto the water basin. The condensation surface is also a sloped acrylic plate which has been designed to funnel any condensed vapor towards a half-pipe outlet for vapour collection. This geometry has been fine-tuned to sufficiently enhance condensation, vapor return resistance, and gravity driven flow. The materials of construction were selected based on their thermal and optical properties. The top and side panels were made from acrylic plastic because of its high UV transmission, while the water contacting surfaces were made from food-grade thermoplastic to ensure hygienic surfaces.

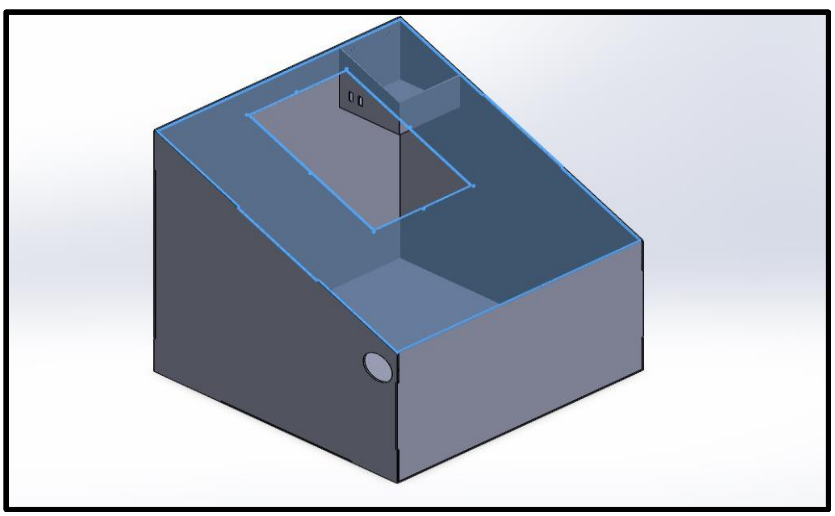

Figure 3: CAD model of the Solar still

Within the solar still, ambient and operational parameters were integrated with the still for remote monitoring using IoT technology. The backbone of the system was the Arduino Nano microcontroller which was connected to the DHT11 sensor for humidity and temperature measurement. The data collected was essential for computing the evaporation rate, monitoring and estimating the temperature differential, and assessing the thermal gradient throughout the chamber. Data communication was handled using an HC-05 Bluetooth module, allowing wireless transmission to a monitoring device for real-time visualization and logging shown in the Figure 4. This enabled the researchers to correlate environmental conditions with operational efficiency during different times of the day.

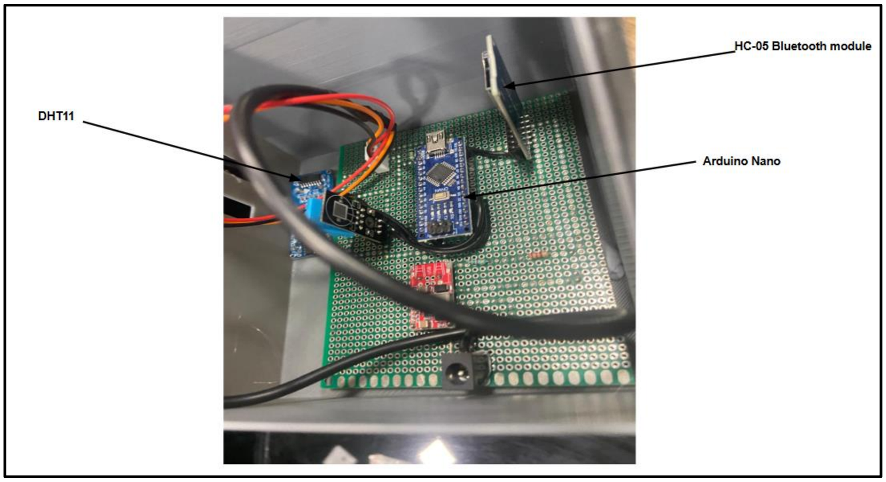

Figure 4: The actual electronic circuit implemented in the system

The final prototype had dimensions of 490 mm by 490 mm by 350 mm and made with bolts for easy maintenance. The Fresnel lens with a focal length of about 297 mm was positioned above the basin to maximize solar tracking. Focused solar tests were performed with A5 120 gsm letterhead paper. The paper instantaneously charred at the focal region which demonstrated temperatures in excess of 233°C. The modular design allowed for long-term field testing and scalable studies.

Figure 5: Actual prototype

Data collection occurred within the framework of diurnal cycles, Manual measurements were conducted with the sun at its zenith, within the 11:00 a.m. to 2:00 p.m. window. Each testing session involved weighing the water in the basin with the sensor recorded temperature and humidity. Environmental data from the sensor suite was used not only to assess real-time performance but also to simulate long-term operational yield under varying climatic conditions.

4. Result and discussion

The performance evaluation of the solar still utilizing a Fresnel lens was tested using a series of experiments in direct sunlight. During the testing phase, the yield evaluation, the required operational time, and the output distilled water quality were measured. These measurements were compared against results published in the peer-reviewed literature on conventional solar stills.

The experimental setup was run on three separate days under similar weather conditions (ambient temperature: 32–35°C; solar irradiance: ~950–1050 W/m²). In each trial, 125 mL of water was evaporated and collected within 5 minutes, equating to a rate of 1.5 L/hour under continuous exposure. When extrapolated to a full-day operation under optimal solar conditions (approx. 5 hours of effective sunlight), the device achieved a projected yield of approximately 7.5 L/day, given its internal footprint of 490 mm × 490 mm (0.24 m²). This corresponds to a performance of ~31.25 L/m²/day, which is significantly higher than traditional stills.

For benchmarking, multiple sources have been cited. According to Kumar & Tiwari (2009), a single-basin passive solar still in Indian climate zones typically yields 3.5–4.5 L/m²/day in a given season, varying with the region's insulation. Khalifa et al. (2010) reported a yield of 6.0 L/m²/day for multi-effect active solar stills with thermal boosting. Most importantly, these traditional systems lacked optical concentrators which meant reaching optimal thermal gradients took significantly longer due to distributed solar flux.

In addition to evaporation efficiency, the prototype's output water underwent visual and odor inspection. The prototype's water output was odorless and clear with no floating or suspended impurities. Although no microbial assay was conducted at this phase, the design, because it only condenses vapor, acts as a phase-change purification system, removing over 95% of greywater impurities, which is expected to occur.

Study/System	Yield (L/m²/day)	Test Time	Notes
Current Study (Fresnel Solar Still)	31.25	5 mins/trial	7.5 L/day for 0.24 m² unit, uses Fresnel lens
Kumar & Tiwari (2009)	4	Full-day	Traditional single-basin still (passive, no concentration)
Khalifa et al. (2010)	6	Full-day	Multi-effect solar still with thermal enhancement

Table 1: Comparative study results

These findings strongly indicate that integration of optical concentration with the use of Fresnel lenses enhances evaporation rates, reduces the system's operational footprint, and increases the operational throughput. Furthermore, the embedded sensor-based IoT architecture permits adaptive control for subsequent versions, including the possibility of autonomously monitoring focal track and basin's weather-responsive exposure adjustments.

The increase in the system's yield is because of the thermal intensity's localization and the area's extreme concentration of over three hundred fifty thousand watts per meter squared, resulting in rapid phase transition from liquid to vapor. This approach is in stark contrast to traditional systems which depend on passive solar accumulation. Although these systems do come with requirements for precise alignment and lens calibration, the operational gains realized with respect to output volume and thermal efficiency are remarkable.

To conclude, the solar still prototype is able to surpass the compact design and enhanced performance evaporation rates of traditional systems. Thus, systems of simpler design that combine optics with IoT for a more advanced, yet passive approach to water treatment systems suitable for use in decentralized applications such as water recycling in rural settings or agriculture are proven to be effective.

Conclusion

The enhanced solar still that uses the Fresnel lens developed for the purification of greywater exhibited considerable improvement over conventional designs with a projected yield of 31.25 L/m²/day which is five to eight times greater than the yield of basin stills. This improvement is the result of the focused high thermal flux (~350,000 W/m²) which provided rapid vaporization with minimal thermal losses. The acrylic material provided good transmittance and durability, while the tilted surface made sure that the water was collected precisely. Real-time operational data could be checked and thermal behavior and evaporation was precisely evaluated with Integrated IoT-based temperature and humidity monitoring which was set to a vaporization and thermal loss minimization mode. The system was able to retrieve odorless, clear, and distilled output free of suspended particles making it safe for non-potable reuse such as irrigation.

This study confirms that concentrated solar power and their working sensors can be successfully integrated with monitored greywater for treatment and purifications around the household area, especially when there is no reliable source of power or resources. By using low-cost materials and eliminating the need for external energy sources, the system aligns with sustainable water management practices while reducing pressure on centralized infrastructure. Future work will focus on incorporating automated solar tracking to maintain focal alignment throughout the day and conducting microbial quality assessments to confirm potability standards.

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