Field Testing of a Solar Pasteurizer Prototype with Automated Flow Control

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Abstract

Considering the global challenge of access to safe drinking water and the need to maximize the use of energy from renewable sources, solar water pasteurization emerges as a viable solution, achieving microbiological decontamination using solar radiation. Accordingly, this study aimed to evaluate the operation and performance of an automated parabolic-trough solar pasteurizer. This is a quantitative, experimental, and descriptive research, in which field tests were conducted to assess the system's effectiveness and productivity. The results confirmed the prototype's ability to inactivate waterborne pathogens, making the water safe for human consumption. Additionally, the automated flow control system operated continuously for several hours, successfully processing 19 batches in just over two hours of operation.

Keywords: Solar pasteurization, SOPAS, Microbiological water decontamination, Parabolic trough collector, Renewable system application.

1. Introduction

One of the major challenges of the 21st century is ensuring access to safe and potable water. According to the United Nations Environment Programme (UNEP), about one-third of the world population lives in regions where freshwater resources are insufficient to meet their needs. It was estimated that by 2025, two-thirds of the global population will experience water scarcity (Jardin, 2012). This situation contradicts the International Covenant on Economic, Social and Cultural Rights (ICESCR), established by the United Nations High Commissioner for Human Rights, which recognizes access to water as a fundamental cultural, economic, and social right (United Nations, 2023).

In addition to limited water availability, there is a regional overlap between social inequality and lack of access to quality water. This combination exacerbates both water and social disparities, constituting a socio-environmental crisis (Maia, 2017).

This crisis worsens already precarious living conditions, forcing vulnerable populations to rely on water of questionable sanitary quality, often in insufficient and irregular amounts to meet basic daily needs (Razzolini and Günther, 2008; Hajissa et al., 2022). As a result, the incidence of infectious and parasitic diseases increases, leading to higher mortality rates, particularly among children (Ehrenberg et al., 2021).

Improving quality of life requires not only access to safe water but also reliable energy supply. Energy availability is essential for enhancing living standards and supporting overall development (Singh and Chandra, 2023). Currently, the world faces a clear energy crisis due to the depletion of conventional sources, such as fossil fuels, and the environmental consequences of their use, including greenhouse gas emissions and acid rain (Javadi, Saidur and Kamalisarvestani, 2013; Verma and Tiwari, 2015; Dutta et al., 2021).

Sustainable energy sources offer a promising solution. Among these, solar energy is particularly attractive due to its wide availability and minimal environmental impact (Xia and Xia, 2010; Kapoor et al., 2014). Despite

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its potential to fully meet global energy demands, only 0.02% of solar energy is currently utilized (Xia and Xia, 2010; Kapoor et al., 2014; Hussein et al., 2017).

Harnessing solar energy to provide potable water in remote regions is a practical and sustainable approach. The parabolic trough solar pasteurizer is one such technology. Using mirrors or reflective materials, it concentrates solar radiation onto a tube containing water. Controlled flow rate and temperature ensure effective pasteurization, inactivating pathogenic microorganisms and producing water suitable for human consumption (Kapoor et al., 2014; Hussein et al., 2017; Bindu and Joseline Herbert, 2020).

Based on this context, the present study aimed to evaluate the operation and performance of an automated parabolic trough solar pasteurizer. The device was designed to achieve microbiological water decontamination, providing a practical solution for populations dependent on unsafe water sources and lacking access to electricity or fuel-based treatment methods.

2. Theoretical Background

2.1 Thermal Inactivation of Pathogens

The thermal inactivation of pathogens is one of the mechanisms aimed at microbiologically decontaminating water through heat. Among these methods are boiling and thermal pasteurization.

Boiling relies on raising the water temperature until it reaches its boiling point (University of Dhaka, 2011). This technique is commonly used in rural areas, typically fueled by charcoal or firewood. On average, burning one kilogram of wood is required to boil one liter of water, which generates environmental impacts due to the degradation of local ecosystems (Acra et al., 1984; Ellis, 1991; WHO, 2011). Therefore, exploring alternative energy sources for heating water in rural settings is crucial, considering both environmental impacts and the scarcity of raw materials.

Thermal pasteurization, on the other hand, involves heating water to a temperature that renders it safe for oral consumption. Unlike boiling, this technique does not require complete elimination of pathogens but aims to reduce the microbial population to a level that does not pose health risks to the consumer (Burch and Thomas, 2018).

The duration of treatment depends on the type of microorganism and the maximum temperature achievable, as each pathogen has its own thermal tolerance. However, studies indicate that most microorganisms have thermal inactivation temperatures below the boiling point of water (Abraham et al., 2015).

Solar energy can be used as a heat source for thermal pasteurization, in which case the process is referred to as solar pasteurization. This approach achieves results equivalent to boiling while minimizing environmental impact. One of the instruments available to achieve this is the parabolic trough concentrator (Fernández-García et al., 2010).

2.2 Parabolic Trough Concentrator

The parabolic trough concentrator is a device capable of capturing solar radiation and converting it into useful heat. Its main components are: (1) a reflective sheet made of reflective material with a cylindrical-parabolic shape; (2) a metal absorber tube containing the working fluid, positioned along the concentrator's focal line; (3) a glass tube surrounding the absorber tube, creating an evacuated space between the two walls to reduce convective heat loss (Jebasingh and Herbert, 2016). The latter component is more relevant in high-temperature applications and is not present in the concentrator used in this study.

The concentrator structure is supported by a rigid base. This base sustains the trough and incorporates a solar-tracking mechanism, which moves the concentrator throughout the day to maintain the opening plane perpendicular to the direction of incident solar rays (Abdulhamed et al., 2018).

In operation, sunlight strikes the reflective sheet, which directs and focuses the radiation onto the absorber tube. This process heats the fluid inside, converting solar radiation into useful thermal energy (Jebasingh and Herbert, 2016).

3. Materials and Methods

This study is a quantitative, experimental, and descriptive research aimed at evaluating the operation of a prototype parabolic trough solar concentrator, describing its construction and analyzing its performance under real conditions. The research was carried out in sequential stages, which included a review of the relevant literature, the development and refinement of the flow control routine, the assembly of the pasteurization system, and field tests of the complete prototype to validate its operational performance.

3.1 Structure of the Prototype

Considering weather resistance, reflected in durability, solar reflectivity, and installation cost, the reflective material used in the prototype was stainless steel type 430. The aperture area of the concentrator is 2.33 m², the rim angle is 65.5°, the focal length is 0,61 m and the collector tube diameter is one inch.

The absorber tube was made of stainless steel, selected for its economic feasibility and its suitability for ensuring efficient heat transfer. In this tube, a threaded stainless-steel T-joint was incorporated to serve as part of the flow control system, providing an outlet that functions as a vent. A third solenoid valve was installed at this vent, operating simultaneously with either the inlet or outlet valve. This configuration ensured that the water inside the tube remained isolated from the external environment during pasteurization, while also allowing air to escape during the filling process and serving as an entry for air during the water discharge.

The upper outlet of the T-joint, where the third valve is connected, was positioned perpendicular to the aperture plane of the trough to avoid casting shadows on the reflective surface. The joint was installed near the southern end of the trough — where water enters the absorber. Since the concentrator is tilted 15° toward the north, the inlet is higher than the outlet, allowing water to flow out of the T-joint only when the tube is almost filled and free of air, as shown in Figure 1.

A solar tracking system was initially planned, consisting of a stepper motor (NEMA 23) with a microstep driver, two light-dependent resistors (LDRs) separated by a vertical shading barrier, and an Arduino UNO control unit programmed to keep the aperture plane perpendicular to the incident solar rays. The barrier between the LDRs enhances the sensor's ability to detect the relative position of the sun by creating a differential light response. However, due to motor failure and limited financial resources at the time of the experiments, the field tests reported here were conducted with the trough orientation manually adjusted every 15 minutes.

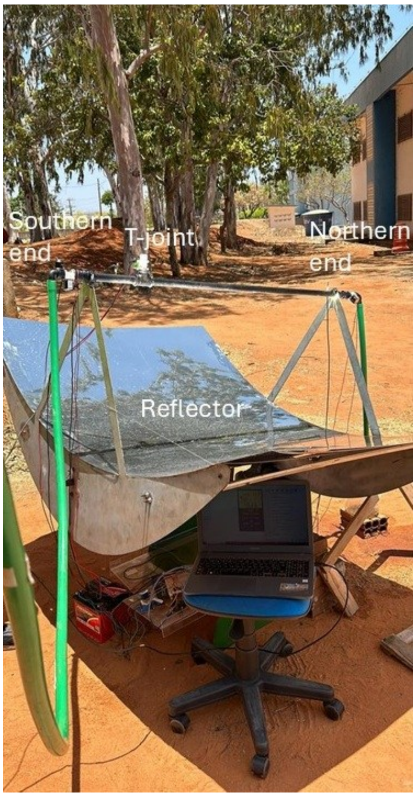

Figure 1: Parabolic trough collector-based solar pasteurizer.

3.2 Flow Control and Pasteurization System

The control system was implemented using an Arduino® microcontroller platform, chosen for its open-source hardware and software architecture, which facilitates rapid prototyping and integration of sensors and actuators (McRoberts, 2018). The Arduino UNO model was sufficient for managing temperature sensors, solenoid valves, and timing routines required for the pasteurization process. Its use provided a flexible and efficient means of acquiring data, controlling valves, and monitoring thermal conditions during operation.

For thermal inactivation of pathogens, it is essential to determine the minimum exposure time required for each microorganism at a specific temperature. Based on these parameters and the satisfactory reduction of pathogens, the inactivation curve — illustrated in Figure 2 — defines the pasteurization process. From this, temperature–time set points can be established, representing conditions that ensure the elimination of pathogenic microorganisms such as Escherichia coli, coliforms, and Pseudomonas aeruginosa. These are completely inactivated under the following set points: 3600 s at 55 °C; 2700 s at 60 °C; 1800 s at 65 °C; 900 s at 75 °C; and 15 s at 85 °C (Carielo da Silva et al., 2016; Carielo, 2017).

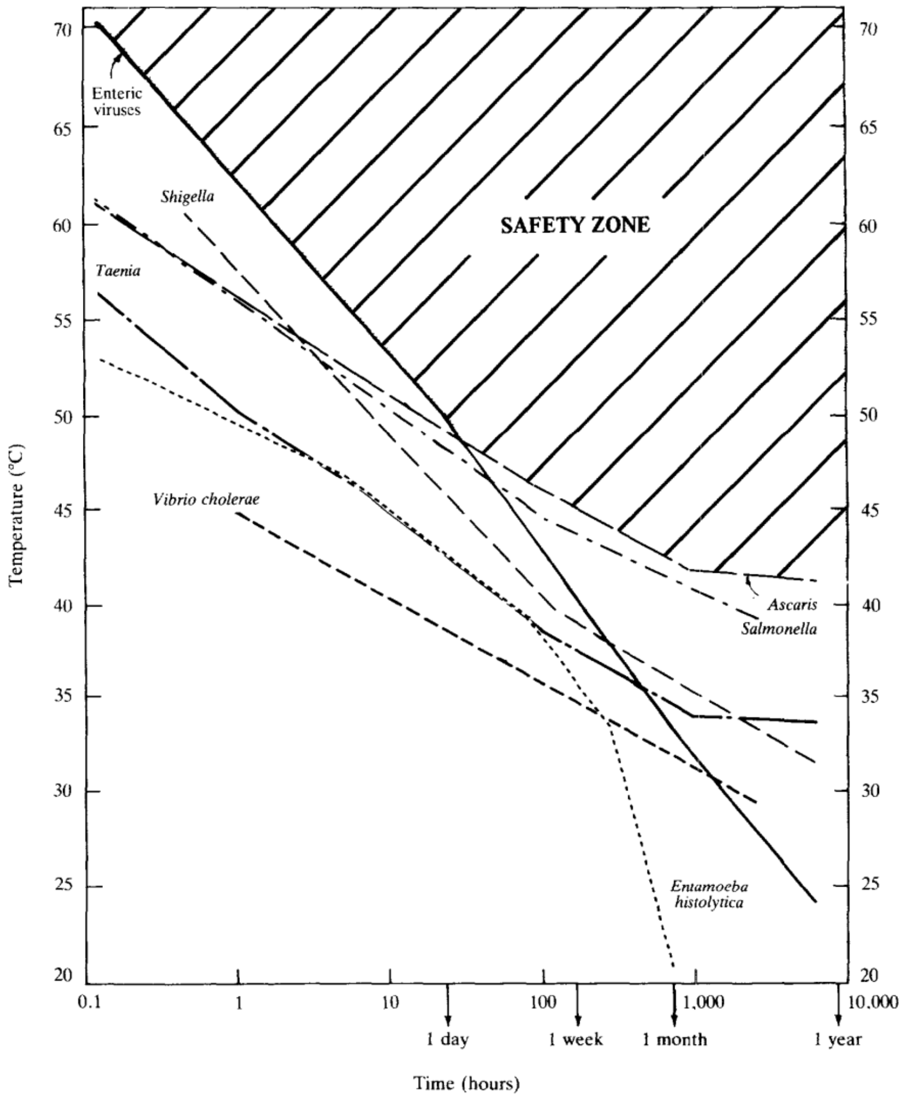

Figure 2: Influence of time and temperature on pathogen inactivation. The plotted lines represent conservative upper limits for pathogen die-off, indicating the estimated combinations of time and temperature required to achieve thermal inactivation. Any treatment process whose time–temperature profile falls within the designated "safety zone" can be considered effective in eliminating all pathogens (Feachem et al., 1983).

To ensure effective flow control, it is crucial to prevent contact between unpasteurized and pasteurized water, thereby avoiding microbial contamination. This control depends on the coordinated operation of the solenoid valves and the precise temperature readings provided by the waterproof thermocouples connected to the Arduino®. The logical structure of this routine is represented in the pseudocode shown in Figure 3.

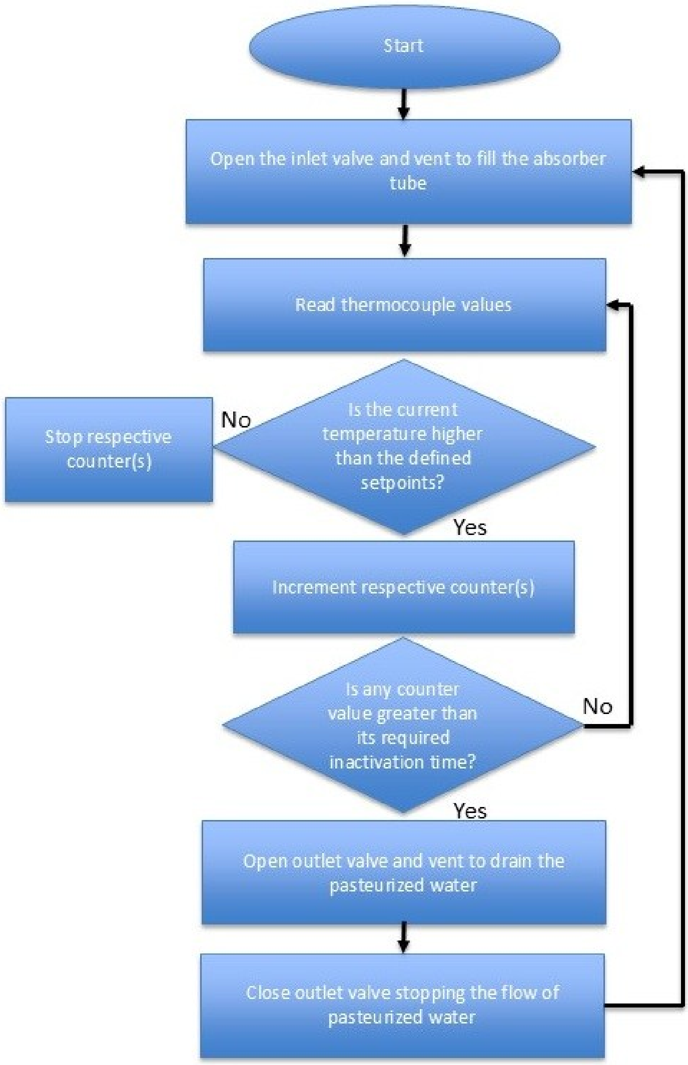

Figure 3: Pseudocode of the flow control system.

4. Results and Discussion

The field performance of the solar pasteurizer prototype was evaluated during two sessions, both conducted near solar noon to minimize alignment errors, since the device operated without a solar tracking system.

4.1 Field Experiments

During field operation, the sky remained mostly clear, with total solar irradiance (direct + diffuse) ranging between 950 and 1100 W/m². The temperature inside the absorber tube and the global irradiance over time for the second experimental session are shown in Figure 4.

The system operated in batch mode, with each batch beginning when the inlet valve opened to load contaminated water at ambient temperature, followed by the closure of both inlet and vent valves to start the heating and pasteurization stage. Once the required time–temperature condition for pasteurization was reached, the outlet solenoid valve opened to discharge the treated water.

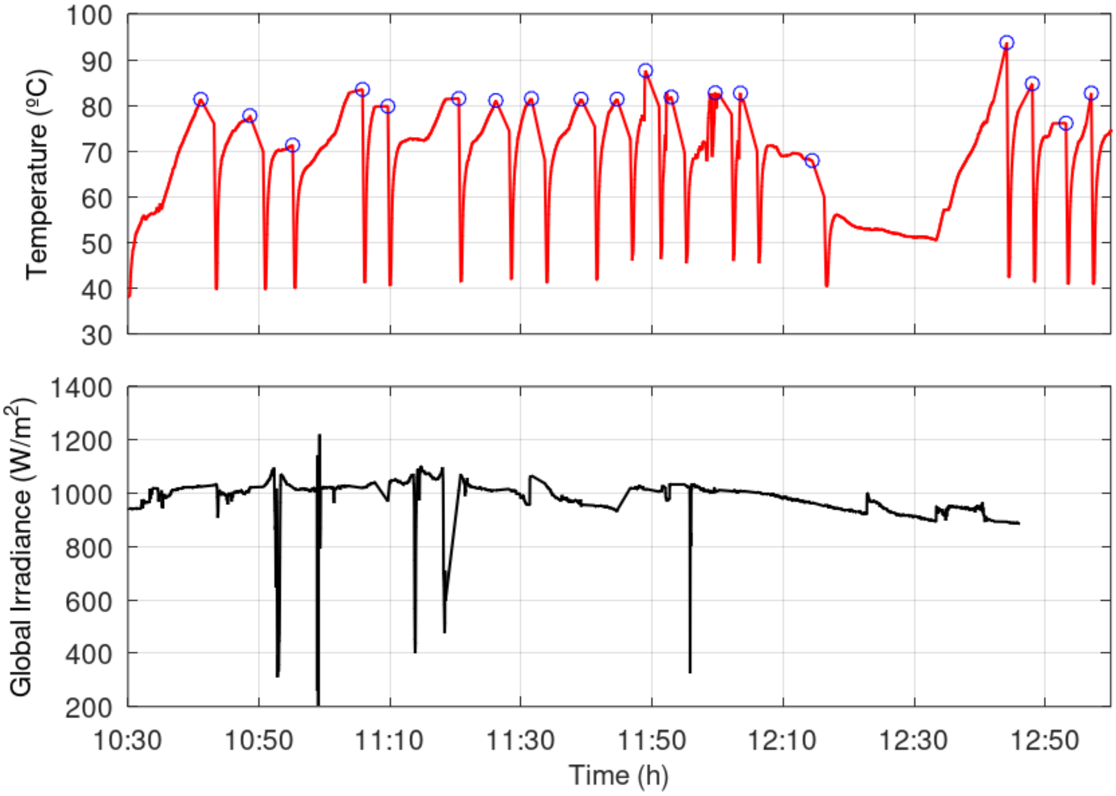

Figure 4: Temperature (top) and Global Irradiance (bottom) vs. Time of Day.

Each batch cycle is delimited on the temperature-time graph by a sharp drop in temperature, which marks the end of the previous cycle. This drop corresponds to the opening of the outlet valve and the release of pasteurized water, along with the entry of ambient air through the air vent. The new cycle begins immediately afterward, as the temperature starts to rise again once the absorber tube is refilled and sealed. From that point on, the system monitors temperature retention to determine the duration of pasteurization until the next temperature drop signals the end of the current cycle. A total of 19 batches were counted, with a blue circle marking each completed batch. A longer batch between 12:20 and 12:40 resulted from manual realignment of the trough due to unintended shading. In the final three batches, data from the pyranometer were lost due to battery depletion, but temperature data remained unaffected.

Table 1 summarizes the energy incident on the concentrator aperture during each batch, calculated from the product of irradiance, aperture area, and batch duration (integrated at 2-s intervals). The average batch duration was approximately 7.7 minutes, consistent with the energy input observed and confirming that the prototype efficiently captured and transferred solar energy during field operation.

The overall operation demonstrated that the pasteurizer could achieve temperatures sufficient for water pasteurization, often exceeding 70 °C, under clear-sky conditions. However, the productivity of the system was lower than expected. Over 2 hours and 20 minutes of operation, approximately 1.4 L of water were pasteurized, corresponding to an average of 600 mL/h. The expected productivity, assuming proper flow discharge, was about 8.55 L for the same period (450 mL per batch across 19 batches).

The reduced flow rate was attributed to the lack of internal pressure in the absorber tube sufficient to overcome the outlet solenoid valve resistance during discharge. Because air could not enter the tube rapidly enough through the vent system (where a unidirectional valve was installed), partial vacuum was formed, restricting the outflow of water and consequently lowering the overall throughput.

When compared with other solar pasteurization systems described in the literature, the throughput obtained here was below the values reported by Carielo da Silva et al. (2016), who achieved about 1.8 L per batch over eight batches in an eight-hour test, and by Carielo et al. (2017), who reported 40 batches of 2 L each during nine hours of operation. Despite this difference, both cited systems share a similar control concept, in which untreated and pasteurized water remain isolated throughout the process. The lower productivity observed in the present study was mainly due to the limited air admission during discharge. Under ideal venting conditions, the expected output of 450 mL per batch would represent a 610% increase in total productivity.

Table 1: Total incident energy on the collector aperture and batch duration for each batch for the same experimental session of Figure 4.

Incident energy (J)	Batch duration (min)
1,53E+06	11,00
7,36E+05	7,48
5,44E+05	6,53
1,19E+06	10,67
2,40E+05	3,87
1,23E+06	10,83
7,77E+05	5,65
4,45E+05	5,43
7,33E+05	7,57
4,33E+05	5,50
3,04E+05	4,35
2,44E+05	3,92
6,33E+05	6,72
2,30E+05	3,85
1,20E+06	10,95
3,36E+06	29,70
Not available	3,90
Not available	5,13
Not available	3,87

4.2 Microbiological Analysis of Water

The microbiological analysis of treated and control water samples, presented in Table 1, was conducted by Professor Gustavo Gonzaga Henry-Silva and the LIMNOAQUA research team (Laboratory of Limnology and Water Quality in Semiarid Regions) at the Federal Rural University of the Semiarid Region (UFERSA).

Contaminated water used for pasteurization was collected from the Mossoró River reservoir in the city center and stored in a clean water tank that served as a supply reservoir for the pasteurizer. Control samples were collected directly from this tank prior to pasteurization. Treated samples corresponded to water discharged from the first three batches during field operation.

The control samples exhibited total coliform counts beyond the quantifiable limit of the method, with high levels of thermotolerant coliforms (fecal coliforms) and Escherichia coli, indicating severe fecal contamination.

After pasteurization, even the first batch—conducted under less-than-ideal flow conditions—showed a substantial reduction in microbial load, with total coliforms decreasing from over 1100 MPN/100 mL to 23 MPN/100 mL, and no fecal coliforms detected. In the second and third batches, for which the thermal process followed the expected timing, no total coliforms were detected at all.

According to standard microbiological criteria, the absence of fecal coliforms and the near-complete removal of total coliforms indicate that the water was rendered potable by pasteurization. These results confirm that the prototype, despite its operational limitations, effectively inactivated the microbial indicators of contamination and achieved the primary goal of solar-driven water pasteurization.

Table 2: *Minimum probable value according to the method, although no turbidity was observed in the culture medium. **Minimum probable value (method detection limit). The culture exhibited turbidity but yielded a negative result for coliforms. * Subsequent tests were not conducted as previous assays did not show positive results.**

Sample	**Total Coliforms (MPN/100 mL)**	**Thermotolerant Coliforms (MPN/100 mL)**	**E. coli (MPN/100 mL)**
Control 1	>1100	240	93
Control 2	>1100	240	240
Control 3	>1100	240	93
Batch 1	23	<3,0**	***
Batch 2	<3,0*	***	***
Batch 3	<3,0*	***	***

5. Conclusions

This study evaluated the operation and characterization of an automated parabolic trough solar pasteurizer, with emphasis on flow control. The system was designed to achieve microbiological decontamination of water, aiming to mitigate the limited access to safe drinking water in areas where only unsafe sources are available and where the population lacks access to electricity or fuel for conventional water disinfection.

In the first field experiment, a microbiological analysis was carried out to assess the system's effectiveness in pathogen inactivation and to verify the proper operation of the control code. Although the flow control code presented operational issues during the test, these did not affect the microbiological results, as the system successfully achieved water pasteurization and microbial inactivation.

In terms of productivity, 1400 mL of water were pasteurized over 2 hours and 20 minutes in the second field experiment. Although this was below the expected 8550 mL (19 batches × 450 mL), the performance limitation was traced to a specific and correctable design issue: the use of a unidirectional air vent valve that prevented air intake during discharge. This restriction impaired outflow and reduced the effective volume per batch to approximately 73.6 mL.

Compared to similar systems reported in the literature - with batch volumes ranging from 1.8 L to 2.0 L and up to 40 batches per day (Carielo et al., 2017) - the current prototype operated with lower throughput. However, the identification of a single, well-defined mechanical limitation provides a clear pathway for optimization. With the implementation of a bidirectional air vent to enable proper discharge, the system is expected to achieve its target of 450 mL per batch, potentially increasing total treated volume by approximately 610%. This highlights the strong underlying potential of the design once minor improvements are made.

Although the overall results were satisfactory, further work is required to enhance system performance. Future developments should include implementing a solar tracking system to reduce manual alignment errors, integrating a bidirectional valve at the vent to improve water discharge, and improving the concentrator's handling and portability, given its size and weight.

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