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Inverted-Pyramid Solar Distiller for Rainwater: A Focus on Bacteriological Potability

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***Abstract*— *Rainwater harvesting can provide an alternative water source, but prolonged storage may result in microbial contamination that makes rainwater unsuitable for direct consumption. This study evaluated an inverted-pyramid solar distiller for improving the microbiological quality of stored rainwater and producing distilled water using solar energy. Rainwater collected from a residential rooftop in Barangay Kasanyangan, Zamboanga City was stored for approximately three months before treatment. Three experimental trials were conducted, each lasting five days, while solar irradiance was recorded hourly from 7:30 AM to 2:30 PM. Raw and treated water were analyzed for total coliform, thermotolerant coliform, and heterotrophic plate count (HPC). Total coliform and thermotolerant coliform were reduced from mean raw-water concentrations of 3,154.33 and 3,075.83 MPN/100 mL, respectively, to 0 MPN/100 mL, representing 100% removal. HPC decreased from a mean of 9,666.67 to 4,071.33 CFU/mL, corresponding to 57.9% average removal. Distillate production ranged from 0.90 to 1.50 L per trial, with productivity of 0.400–0.667 L/m²/day and daily efficiency of 22.24–34.22%. The highest output occurred in Trial 3, which also recorded the highest five-day mean solar irradiance (744.03 W/m²). The Friedman test showed a statistically significant difference in the microbial measurements ($\chi^2 = 13.713$, $p = 0.018$). Although coliform indicators were completely removed, HPC was not consistently reduced to the level reported as the study's reference criterion. The findings indicate that the inverted-pyramid solar distiller has potential as a low-cost supplementary treatment technology for stored rainwater, while further design optimization and post-treatment are needed for broader household application.**

***Keywords*— *inverted-pyramid solar distiller; rainwater; solar distillation; bacteriological potability; total coliform; thermotolerant coliform; heterotrophic plate count; solar irradiance**

I. INTRODUCTION

Water scarcity continues to challenge communities that have limited access to reliable freshwater supplies. Although rainfall is abundant in many tropical areas, harvested rainwater may become contaminated through roof catchments, environmental exposure, and prolonged storage. Previous studies have documented microbial contamination in roof-harvested rainwater and emphasized the importance of treatment before potable use [1]–[4]. In the Philippines, rainwater harvesting has also been considered a supplementary water source for communities experiencing water-supply constraints [5], [6].

Solar distillation offers a low-cost treatment approach because it uses solar energy to drive evaporation and condensation. The phase-change process can separate microorganisms and other non-volatile contaminants from the feed water. Pyramid-type solar stills have received attention because their geometry can improve solar exposure and condensation compared with some conventional configurations [7], [8]. Previous studies have reported effective microbial inactivation and improved water quality through solar distillation and solar-based disinfection [9], [10].

Microbiological assessment is particularly important for evaluating treated rainwater. Total coliform and thermotolerant coliform are used as indicators of sanitary and fecal contamination, while heterotrophic plate count (HPC) provides a broader indication of bacterial population in water [11], [12]. The Philippine National Standards for Drinking Water (PNSDW) require the absence of thermotolerant coliform/E. coli in drinking water and provide microbiological criteria used in evaluating water safety [13].

This study evaluated an inverted-pyramid solar distiller using stored rooftop rainwater from Barangay Kasanyangan, Zamboanga City. Specifically, the study assessed the microbiological quality of the treated water, determined microbial removal efficiency, and evaluated the productivity and daily efficiency of the solar still under natural sunlight.

II. METHODOLOGY

A. *Experimental Site and Research Design*

The experimental study was conducted at the researcher's residence in Kasalamatan Village, Barangay Kasanyangan, Zamboanga City, Zamboanga del Sur, Philippines. A quantitative experimental approach was used to evaluate stored rainwater treated through an inverted-pyramid solar still. Three trials were performed, with each trial operated continuously for five days under natural sunlight.

B. *Rainwater Collection and Sample Preparation*

A total of 60 L of rainwater was collected from a residential rooftop in Kasalamatan Village, Barangay Kasanyangan. The harvested rainwater was stored for approximately three months before experimentation. For each trial, 15 L of stored rainwater was introduced into the solar still. A 350-mL sample of raw water and a 350-mL sample of treated water were collected for bacteriological analysis and transported to the Department of Science and Technology Region IX Regional Standards and Testing Laboratories.

C. *Inverted-Pyramid Solar Distiller*

The solar still consisted of a plain-sheet basin, an inverted-pyramid glass structure, transparent glass surfaces, PVC

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piping, an outlet, and a distilled-water collection container. The unit was cleaned and disinfected before and after each trial. During operation, sunlight heated the rainwater in the basin, producing vapor that condensed on the glass surfaces. Condensed water flowed toward the collection outlet while non-volatile contaminants remained in the basin. The reported basin storage capacity was 47.40 L, and the effective surface area used in the productivity and efficiency calculations was 0.45 m².

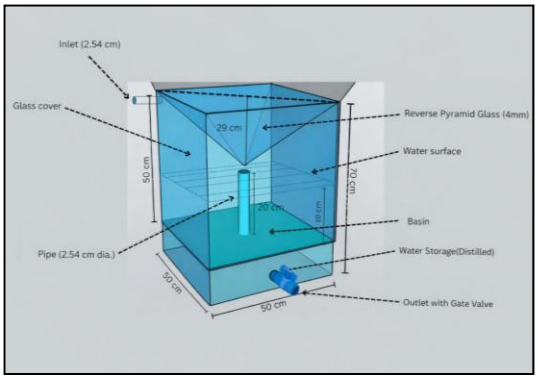

Fig. 1. Schematic/design of the inverted-pyramid solar distiller

Fig. 2. Inverted-pyramid solar still undergoing the distillation process

D. Experimental Operation and Solar Irradiance

Each trial was operated for five consecutive days from 7:30 AM to 2:30 PM. Solar irradiance was measured hourly using a solar power meter. Daily distilled-water production was recorded, and the accumulated output was used to calculate productivity and thermal efficiency.

E. Microbiological Analysis

Raw and treated water samples were analyzed for total coliform and thermotolerant coliform using the Multiple Tube Fermentation Method, SMEWW 24th edition, Method 9221B. HPC was determined using the Pour Plate Method, SMEWW 24th edition, Method 9215B. Results were expressed as MPN/100 mL for coliform parameters and CFU/mL for HPC. Results were compared with the PNSDW 2017 criteria used in the study.

F. Performance Calculations

Microbial removal efficiency was calculated as $RE = [(C\_influent - C\_effluent) / C\_influent] \times 100$. Daily productivity was calculated as $P = V/(A \times N)$, where V is total distilled-water volume, A is effective surface area, and N is the number of operating days. Daily thermal efficiency was calculated using accumulated distilled-water mass, latent heat of evaporation, surface area, and total solar energy received.

G. Statistical Analysis

Shapiro–Wilk testing was used to examine microbial-data distribution. HPC was normally distributed ($p = 0.556$), while total coliform ($p = 0.040$) and thermotolerant coliform ($p = 0.003$) were not. A related-samples Friedman two-way analysis of variance by ranks was applied across the microbial measurements at a 0.05 significance level. Microsoft Excel was used for tabulation and performance calculations, while IBM SPSS was used for statistical analysis.

III. Results and Discussion

A. Solar Irradiance and Distillation Performance

Solar irradiance followed a typical diurnal pattern, increasing from morning toward midday and declining during the afternoon. The five-day mean irradiance was 721.81 W/m² for Trial 1, 687.05 W/m² for Trial 2, and 744.03 W/m² for Trial 3. Trial 3 therefore received the highest mean solar irradiance and produced the highest distilled-water volume. The observed pattern supports the relationship between solar energy input, basin heating, evaporation, and distillate production [14], [15].

TABLE I. Summary of Solar Still Performance

Trial	Distilled Water (L)	Mean Solar Irradiance (W/m²)	Efficiency (%)	Productivity (L/m²/day)
1	1.25	721.81	28.22	0.556
2	0.90	687.05	22.24	0.400
3	1.50	744.03	34.22	0.667

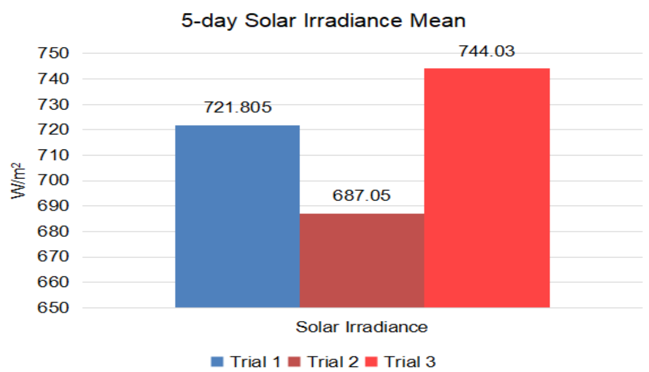

Fig. 3. Five-day mean solar irradiance recorded during the three experimental trials

Trial 3 recorded the highest distilled-water output at 1.50 L, with 34.22% daily efficiency and 0.667 L/m²/day productivity. Trial 2 recorded the lowest output at 0.90 L, corresponding to 22.24% efficiency and 0.400 L/m²/day productivity. Across the three trials, higher solar irradiance generally coincided with higher production and efficiency. The observed efficiency range of 22.24–34.22% is consistent with the broad performance range reported for solar stills under varying design and climatic conditions [14], [16].

B. Microbiological Quality and Removal Efficiency

TABLE II. Microbial Removal Efficiency

Parameter	Mean Raw	Mean Treated	Average Removal
Total Coliform (MPN/100 mL)	3,154.33	0	100%
Thermotolerant Coliform (MPN/100 mL)	3,075.83	0	100%
HPC (CFU/mL)	9,666.67	4,071.33	57.9%

The raw rainwater showed substantial microbial contamination. Total coliform ranged from 23 to 9,200 MPN/100 mL, thermotolerant coliform ranged from 2.0 to 9,200 MPN/100 mL, and HPC ranged from 2,000 to 14,000 CFU/mL. After treatment, total coliform and thermotolerant coliform were reduced to 0 MPN/100 mL in all three trials, corresponding to 100% removal. This result is consistent with the principle of distillation, in which microorganisms do not readily transfer with water vapor, and with previous reports of microbial inactivation through solar distillation [9], [17].

HPC was reduced from a mean of 9,666.67 to 4,071.33 CFU/mL, corresponding to 57.9% average removal. Trial-specific HPC removal was 61.54% in Trial 1, 50.00% in Trial 2, and 89.30% in Trial 3. The incomplete removal of HPC is important because HPC represents a broad population of environmental bacteria rather than a specific fecal indicator [11]. The result also suggests that treatment performance may be influenced by initial microbial load, solar exposure, and possible post-condensation contamination.

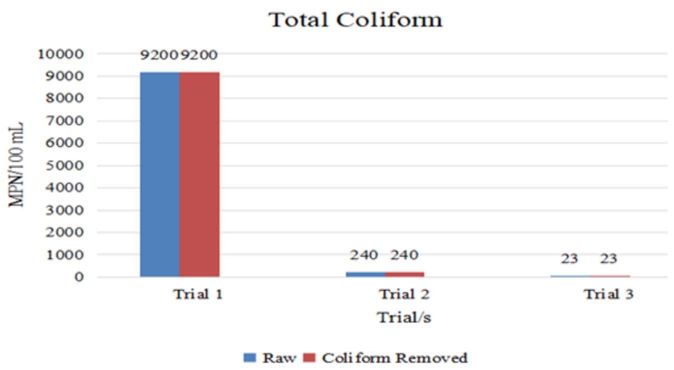

Fig. 4. Total Coliform Reduction across all 3 trials

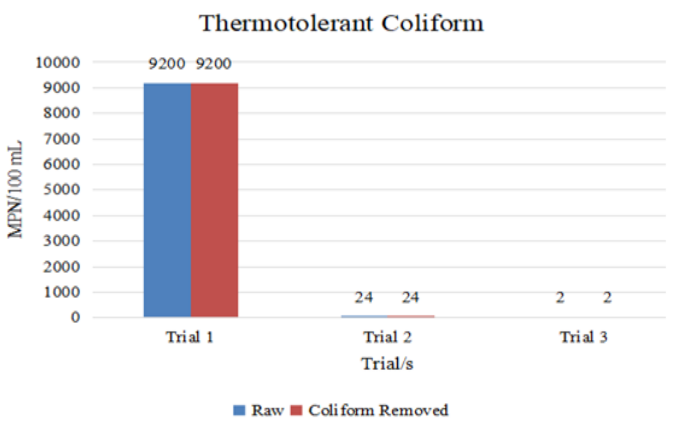

Fig. 5. Thermotolenrant Coliform Reduction across all 3 trials

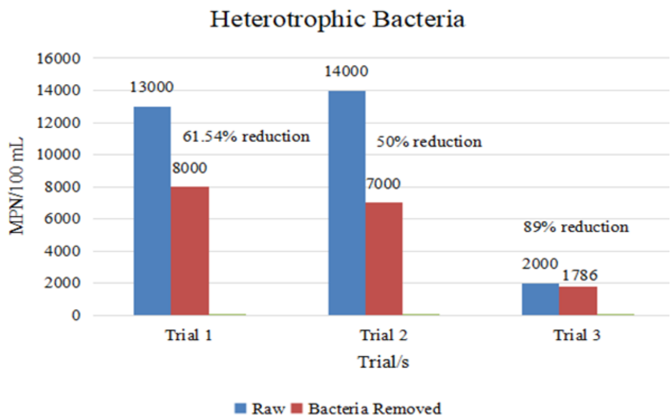

Fig. 6. HPC Reduction across all 3 trials

Figures 4–6 show the reduction in total coliform, thermotolerant coliform, and heterotrophic plate count (HPC) following treatment with the inverted-pyramid solar still. Total coliform and thermotolerant coliform were reduced to 0 MPN/100 mL in all three trials, indicating complete removal of the tested coliform indicators. HPC was reduced by 61.54%, 50.00%, and 89.30% in Trials 1, 2, and 3, respectively. Bacteria are physically separated from the water because they do not vaporize during evaporation [17]. However, the incomplete and variable reduction in HPC indicates that microbial removal was not uniform across all trials. Differences in initial microbial concentration, solar exposure, operating conditions, and possible post-condensation contamination may have contributed to the observed variation. The inverted-pyramid solar still significantly reduced HPC across all trials while eliminating total and thermotolerant coliforms. HPC reduction was influenced by the initial microbial load and solar irradiance during each day [18], [19].

C. Comparisons to the Bacteriological Standards of PNSDW 2017

Based on the Philippine National Standards for Drinking Water (2017), drinking water must contain zero total coliform and zero thermotolerant coliform per 100 mL sample. The treated water met these standards in all trials, indicating compliance with microbiological safety requirements for these parameters. HPC does not have a strict regulatory limit, its presence in treated water suggests that further treatment or handling precautions may be necessary to ensure overall water quality.

TABLE III.Trial 1 Results with Comparison to PNSDW 2017 Standard

Parameter	Raw	Treated	Standard	Remarks
Total Coliform	9200	0	0	PASSED
Thermotolerant Coliform	9200	0	0	PASSED
HPC	13000	5000	<500	FAILED

The treated water met the study's PNSDW 2017 criterion for zero total coliform and zero thermotolerant coliform in all trials. The 3-trial reports treated HPC values of 5,000, 7,000, and 214 CFU/mL for Trials 1, 2, and 3, respectively. Thus, the distiller achieved complete removal of the tested coliform indicators, while HPC was only partially reduced. Because HPC is a general indicator of bacterial population and the thesis notes that its presence may require further treatment or handling precautions, the system should not be described as consistently producing potable water based only on these parameters.

TABLE IV. Trial 2 Results with Comparison to PNSDW 2017 Standard

Parameter	Raw	Treated	Standard	Remarks
Total Coliform	240	0	0	PASSED
Thermotolerant Coliform	4.5	0	0	PASSED
HPC	14000	7000	<500	FAILED

TABLE V. Trial 3 Results with Comparison to PNSDW 2017 Standard

Parameter	Raw	Treated	Standard	Remarks
Total Coliform	23	0	0	PASSED
Thermotolerant Coliform	2	0	0	PASSED
HPC	2000	214	<500	PASSED

D. Relationship Between Solar Irradiance and Microbial Removal

The results indicate a direct relationship between solar irradiance and the performance of the solar still in terms of both productivity and microbial removal efficiency. Higher solar irradiance increases the thermal energy available for evaporation, which accelerates the phase change process and enhances the separation of contaminants. As evaporation rates increase, the system produces more distilled water and improves the removal of microorganisms [14].

For coliform bacteria, complete removal was achieved regardless of irradiance level due to their inability to survive the phase-change process. However, the reduction of heterotrophic bacteria showed dependence on solar intensity. Higher irradiance resulted in greater temperature within the still, which contributed to increased bacterial inactivation. Elevated temperature and ultraviolet (UV) exposure significantly reduce microbial survival in water systems [26].

This relationship confirms that solar energy plays a critical role not only in water production but also in improving microbiological quality. The findings support previous studies indicating that increased solar exposure enhances both evaporation efficiency and microbial reduction [9].

E. Statistical Analysis

Test	N	χ^2	df	p-value
Friedman two-way ANOVA by ranks	3	13.713	5	0.018

The Friedman analysis yielded $\chi^2 = 13.713$ with $p = 0.018$, indicating a statistically significant difference at $\alpha = 0.05$. The result supports a difference among the microbial measurements evaluated in the study and is consistent with the observed complete removal of total and thermotolerant coliform and the substantial reduction in HPC.

F. Practical Applicability

The inverted-pyramid solar distiller demonstrated potential as a low-cost supplementary treatment system for stored rainwater in areas with adequate sunlight. Its principal microbiological result was the complete removal of total coliform and thermotolerant coliform in all three trials. However, productivity ranged only from 0.400–0.667 L/m²/day, which may limit its ability to meet household water demand. The thesis recommends increasing the evaporation surface area, improving insulation, optimizing the condensation surface, and considering other solar-assisted technologies to improve production and efficiency. Because HPC remained present after treatment, further treatment or handling precautions should be considered before direct drinking-water use.

IV. CONCLUSIONS

The inverted-pyramid solar distiller improved the microbiological quality of stored rooftop rainwater under the experimental conditions. Total coliform and thermotolerant coliform were completely eliminated in all three trials, achieving 100% removal. HPC was reduced by an average of 57.9%, although the reduction was inconsistent and remained above the study's reference criterion in two trials. The system produced 0.90–1.50 L of distilled water per trial, with productivity of 0.400–0.667 L/m²/day and daily efficiency of 22.24–34.22%. The highest performance occurred in Trial 3, which had the highest five-day mean solar irradiance. Statistical analysis using the Friedman test showed a significant difference in the microbial measurements ($p = 0.018$). Overall, the system shows promise as a low-cost supplementary rainwater treatment technology, but its limited productivity, incomplete HPC removal, and the absence of physico-chemical testing indicate that further optimization and post-treatment are necessary before broader household drinking-water application.

V. RECOMMENDATIONS

- Improve the inverted-pyramid solar still by increasing effective evaporation surface area, improving insulation, and optimizing the condensation surface to increase productivity and thermal efficiency.
- Consider supplementary treatment, such as ultraviolet disinfection or other solar-assisted purification processes, to improve removal of heterotrophic bacteria.
- Evaluate larger-scale prototypes and longer operating periods to determine whether the system can contribute meaningfully to household water demand.
- Investigate the relationship among solar irradiance, internal temperature, productivity, and microbial removal under different seasons and climatic conditions.
- Include physico-chemical parameters such as pH, turbidity, total dissolved solids, conductivity, and dissolved oxygen in future evaluations.
- Further investigate the effect of prolonged rainwater storage.

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