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Comparative Assessment of Solar Distillation of Graywater with and without Boiling for the Production of Distilled Water

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ABSTRACT

Water scarcity in dry urban areas has led to increased use of graywater for potential reuse. Among affordable water treatment methods, solar distillation stands out as an appealing option; however, there is limited documentation on its performance with actual effluents and a direct comparison between boiling and non-boiling configurations. In this study, we compared the solar distillation of domestic graywater using two setups: (i) a boiling system, comprising a CK-002 solar cooker connected to a black-painted copper still, copper coil, and condenser, and (ii) a non-boiling system, featuring a single-slope glass-covered solar still. Graywater was collected from five households in Tacna, Peru, with 5-liter batches treated over 11 h on sunny days. The study recorded distillate volume, physicochemical parameters (pH, conductivity, turbidity, nitrates, nitrites, sulfates, BOD_5, and COD), metal concentrations, and microbiological indicators such as fecal coliforms, Escherichia coli, and heterotrophic bacteria. Results indicated that the boiling distillation produced 2,790 mL of distillate, while the non-boiling system yielded 1,725 mL, a statistically significant difference ($\alpha = 0.05$). Physicochemical analysis showed significant differences only in turbidity, conductivity, and nitrates, with the non-boiling system demonstrating superior removal (>90%). Total metal removal was 98.63% (reducing from 445.03 mg L^{-1} to 6.06 mg L^{-1}) in the boiling setup and 98.56% (to 6.37 mg L^{-1}) in the non-boiling. Microbiological testing revealed both systems effectively reduced contaminants: fecal coliforms by 99.76%, heterotrophic bacteria by 99.99%, and E. coli by 98.04%. Overall, solar distillation-whether boiling or not-substantially decreases microbiological pathogens and metals. Nonetheless, due to the persistence of certain organic compounds, such as biodegradable organic matter that exceeds Peruvian environmental standards, solar distillation is best used as a barrier step within a treatment chain designed for limited reuse or combined with additional treatments to meet regulatory limits.

INTRODUCTION

At the global level, the demand for freshwater continues to rise due to population growth, the need to meet basic consumption requirements, pollution, global warming, and climate change, factors that reduce water availability and threaten sustainability (González 2013, Huaquisto & Chambilla 2019, Castro & Rajadel 2021, Petrescu et al. 2022, Matta et al. 2024). This issue is particularly critical in arid and semi-arid regions (Jalink & Dieperink 2024), where water stress occurs more frequently (Xu et al. 2022, Karmaker et al. 2024). The city of Tacna, located in the desert zone of southern Peru, faces severe water scarcity exacerbated by decreasing precipitation in the high Andean region, climate change, and inefficient water resource management, factors linked to urbanization processes (Meng et al. 2022, Shen & Yao 2022). Domestic activities generate wastewater whose inadequate disposal poses a sanitary risk (Horbatuck & Beruvides 2024). Among these is graywater, which in some cases is discharged into open channels (Nuñez et al. 2014), originating from sinks, showers, washing machines, dishwashers, and laundries, and accounting for approximately 75% of the total volume of domestic wastewater (Murcia-Sarmiento et al. 2014, Anaya et al. 2022). Such disposal and management practices do not ensure sustainable use of water resources, underscoring the need to implement safe treatment and reuse technologies (Castro & Moncada 2022).

Studies have reported water consumption levels of up to 275 L per person per day, exceeding the international averages of 200 to 250 $L.day^{-1}$ (Blanco et al. 2014). It is estimated that, per person, graywater generation reaches approximately 48 $L.day^{-1}$ from showers and 17.6 $L.day^{-1}$ from sinks (Burbano 2015), volumes that represent significant potential for reuse, making their treatment a priority strategy to optimize water use. Safe graywater reuse requires treatment technologies that ensure the removal of physical, chemical, and microbiological contaminants, minimizing risks and preventing adverse environmental impacts (Montalván-Estrada et al. 2019, Hernández-Aguilar et al. 2022, Araque 2022). Several studies indicate that, for this type of effluent, physicochemical treatments are more effective than biological ones due to the low biodegradability of some compounds present (González & Chiroles 2010, Borsato et al. 2018). Within the global transition toward a net-zero emissions economy (Osman et al. 2019, Czepło & Borowski 2024, Krátký et al. 2024), international commitments to mitigate climate change are driving the adoption of solar energy (Lee et al. 2020), a widely available resource with zero direct CO_2 emissions during operation. Sustainable development must be applied by improving environmental, social, and economic indicators, ensuring living conditions for humanity (Casulo 2018, Madroñero-Palacios & Guzmán-Hernández 2018, García-Parra et al. 2022). The expansion of renewable energies, including solar, aligns with SDG 7 by promoting access to affordable, reliable, sustainable, and modern energy (Hernandez-Escobedo et al. 2023, Rekeraho et al. 2024, Jiménez-García et al. 2024). In parallel, climatic, demographic, and social changes are putting pressure on water resource availability, reinforcing the need for its safe reuse (Bruzzoniti et al. 2024, Ramaprasad & Syn 2024).

The use of solar thermal energy is a viable alternative for water distillation processes, especially in regions with high solar radiation (Amin et al. 2022, Bacha et al. 2023). Among the simplest technologies are single-slope solar stills with glass covers, used for seawater desalination in coastal areas (Alsaman et al. 2022). Their operation is based on the direct utilization of solar radiation as a heat source (Torchia-Nuñez et al. 2010), avoiding the use of fossil fuels during operation, therefore, the cost of using solar energy is negligible (Chaparro 2015), making it an economically viable alternative and highlighting its contribution to reducing greenhouse gas emissions (Coelho et al. 2020, Abdalha et al. 2022). Although numerous studies have explored alternative treatments for graywater, research applying solar energy in distillation processes for its recovery remains limited. Therefore, it is relevant to evaluate the process and its configurations to generate experimental evidence of its feasibility (Hussein et al. 2022, Kaviti et al. 2023, Soltanian et al. 2024). This study aimed to compare two solar distillation systems, one with boiling and one without boiling, to assess their efficiency in producing distillate under high-radiation climatic conditions characteristic of arid zones, such as those found in the city of Tacna.

MATERIALS AND METHODS

Research Site

The experimental procedures were conducted at the School of Environmental Engineering, Jorge Basadre Grohmann National University, and in the Pocollay district, both located in the province of Tacna. During November and December 2022, solar irradiance was recorded from 6:00 a.m. to 5:00 p.m. using a horizontal solarimeter throughout the experiments (Fig. 1).

Graywater Sampling

A non-probabilistic convenience sampling was conducted in five households located in the PJ Para Chico neighborhood, in the district of Tacna, Peru. In each household, 20 liters of graywater were collected from three sources: kitchen sinks, laundry areas, and personal hygiene stations. Samples were collected in high-density polyethylene (HDPE) containers that had been previously washed and rinsed with distilled water. Sampling was carried out over 24 h to account for daily variations, resulting in a total of 100 liters of composite sample stored in a 200-liter polyethylene tank. To maintain the original characteristics of the water, the composite sample was kept in a covered and ventilated area at ambient temperature (20–25°C).

Graywater Analysis

pH and electrical conductivity were measured with a Hach HQ40D multiparameter instrument, calibrated before each session with traceable standard solutions. Turbidity was measured with a TurbiQuant 1100 T turbidimeter (±0.01 NTU) following the SM 2130B method. Nitrates and nitrites were determined by spectrophotometry according to SM 4500-NO_3^- E and SM 4500-NO_2^- B. Sulfates were quantified by turbidimetry (SM 4500-SO_4^{2-} E). COD was measured by

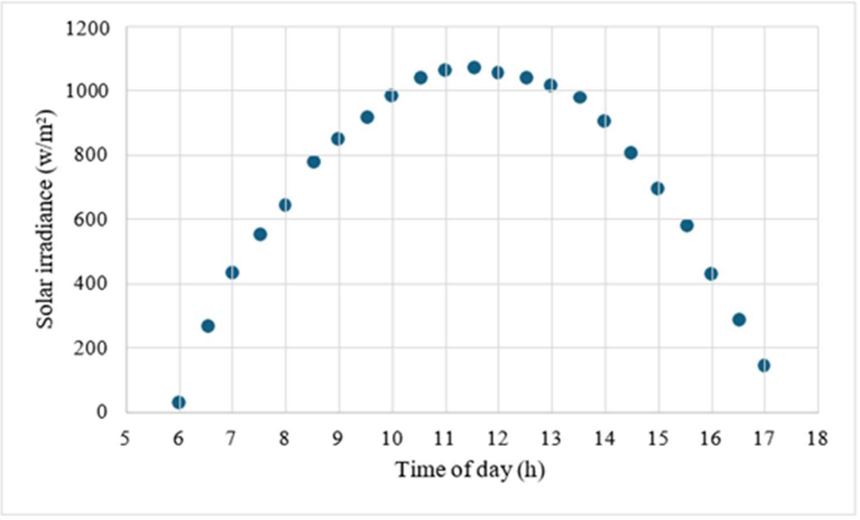

Fig. 1: Time of day vs average solar irradiance (W.m⁻²) on clear days during November and December 2022.

closed digestion and spectrophotometry (SM 5220 D), and BOD_5 by incubation at 20°C for 5 days (SM 5210 B). Total metals were determined by ICP-AES (EPA 200.7) after acid digestion (SM 3030 B). Microbiological parameters were analyzed using the MPN method for fecal coliforms (SM 9221 E) and E. coli (SM 9223 B), and plate count for heterotrophic bacteria (SM 9215 B).

Solar Distillation with and Without Boiling

Solar distillation was performed under ambient conditions from 6:00 a.m. to 5:00 p.m. Both distillation units were reoriented toward the sun every 30 minutes. Solar irradiance was measured using a horizontal solarimeter. Graywater temperature was monitored using an alcohol thermometer (0–150°C) and a thermocouple connected to a multitester.

For the distillation without boiling, the methodology of Rodriguez (2021) was followed using a single-slope solar still (dimensions: length = 96 cm, width = 80 cm, height = 50 cm, base height = 10 cm, air chamber height = 40 cm, volume = 57 L, weight = 18 kg), as shown in Fig. 2. In each trial, 5 L of graywater was introduced into the still. Distillation time was monitored using a clock under clear sky conditions.

For the boiling-based distillation, as shown in Fig. 3, a reused CK-002 parabolic solar cooker was employed. The system included a copper still (capacity = 5 L, painted black, weight = 3.3 kg), with a copper coil (diameter = 2.54 cm, length = 1.95 m) and a condenser (capacity = 10 L). The solar cooker had a diameter of 1.5 m and a solar collection area of 1.767 m². The total system weight was 12.6 kg. The procedure was based on the methodology of Chaparro (2015) with modifications. The distilled water volume was measured using a 250 mL graduated cylinder.

Solar Distillation Process Temperatures

For the solar distillation without boiling, the best-fitting model for temperature evolution was an inverse cubic polynomial with a coefficient of determination of $R^2 = 0.9894$ and an adjusted $R^2 = 0.9877$:

$$Y\ (\text{temperature, °C}) = -97.6812 + 26.9455X - 1.1616X^2 + 0.0021X^3 \qquad \text{...(1)}$$

For distillation with boiling, the best-fitting model was also an inverse cubic polynomial ($R^2 = 0.8366$, adjusted $R^2 = 0.8108$) :

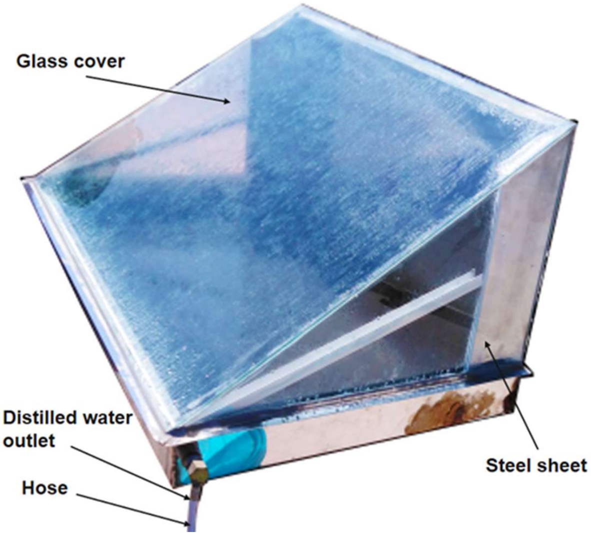

Fig. 2: Single-slope solar still.

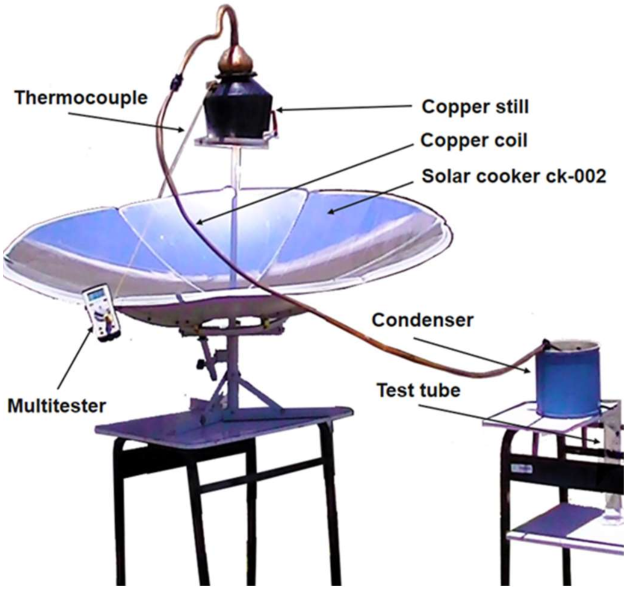

Fig. 3: Solar still with a solar cooker CK-002.

$$Y\ (\text{temperature, °C}) = 196.1971 - 4067.7237X + 50030.1661X^2 - 188974.39X^3 \ldots \quad \ldots(2)$$

Volume of Distilled Water

The distillation volume over time without boiling followed a cubic polynomial ($R^2 = 0.9997$, adjusted. $R^2 = 0.9997$):

$$Y\ (\text{volume, mL}) = 1503.9430 - 596.2048X + 69.5195X^2 - 1.9796X^3 \quad \ldots(3)$$

With boiling, the distillation volume also followed a cubic polynomial ($R^2 = 0.9993$, adjusted $R^2 = 0.9992$):

$$Y\ (\text{volume, mL}) = 7494.2990 - 2546.5682X + 263.5392X^2 - 7.6593X^3 \quad \ldots(4)$$

Analysis of Distilled Water

The pH and electrical conductivity of the distilled water were measured with a Hach HQ40D multiparameter instrument calibrated before each session using traceable standard solutions, following methods SM 4500-H^+ B and SM 2510 B, respectively. Turbidity was determined with a TurbiQuant 1100 T turbidimeter (±0.01 NTU) according to SM 2130 B, and removal efficiency was calculated according to Martínez-Orjuela et al. (2020):

$$\textbf{Turbidity efficiency}\ (\%) = \frac{(\mathbf{T0} - \mathbf{T1}) \times \mathbf{100}}{\mathbf{T0}} \ldots(5)$$

Where T_0 = turbidity of graywater and T_1 = turbidity of distilled water.

Nitrate, nitrite, sulfate, COD (SM 5220 D), BOD_5 (SM 5210 B), and total metal concentrations (EPA 200.7 after digestion SM 3030 B) were determined following the same procedures described for graywater.

Microbiological analysis included fecal coliforms (SM 9221 E), Escherichia coli (SM 9223 B), and heterotrophic bacteria counts (SM 9215 B), expressed as MPN 100 mL^{-1} or CFU mL^{-1}, as appropriate. All samples were analyzed in duplicate, with quality control through blanks and verification standards.

Statistical Analysis

The evolution of temperature and volume in the distillation process was analyzed using the coefficient of determination (R^2). Each experiment was conducted in triplicate. Normality (Shapiro–Wilk) and homoscedasticity (Levene) were verified. For multiple comparisons, a one-way ANOVA and Tukey HSD test were applied with a 95% confidence interval. (Wong-González 2010). The analysis was performed using Excel software.

RESULTS

Solar Distillation Temperatures with and Without Boiling

Fig. 4 shows the graywater temperature profiles during solar distillation with and without boiling. The highest solar irradiance occurred between 10:00 a.m. and 2:00 p.m. (Fig. 1), significantly influencing the increase in temperature.

The distillation process started at 6:00 a.m. with graywater at 20°C. In the boiling-based system, the temperature rose rapidly and linearly due to the concentration of solar thermal energy reflected by the parabolic solar cooker onto the black-painted copper still. At 7:30 a.m., the temperature reached 96.3°C, at which point the first drop of distillate was collected. The temperature then increased slightly, reaching a peak of 97°C at 9:30 a.m., and remained constant until 3:00 p.m., after which it decreased linearly, ending at 5:00 p.m. at 77°C.

In the system without boiling, the water temperature also started at 20°C and increased linearly. The first distillate was collected at 6:30 a.m. The maximum temperature of 64°C was reached at 11:30 a.m., followed by a linear decrease until the process ended at 5:00 p.m. with a final temperature of 37°C.

At 9:30 a.m., a comparison showed that graywater in the boiling-based system reached 97°C, significantly higher than the 54°C recorded in the non-boiling system.

Solar distillation was conducted over three cloudless days, with both distillers reoriented every 30 minutes. Fig. 5 shows the accumulated volume of distilled water. In the boiling-based system, the first drop was collected at 7:30 a.m., and distillation ended at 3:30 p.m., with a total volume of 2790 ml. In the non-boiling system, distillation began at 6:30 a.m. and ended at 5:00 p.m., yielding 1725 mL.

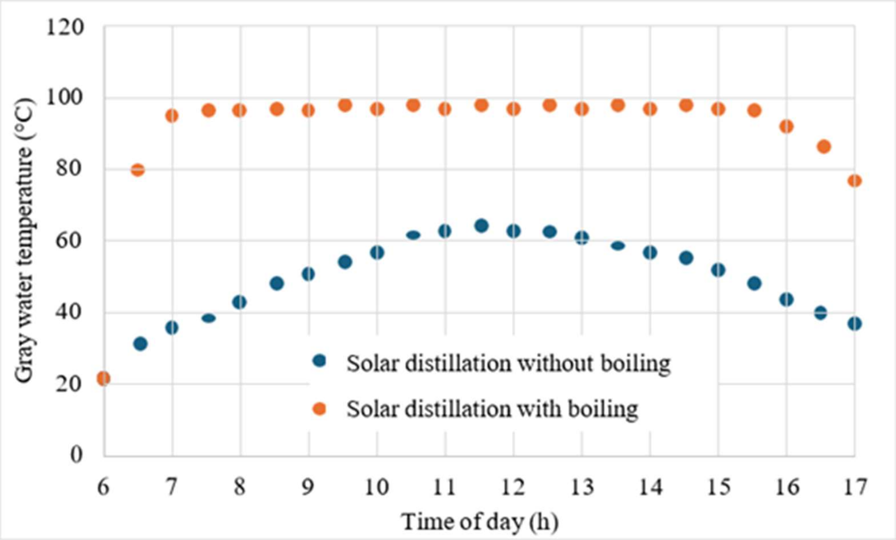

Fig. 4: Graywater temperatures during solar distillation with and without boiling.

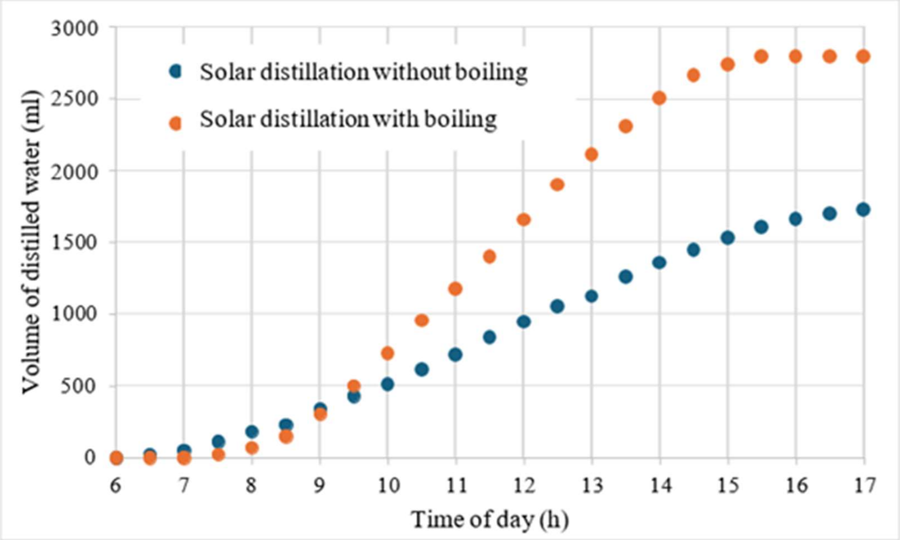

Fig. 5: Accumulated volume of distilled water during solar distillation with and without boiling.

Table 1: Tukey test ($\alpha = 0.05$) for the volume and physicochemical parameters of distilled water obtained from 5 l of graywater in two solar stills for 11 h on sunny days.

Parameter	Graywater	Non-boiling distillation	Boiling-based distillation
Distillate volume [mL]	-	1725.00^{b}	2790.00^{a}
pH	6.54^{a}	6.238^{b}	6.24^{b}
Turbidity (NTU)	501.30^{a}	2.60^{c}	21.10^{b}
Electrical conductivity[$\mu S\ cm^{-1}$]	2560.00^{a}	37.30^{c}	119.80^{b}

^{abc} Different superscript letters indicate significant differences.

Table 2: Physicochemical parameters and removal efficiencies.

Parameter	Graywater	Non-boiling distillation		Boiling-based distillation	
		Distilledwater	Removal[%]	Distilledwater	Removal[%]
Nitrates [mg L^{-1}]	26.69	0.34	98.72	10.25	61.59
Nitrites [mg L^{-1}]	2.21	< 2	90.49	< 2	90.49
Sulfates [mg L^{-1}]	107.52	< 5	95.34	< 5	95.34
COD [mg L^{-1}]	1936.63	< 100	94.83	< 100	94.83
BOD_5 [ppm]	1600.20	< 100	93.75	< 100	93.75

Table 3: Total metal concentrations and removal efficiencies.

Parameter	Graywater	Non-boiling distillation		Boiling-based distillation	
		Distilled water	Removal [%]	Distilled water	Removal [%]
Aluminum [mg L^{-1}]	1.46	0.53	63.65	0.28	80.63
Arsenic [mg L^{-1}]	0.06	0.05	22.38	0.05	22.38
Boron [mg L^{-1}]	1.41	0.06	95.63	0.05	96.26
Barium [mg L^{-1}]	0.03	0.01	54.28	0.01	60.00
Calcium [mg L^{-1}]	68.95	1.46	97.87	1.63	97.62
Cobalt [mg L^{-1}]	0.01	0.00	100.00	0.00	40.00
Chromium [mg L^{-1}]	0.07	0.03	62.02	0.02	67.08
Iron [mg L^{-1}]	3.69	0.15	95.83	0.15	95.91
Potassium [mg L^{-1}]	17.14	0.75	95.59	0.70	95.91
Lithium [mg L^{-1}]	0.14	0.07	47.65	0.03	79.19
Magnesium [mg L^{-1}]	19.09	0.31	98.36	0.40	97.85
Manganese [mg L^{-1}]	0.09	0.01	86.31	0.01	87.36
Molybdenum [mg L^{-1}]	0.06	0.05	12.30	0.04	27.69
Sodium [mg L^{-1}]	330.10	2.77	99.16	2.66	99.1
Nickel [mg L^{-1}]	0.01	0.00	100.00	0.00	100.00
Phosphorus [mg L^{-1}]	1.36	0.01	98.90	0.00	100.00
Selenium [mg L^{-1}]	0.01	0.01	0.00	0.01	13.33
Tin [mg L^{-1}]	0.05	0.04	17.24	0.00	100.00
Strontium [mg L^{-1}]	0.37	0.00	100.00	0.00	100.00
Titanium [mg L^{-1}]	0.13	0.00	100.00	0.00	100.00
Zinc [mg L^{-1}]	0.80	0.06	52.26	0.02	96.62

Volume and Analysis of Distilled Water

Both distillation systems operated for 11 h. However, the boiling-based system yielded a significantly higher volume of distilled water ($\alpha = 0.05$). While both processes ran for the same duration, their efficiency differed. The non-boiling process achieved greater removal efficiencies: The non-boiling process achieved greater removal efficiencies in turbidity (99.48% vs. 95.79%) and electrical conductivity (98.54% vs. 95.32%) (Table 1).

Table 2 presents the physicochemical analysis and removal efficiencies. Nitrate removal ranged from 61.59% to 98.72%, with the non-boiling method showing greater nitrate removal. Removal of nitrites (90.49%), sulfates (95.34%), COD (94.83%), and BOD_5 (93.75%) was similar for both methods.

Table 3 shows total metal concentrations and removal efficiencies. The initial graywater sample contained 445.03 mg L^{-1} of total metals. Removal was 98.63% (6.06 mg L^{-1}) in the boiling system and 98.56% (6.37 mg L^{-1}) in the non-boiling system. While both methods effectively removed metals, the boiling-based system required higher solar irradiance, whereas the non-boiling system performed consistently even under cloud cover.

Table 4 presents the microbiological results. Both distillation methods achieved similar reductions: fecal coliforms by 99.76%, heterotrophic bacteria by 99.99%, and *E. coli* by 98.04%.

DISCUSSION

Temperatures in the Two Solar Distillation Processes

In the boiling system, water reached maximum temperatures between 96.3 and 97°C, whereas in the non-boiling system the maximum range was 37 to 64°C (Fig. 4). These differences are attributed to the capacity of the CK-002 parabolic solar cooker to concentrate solar energy at a focal point, increasing the internal temperature of the copper still coated with black paint, which enhances thermal absorption due to its low reflectance (3–4%) (Manchado 2010) and high thermal conductivity (Otiniano et al. 2013). This behavior is consistent with Chaparro (2016), who reported a rapid temperature increase in parabolic systems with dark surfaces, and contrasts with the gradual heating observed in single-slope solar stills (Rodriguez 2021).

The rapid attainment of boiling temperature in the parabolic system (7:30 a.m., irradiance 931.16 $W.m^{-2}$) contrasts with the earlier onset of distillate production in the non-boiling system (6:30 a.m., irradiance 647.76 $W.m^{-2}$). This indicates that the non-boiling configuration initiates condensation at lower thermal input. The literature indicates that irradiance and exposure time are critical determinants in initiating and sustaining the evaporation process (Salinas-Freire et al. 2019, Fernández & Gentili 2021). Likewise, seasonality plays a critical role: in Tacna, the highest irradiance values are recorded in spring and summer (Rodriguez 2021), which explains the maintenance of temperatures near boiling for several h in this study.

Seasonality also plays a critical role: In the boiling system, the higher temperature promotes pathogen removal through prolonged thermal inactivation (Rougier et al. 2021), whereas in the non-boiling system, the main mechanism is physical separation by evaporation–condensation, dependent on lower thermal gradients.

Volume and Analysis of Distilled Water

The distillate yield was significantly higher ($p < 0.05$) in the boiling system (55.8%, 2,790 mL) compared to the non-boiling system (34.5%, 1,725 mL) (Fig. 5). This result is explained by the higher evaporation rate associated with temperatures close to 100 °C and the high heat transfer in the copper still exposed to concentrated radiation (Chaparro 2015). The hourly production was 167.68 mL h^{-1} with boiling and 156.82 mL h^{-1} without boiling, values similar to those reported by Rodriguez (2021) for seawater distillation using a single-slope still (167.58 mL h^{-1}), but lower than those of Bustinza (2020) in larger-scale systems (452 L day^{-1}), a difference attributable to variations in design, capture area, and irradiance conditions (Sanchez & Yagkug 2020, Cordova et al. 2021). Both systems, by using solar thermal energy, do not generate carbon dioxide emissions (Halvorsen & Skogestad 2011). Efficiency could be improved by integrating flat-plate solar collectors (Wei et al. 2021).

In the physicochemical analysis, the pH of the recovered water in both systems ranged from 6.23 to 6.24, with no significant differences ($p < 0.05$) (Table 1), which is attributed to atmospheric CO_2 absorption and the formation of carbonic acid in the distilled water, a phenomenon reported by Flores (2015), Rojas (2018), and Yusof et al. (2022).

The initial turbidity of graywater (501.3 NTU) was significantly reduced after solar distillation, with values between 2.6 and 21.1 NTU (removal from 99.48% to 95.79%), results consistent with Yusof et al. (2022), who reported reductions from 79.1 NTU to 2–2.6 NTU. The electrical conductivity of the distillate ranged from 37.30

Table 4: Microbiological analysis of graywater, distilled water, and removal.

Parameter	Graywater	Non-boiling solardistillation		Boiling-based distillation	
		Distilledwater	Removal[%]	Distilledwater	Removal[%]
Fecal coliform [MPN 100 mL^{-1}]	75x10	< 1.8	99.76	< 1.8	99.76
Heterotrophic bacteria[CFU mL^{-1} at 35°C]	$47x10^5$	< 10	99.99	< 10	99.99
E. coli [MPN 100 mL^{-1} at 44.5°C]	92	< 1.8	98.04	< 1.8	98.04

to 119.80 μS cm^{-1} (removal from 98.54% to 95.32%), also differing significantly, indicating lower dissolved salt concentrations. These results are close to those obtained by Yusof et al. (2022) (41.2–48.3 μS cm^{-1}) and Mendez (2021) (60.984 μS cm^{-1} in distilled seawater). However, they exceed the 5–10 μS cm^{-1} range reported by Rodríguez-Mambuca et al. (2013), which could be due to bubbling and agitation in the boiling system carrying microdroplets or volatile salts into the condensate, increasing dissolved solids (Wei et al. 2021).

Nitrate concentrations ranged from 0.34 to 10.34 mg L^{-1} (Table 2). In the boiling system, the value was similar to that of Yusof et al. (2022) (0.9–1.1 mg L^{-1}). The greater efficiency of the non-boiling system in this parameter could be due to a milder thermal regime, which may limit volatilization of intermediate nitrogen species, preventing their reintroduction into the condensate, whereas in boiling conditions, volatile/semi-volatile species or aerosols may be carried over.

Nitrite content decreased from 2.21 mg L^{-1} in graywater to 2 mg L^{-1} in both treatments, above the range of 0.03–0.04 mg L^{-1} reported by Yusof et al. (2022). Sulfates decreased significantly ($p < 0.05$) from 107.52 mg L^{-1} to 5 mg L^{-1} in both systems, representing a 95.34% removal, consistent with the value of 7 mg L^{-1} and 97.2% efficiency reported by Bustinza (2020).

Regarding organic matter, the initial COD and BOD_5 values (1,936.63 mg L^{-1} and 1,600.2 mg L^{-1}, respectively) were reduced by 94.84% and 93.75% in both systems, reaching concentrations below 100 mg L^{-1}. These results are higher than those obtained by Rojas (2018) in his hydraulic system (COD: 42 mg L^{-1}, BOD_5: 30 mg L^{-1}), although still above those reported by Yusof et al. (2022) (COD: 8–9.2 mg L^{-1}, BOD_5: 0.2–0.5 mg L^{-1}). The difference may be due to the initial organic load; likewise, this persistence is explained by the fact that a large proportion of dissolved organic matter in graywater corresponds to surfactants, detergents, and low-volatility compounds that do not enter the vapor phase and are therefore not removed by simple phase change. In the boiling system, microdroplet carryover can reintroduce organic fractions into the condensate, increasing residual COD. Differences with studies reporting much lower COD/BOD_5 after distillation can be attributed to still design, influent quality (initial surfactant load), and operational conditions (capture area, thermal regime). Intermediate values obtained with other hydraulic treatments (Rojas 2018) support the conclusion that distillation alone does not ensure regulatory compliance for biodegradable organics, and post-treatments are therefore required.

Total metal removal was high in both systems (> 98.5%) (Table 3), consistent with Tleimat et al. (1992) (≈ 99%) for vapor-compression distillation. This supports the effectiveness of phase-change separation for metal removal, although residual traces may persist due to fine droplet entrainment in the vapor, as variability in individual removal efficiency was observed. Elements such as Na, Ca, Mg, Fe, and K showed removal rates above 95%, whereas As, Se, and Mo had efficiencies below 30% in some cases. This may be explained by the formation of more volatile or soluble chemical species at distillation temperatures, such as hydrides or organometallic compounds, which can pass through the condensation system (Krishnan et al. 2008).

Microbiological analysis (Table 4) showed that in both systems, fecal coliform concentrations were below 1.8 MPN 100 mL^{-1}, meeting DIGESA (2010) limits. Yusof et al. (2022) reported values of 2–3 CFU 100 mL^{-1} in their study, and Flores (2015) reported total absence of microorganisms. Heterotrophic bacteria counts were reduced to below 10 CFU mL^{-1} at 35°C, far below the limit of 500 CFU 100 mL^{-1} established by the Environmental Health Directorate (DIGESA, 2010). E. coli counts were also below 1.8 MPN 100 mL^{-1}, meeting regulatory standards. Microbiological inactivation in the boiling system is primarily due to sustained exposure to temperatures near 100°C, whereas in the non-boiling system, the probable mechanism is physical separation of microorganisms during evaporation and subsequent condensation, a process that prevents the transfer of intact cells into the distillate (Yusof et al. 2022, Flores, 2015). The data confirm that while a boiling system produces a higher volume of distillate, a non-boiling system shows greater efficiency in the removal of turbidity, conductivity, and nitrates. Both achieved microbiological and total metal reductions above 98%, although certain parameters (COD, BOD_5) do not meet the reference values for direct reuse established by Supreme Decree No. 004-2017-MINAM (Ministry of the Environment [MINAM], 2017), indicating the need for post-treatment.

CONCLUSIONS

The treatment of urban graywater through solar distillation constitutes an environmentally sustainable alternative, utilizing renewable energy and producing no greenhouse gas emissions. Both systems evaluated, with and without boiling, proved technically viable for obtaining distilled water from 5 L of graywater, achieving yields of 55.8% in the boiling system and 34.5% in the non-boiling system. The maximum temperature recorded in the solar still with boiling (CK-002 parabolic solar cooker), 97°C, was considerably higher than that obtained in the single-slope non-boiling still (64°C), which explains its greater volumetric yield.

In terms of quality, the distilled water from both systems exhibited comparable physicochemical and microbiological characteristics. The Environmental Quality Standards (EQS) were met for microbiological parameters, including fecal coliforms (MPN 100 mL^{-1}), heterotrophic bacteria (CFU.mL^{-1} at 35°C), and E. coli (MPN 100 mL^{-1} at 44.5°C), as well as for most of the physicochemical parameters required for irrigation water, except for chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5). The total metal removal efficiency was high in both cases, ranging from 98.56% (boiling) to 98.63% (non-boiling).

These results demonstrate that solar distillation, both with and without boiling, is an efficient option that can be considered as an alternative graywater treatment technology, applicable and improvable to contribute to the sustainable management of water resources.

RECOMMENDATIONS

It is recommended to implement post-treatment processes for distilled water obtained through solar distillation of graywater, in order to make it suitable for human consumption and for irrigating horticultural crops in domestic gardens. Suggested options include physicochemical treatments with coagulant–flocculants (conventional or organic), activated carbon adsorption, or other complementary methods that can reduce COD and BOD_5 to levels compatible with quality standards for potable and agricultural use.

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