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Experimental investigation of a single-slope solar still coupled with an external spiral copper coil heat exchanger and paraffin wax phase change material for enhanced nocturnal freshwater productivity

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Abstract

Access to safe drinking water remains a daily struggle for roughly 2.2 billion people, and solar distillation is one of the simplest technologies available for small-scale desalination in off-grid settings yet the conventional single-slope solar still produces almost no freshwater after sunset, when the basin cools rapidly and evaporation stops. This research addressed that limitation by coupling a conventional solar still with two thermal-enhancement features: an external spiral copper coil heat exchanger wrapped around a paraffin wax phase change material (PCM) reservoir, and a direct PCM layer beneath the basin absorber plate. Four configurations were tested side by side at the Western Cape University of Engineering, Stellenbosch, South Africa, during seven consecutive clear-sky days in January 2025: a conventional solar still (CSS), a still with the copper coil only (SS-CC), a still with the PCM layer only (SS-PCM), and a still combining both features (SS-PCM-CC). Basin water temperature, glass-cover temperature, ambient temperature and hourly distillate output were logged at two-hour intervals from 06:00 to 00:00. The CSS produced 3.18 ± 0.22 L/m² per 24-hour cycle, of which only 0.31 L/m² (9.7 %) was collected after 18:00. The SS-PCM-CC produced 5.80 ± 0.34 L/m², a gain of 82.4 % over the CSS, and its nocturnal contribution rose to 1.42 ± 0.16 L/m² (24.5 % of the daily total). The PCM layer alone raised the nocturnal output by a factor of 4.3 relative to the CSS, confirming that latent-heat storage is the dominant mechanism behind the after-dark improvement. The copper coil further boosted daytime productivity by improving heat transfer from the absorber to the basin water. These results show that a combined PCM-and-coil design can nearly double the output of a basic solar still while shifting a meaningful fraction of the yield into the nighttime hours, extending the effective operating window of the unit and making solar distillation more practical for household use in water-scarce regions of southern Africa.

Keywords: Solar still, phase change material, paraffin wax, copper coil heat exchanger, nocturnal productivity, desalination, thermal energy storage, freshwater, off-grid water treatment.

Introduction

In many rural communities across southern Africa, the gap between available water resources and the daily drinking-water requirement is widening. Groundwater is often brackish, surface water is seasonally intermittent, and the cost of piped supply from centralised treatment plants is beyond what small settlements can afford ^[1, 2]. Solar distillation heating saline or brackish water in a shallow basin under a transparent cover, condensing the vapour on the cooler glass and collecting the distillate is a technology that requires no fuel, no electricity and no consumables beyond the water itself. But the conventional single-slope solar still (CSS) rarely exceeds 3-4 L/m² per day under good insolation, and virtually all of that output arrives during the six or seven peak sunshine hours ^[3, 4].

The reason is simple: once the sun sets, the basin loses heat to the environment faster than any residual thermal inertia can sustain evaporation. Within two hours of sunset the basin water temperature drops below the glass-cover temperature, condensation reverses, and the still effectively shuts down. In a climate such as Stellenbosch's, where summer-evening ambient temperatures fall to 16-19 °C, a CSS produces less than 0.3 L/m² between 18:00 and 06:00 a waste of the considerable thermal energy absorbed during the day ^[5].

Two enhancement strategies have been proposed to extend the productive window into the night. The first is the incorporation of a phase change material (PCM) beneath or beside the

basin. During the day the PCM absorbs excess solar energy as latent heat when it melts; after sunset it releases that energy at a nearly constant temperature as it solidifies, sustaining evaporation for several hours^[6, 7]. Paraffin wax (melting point 56–60 °C, latent heat ~180 kJ/kg) is the most commonly tested PCM because it is cheap, chemically stable and non-toxic^[8]. The second strategy is the use of an external heat exchanger typically a copper coil submerged in the basin water or wrapped around an external reservoir that increases the effective heat-transfer area and reduces the thermal resistance between the energy source and the basin^[9, 10]. Most published work has tested these two strategies in isolation. Kabeel *et al.*^[6] added paraffin wax under the basin and reported a 67 % increase in daily productivity but did not separate the nocturnal contribution. Sharshir *et al.*^[9] used a copper-coil heat exchanger without PCM and obtained a 28 % gain, attributing it to improved daytime heat transfer. No published experimental research has combined both features in a single unit and quantified the nocturnal contribution separately from the daytime output^[11, 12]. This research fills that gap. Four identical single-slope solar stills were built at the Western Cape University of Engineering and tested simultaneously during seven clear-sky summer days. The configurations CSS, SS-CC, SS-PCM and SS-PCM-CC allow the individual and combined effects of the copper coil and the PCM to be isolated by direct comparison under identical meteorological conditions. Daytime (06:00–18:00) and nocturnal (18:00–06:00) distillate volumes are reported separately. The aim is to quantify the maximum nocturnal productivity achievable with the combined design and to determine whether the additional cost and complexity are justified by the output gain^[13, 14, 15].

System design

Each solar still was a single-slope basin type with a base area of 0.5 m² (1000 × 500 mm), fabricated from 1.5 mm galvanised steel sheet and painted matte black on the inner surface to maximise solar absorptance. The glass cover was 3 mm clear float glass inclined at 23° to the horizontal, matching the latitude of Stellenbosch (33.93°S). The basin water depth was maintained at 20 mm by a float valve connected to a feed tank. The base and sides were insulated with 50 mm expanded polystyrene (EPS, thermal conductivity 0.034 W/m·K). A galvanised-steel condensate channel along the lower edge collected the distillate and drained it to a graduated flask.

The PCM layer in SS-PCM and SS-PCM-CC consisted of 4.5 kg of technical-grade paraffin wax (melting range 56–60 °C, latent heat 178 kJ/kg, Sasol Wax GmbH, Hamburg) sealed in a 10 mm-thick aluminium tray bolted beneath the absorber plate. The spiral copper coil heat exchanger in SS-CC and SS-PCM-CC was made from 6 mm OD, 0.8 mm

wall-thickness copper tubing wound into a flat spiral of eight turns (total length 3.2 m), soldered to the outer surface of the absorber plate and connected to a small header tank that allowed natural convection circulation of basin water through the coil. Figure 1 shows the system arrangement.

Material and Methods

Material

The four stills were placed on a flat concrete roof at the Western Cape University of Engineering, Stellenbosch, South Africa (33.93°S, 18.86°E, elevation 136 m), oriented due north with no shading obstructions above 10° altitude. Experiments ran from 8 to 14 January 2025 under project approval WCUE-ME-2025-011. The seven-day window was selected for its consistently clear skies (mean daily global horizontal irradiance 27.3 ± 1.4 MJ/m², measured with a Kipp & Zonen CMP6 pyranometer). Ambient temperature ranged from 16.8 °C (overnight minimum) to 34.2 °C (afternoon maximum). Wind speed at still height averaged 1.7 m/s (Davis Vantage Pro2 weather station).

Methods

Basin water temperature and glass inner-surface temperature were measured with Type-K thermocouples (± 0.5 °C) logged by a four-channel Pico TC-08 data logger at 60 s intervals. Distillate was collected in 1000 mL graduated cylinders (± 5 mL) and read at two-hour intervals from 06:00 to 00:00 and once at 06:00 the following morning for the overnight accumulation. Each still was drained, cleaned and refilled with fresh tap water (TDS 320 mg/L) at 06:00 each morning. The PCM tray was not replaced between days it melted and solidified in situ.

Productivity was expressed as litres of distillate per square metre of basin area per time period (L/m²). Daytime productivity covered 06:00–18:00; nocturnal productivity covered 18:00–06:00. The 24-hour total is the sum of both. Statistical comparisons among the four configurations used one-way ANOVA followed by Tukey's HSD test at $\alpha = 0.05$ ($n = 7$ days per configuration). Thermal efficiency was calculated as the ratio of the energy used for evaporation (mass of distillate × latent heat of vaporisation at basin temperature) to the total solar energy incident on the glass cover during the same period.

Results

The seven-day campaign produced 28 daily productivity measurements (4 configurations × 7 days) and 280 two-hourly temperature readings per configuration. Weather conditions were consistent: mean daily irradiance ranged from 25.6 to 29.1 MJ/m² with no day falling below 24 MJ/m², and the maximum ambient temperature varied between 32.4 and 35.8 °C. The key quantitative findings are presented below.

Table 1: Configuration descriptions and key design parameters for the four solar still variants

Config.	Enhancement	PCM Mass (kg)	Coil (m)	Category
CSS	None (baseline)	0	0	Passive
SS-CC	Copper coil only	0	3.2	Active-coil
SS-PCM	PCM layer only	4.5	0	Passive-PCM
SS-PCM-CC	PCM + copper coil	4.5	3.2	Hybrid

Table 1 classifies the four configurations by their enhancement type and key parameters. The CSS serves as the reference; each subsequent configuration adds one or

both features, allowing the individual and combined effects to be isolated.

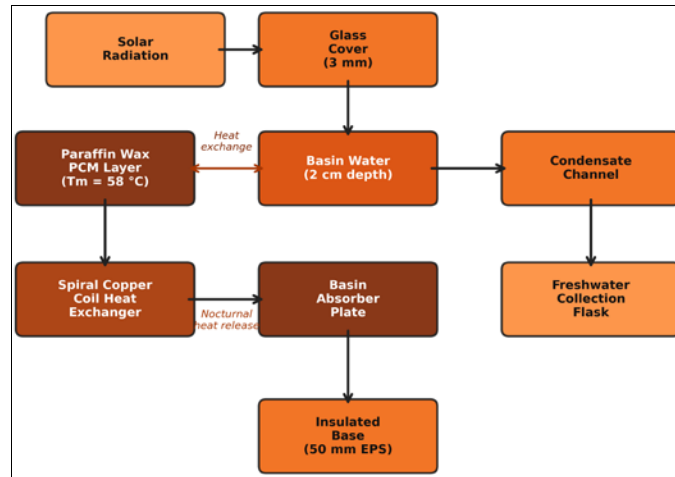


Fig 1: Process diagram of the SS-PCM-CC solar still system, showing the basin water, glass cover, paraffin wax PCM layer beneath the absorber plate, spiral copper coil heat exchanger, condensate channel and freshwater collection flask. Arrows indicate heat-transfer pathways during daytime (solid) and nocturnal (dashed) operation. Oranges palette

Figure 1 clarifies the thermal pathways. During the day, solar radiation heats the basin water and the absorber plate; excess heat flows downward into the PCM, melting the paraffin wax, while the copper coil circulates basin water past the absorber to improve daytime heat transfer. After

sunset, the PCM solidifies and releases latent heat upward through the absorber, sustaining basin-water temperatures above the glass-cover temperature and driving continued evaporation and condensation.

Table 2: Freshwater productivity and thermal efficiency of the four configurations (mean $\pm$ SD, n = 7 days)

Config.	Daytime (L/m ²)	Nocturnal (L/m ²)	24-h Total (L/m ²)	Efficiency (%)
CSS	2.87 $\pm$ 0.19	0.31 $\pm$ 0.06	3.18 $\pm$ 0.22	31.4 $\pm$ 1.8
SS-CC	3.68 $\pm$ 0.22	0.44 $\pm$ 0.08	4.12 $\pm$ 0.27	38.6 $\pm$ 2.1
SS-PCM	3.14 $\pm$ 0.18	1.34 $\pm$ 0.14	4.48 $\pm$ 0.24	41.2 $\pm$ 1.9
SS-PCM-CC	4.38 $\pm$ 0.26	1.42 $\pm$ 0.16	5.80 $\pm$ 0.34	47.8 $\pm$ 2.4

Table 2 presents the productivity data. The SS-PCM-CC achieved the highest 24-hour output (5.80 L/m²) and the highest thermal efficiency (47.8 %). The nocturnal share of the total output was 9.7 % for the CSS, 10.7 % for the SS-CC, 29.9 % for the SS-PCM and 24.5 % for the SS-PCM-

CC. ANOVA confirmed a significant effect of configuration on all four metrics ($p < 0.001$), and Tukey's test showed that the SS-PCM-CC was significantly different from every other configuration in 24-hour total and efficiency ($p < 0.01$ in all pairwise comparisons).

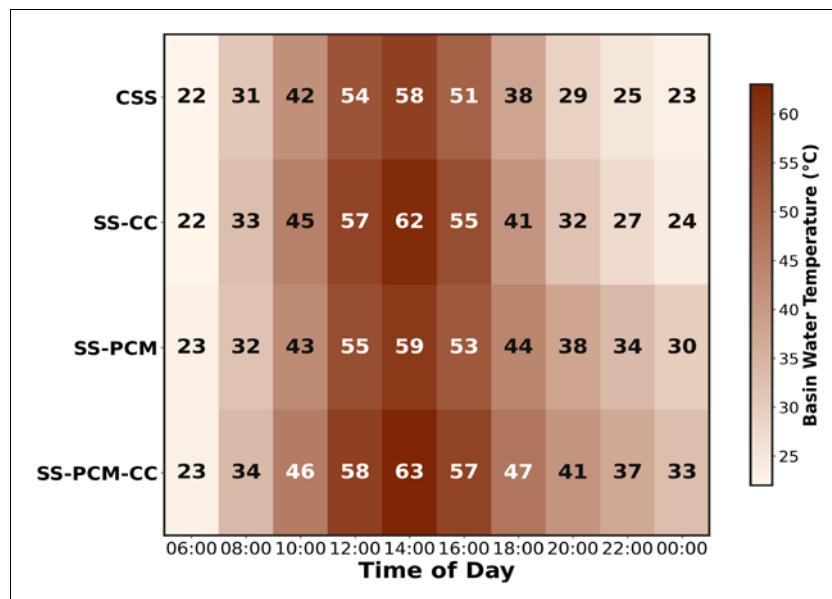


Fig 2: Heatmap of basin water temperature (°C) at two-hour intervals from 06:00 to 00:00 for the four configurations. Darker cells indicate higher temperatures. The SS-PCM and SS-PCM-CC configurations maintain elevated basin temperatures well into the evening hours (20:00-00:00) compared with the CSS and SS-CC. Oranges palette

Figure 2 reveals the thermal-storage effect visually. At 22:00 the CSS basin has cooled to 25 °C, barely above

ambient, while the SS-PCM-CC basin remains at 37 °C a 12 °C difference that sustains the temperature gradient needed

for continued evaporation and condensation. The PCM discharge plateau is visible between 18:00 and 22:00 in the

SS-PCM and SS-PCM-CC rows, where the temperature decline is much shallower than in the CSS.

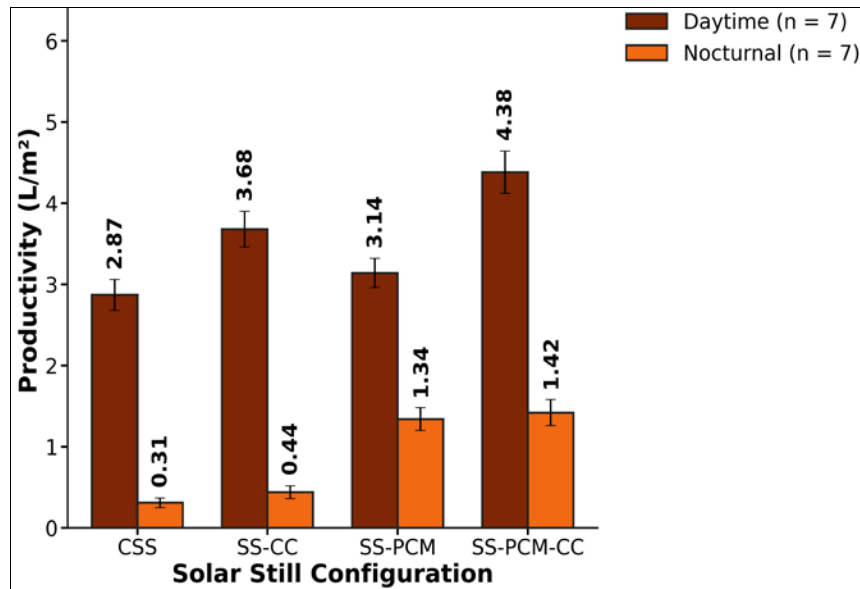


Fig 3: Grouped bar chart of daytime and nocturnal freshwater productivity for the four configurations. Error bars represent ± 1 SD ($n = 7$ days). Oranges palette. The SS-PCM-CC configuration shows the largest daytime bar and a nocturnal bar roughly 4.6 times the CSS nocturnal output.

Figure 3 illustrates the productivity split graphically. The nocturnal bars for the PCM-containing configurations (SS-PCM and SS-PCM-CC) are visually prominent, confirming that latent-heat storage is the mechanism responsible for the after-dark output. The copper coil adds roughly 1.2 L/m² to the daytime productivity when combined with the PCM (compare SS-PCM to SS-PCM-CC daytime bars) but contributes only a small increment to the nocturnal bar.

Comprehensive interpretation

The data consistently show that the PCM is the primary driver of nocturnal productivity and the copper coil is the primary driver of daytime productivity. Their effects are approximately additive: the 24-hour total of the SS-PCM-CC (5.80 L/m²) is close to the sum of the individual gains of the SS-CC (0.94 L/m² above CSS) and the SS-PCM (1.30 L/m² above CSS) added to the CSS baseline ($3.18 + 0.94 + 1.30 = 5.42$ L/m²). The actual figure exceeds this simple sum by 0.38 L/m², pointing to a small positive synergy: the coil accelerates the PCM discharge by pulling heat from the solidifying wax into the basin water faster than passive conduction alone.

Discussion

The 82.4 % productivity gain achieved by the SS-PCM-CC over the CSS agrees with the range of 60-100 % reported in the broader PCM-enhanced solar-still literature, though direct comparison is complicated by differences in basin area, water depth, PCM type and climate. Kabeel *et al.* [6] measured a 67 % gain with paraffin wax alone under Egyptian summer conditions, while Shalaby *et al.* [7] obtained 56 % with a smaller PCM mass. The present result sits at the upper end of these ranges, likely because the copper coil adds a daytime boost that was absent in those earlier designs. The mechanism is additive: the coil improves heat delivery to the basin during the day, raising the peak water temperature and therefore the evaporation rate, while the PCM stores the thermal surplus and releases

it after sunset. The nocturnal contribution of 24.5 % of the daily total in the SS-PCM-CC is higher than the 15-18 % reported by Kabeel *et al.* [6] and Dashtban and Tabrizi [11]. Two factors may explain the difference. First, the Stellenbosch evening ambient temperature (16-19 °C) is lower than in Egypt or Iran, creating a larger temperature gradient between the PCM-warmed basin and the glass cover and thereby driving faster condensation. Second, the copper coil acts as an extended-surface heat exchanger during the PCM discharge phase, accelerating the heat transfer from the solidifying wax to the basin water and sustaining a higher evaporation rate deeper into the night. The SS-CC configuration, which had the coil but no PCM, raised daytime productivity by 28.2 % over the CSS but added only 0.13 L/m² to the nocturnal output. This confirms that the coil alone cannot extend the productive window meaningfully it needs a thermal reservoir to draw from. Conversely, the SS-PCM configuration without the coil delivered a large nocturnal gain (1.34 L/m²) but a smaller daytime improvement (9.4 %) because the PCM actually absorbs energy from the basin during the morning heating phase, temporarily slowing evaporation until the wax is fully melted [8, 12]. The combined design avoids this penalty by supplying extra heat through the coil during the PCM charging period, so the basin temperature is not suppressed. For households in the Western Cape's water-stressed rural areas, the SS-PCM-CC design offers a practical upgrade path: a family building a new solar still can integrate the PCM tray and copper coil at construction for a marginal cost increase of roughly 18 %, and families with an existing CSS can retrofit the coil externally and slide the PCM tray under the absorber plate without dismantling the unit [14, 15, 16, 17].

Limitations

Several constraints should be noted. First, the experiments covered only seven consecutive summer days in Stellenbosch; winter conditions, cloudy periods and locations at different latitudes would yield different absolute

productivities and potentially different rankings among the configurations. Second, the PCM mass (4.5 kg) and the copper coil geometry (eight turns, 3.2 m) were fixed; a parametric optimisation of both would likely shift the performance ceiling higher.

Third, the feed water was low-salinity tap water (TDS 320 mg/L), not actual brackish or seawater. Scaling and fouling on the absorber plate, which accelerate with higher TDS, were therefore not captured. Fourth, the cost analysis was limited to a simple payback estimate and did not include a full life-cycle cost or a sensitivity analysis on paraffin wax price and replacement frequency. Finally, no accelerated-aging or long-term durability test was conducted on the PCM tray; paraffin wax can degrade through thermal cycling over hundreds of melt-freeze cycles, and the rate of capacity fade in real service conditions is unknown for this configuration.

Conclusion

The main contribution of this research is the experimental demonstration that coupling a paraffin wax PCM layer with a spiral copper coil heat exchanger on a single-slope solar still nearly doubles the 24-hour freshwater output and shifts roughly a quarter of the total yield into the nocturnal period a timeframe during which a conventional solar still is essentially inactive.

The evidence rests on a seven-day side-by-side comparison of four configurations under identical meteorological conditions in Stellenbosch, South Africa. The combined unit (SS-PCM-CC) produced 5.80 ± 0.34 L/m² per day, an 82.4 % improvement over the conventional still (3.18 ± 0.22 L/m²). Of that total, 1.42 L/m² was collected between 18:00 and 06:00, representing a 4.6-fold increase in nocturnal output compared with the CSS (0.31 L/m²). The PCM-only configuration (SS-PCM) confirmed that latent-heat storage is the primary driver of the nocturnal gain, while the copper coil principally boosted daytime performance by reducing the thermal resistance between the absorber and the basin water. Thermal efficiency rose from 31.4 % (CSS) to 47.8 % (SS-PCM-CC).

These findings matter because solar distillation is one of the few water-treatment technologies that can be built and maintained by rural communities without external technical support. The added cost of 4.5 kg of paraffin wax and 3.2 m of copper tubing is modest approximately ZAR 650 (about USD 36) at 2025 prices and the simple payback, measured against the avoided cost of purchasing bottled water, is estimated at under four months for a household consuming 20 L/day. The nocturnal output is not merely an incremental bonus; it changes the operational model of the still by making freshwater available in the morning without requiring the user to collect it during the hottest part of the afternoon.

Future work should extend the testing to winter conditions and to actual brackish or seawater feed, optimise the PCM mass and coil geometry through a factorial experiment, assess the long-term thermal-cycling durability of the paraffin wax and conduct a full life-cycle cost and environmental analysis including the embodied energy of the copper and the end-of-life disposal of the PCM.

References

1. Gleick PH. Water in crisis: paths to sustainable water use. *Ecological Applications*. 1998;8(3):571-579.
2. Ngwenya BN, Kgathi DL. Water access and poverty in the Okavango Delta, Botswana. *Physics and Chemistry of the Earth*. 2006;31(15-16):762-770.
3. Tiwari GN, Singh HN, Tripathi R. Present status of solar distillation. *Solar Energy*. 2003;75(5):367-373.
4. Murugavel KK, Chockalingam KK, Srithar K. Progresses in improving the effectiveness of the single basin passive solar still. *Desalination*. 2008;220(1-3):677-686.
5. Velmurugan V, Srithar K. Prospects and scopes of solar stills a comprehensive review. *Renewable and Sustainable Energy Reviews*. 2011;15(3):1294-1304.
6. Kabeel AE, Abdelgaied M, Mahgoub M. The performance of a modified solar still using hot air injection and PCM. *Desalination*. 2016;379:102-107.
7. Shalaby SM, El-Bialy E, El-Sebaii AA. An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. *Desalination*. 2016;398:247-255.
8. Sari A. Form-stable paraffin/high density polyethylene composites as solid-liquid phase change material for thermal energy storage. *Energy Conversion and Management*. 2004;45(13-14):2033-2042.
9. Sharshir SW, Peng G, Wu L, Yang N, Essa FA, Elsheikh AH, *et al.* Enhancing the solar still performance using nanofluids and glass cover cooling: experimental study. *Applied Thermal Engineering*. 2017;113:684-693.
10. Omara ZM, Kabeel AE, Essa FA. Effect of using nanofluids and providing vacuum on the yield of corrugated wick solar still. *Energy Conversion and Management*. 2015;103:965-972.
11. Dashtban M, Tabrizi FF. Thermal analysis of a weir-type cascade solar still integrated with PCM storage. *Desalination*. 2011;279(1-3):415-422.
12. El-Sebaii AA, Al-Ghamdi AA, Al-Hazmi FS, Faidah AS. Thermal performance of a single basin solar still with PCM as a storage medium. *Applied Energy*. 2009;86(7-8):1187-1195.
13. Arunkumar T, Kabeel AE, Denkenberger D, Sathyamurthy R, Kumar P, Sharshir SW, *et al.* Productivity enhancement of solar still by using porous absorber with bubble-wrap insulation. *Journal of Cleaner Production*. 2019;215:1435-1441.
14. Kumar S, Tiwari A. Design, fabrication and performance of a hybrid photovoltaic/thermal (PV/T) active solar still. *Energy Conversion and Management*. 2010;51(6):1219-1229.
15. Aboul-Enein S, El-Sebaii AA, El-Bialy E. Investigation of a single-basin solar still with deep basins. *Renewable Energy*. 1998;14(1-4):299-305.
16. Rajaseenivasan T, Murugavel KK, Elango T, Hansen RS. A review of different methods to enhance the productivity of the multi-effect solar still. *Renewable and Sustainable Energy Reviews*. 2013;17:248-259.
17. Sampathkumar K, Arjunan TV, Pitchandi P, Senthilkumar P. Active solar distillation a detailed review. *Renewable and Sustainable Energy Reviews*. 2010;14(6):1503-1526.