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ARTICLE

Hybrid Life Cycle Assessment of a Nano-Enhanced Phase Change Material (NEPCM) Integrated Double-Effect Single-Slope Solar Still in Nigeria

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ABSTRACT: Increasing demand for freshwater and the need to reduce the carbon intensity of conventional desalination have accelerated interest in solar-driven distillation technologies. This study performs a cradle-to-grave Life-Cycle Assessment (LCA) of a nano-enhanced, double-effect single-slope Solar Still fabricated in Nigeria to quantify its embodied environmental impacts and identify material-level hotspots. Modeling was conducted in openLCA v2.4.1 using the Australian Life-Cycle Inventory (2019) database as a proxy. The functional unit was defined as the production of 1 m^3 of freshwater distillate over a ten-year operational lifetime. From the analysis, the total Global Warming Potential (GWP_{100}) of the fabricated Solar Still was 337.3 kg CO_2-eq, which corresponds to a normalized carbon intensity of 25.21 kg CO_2-eq m^{-3} for a lifetime yield of 13.38 m^3. Contribution analysis revealed that Al_2O_3 nanoparticles (31.5%), paraffin wax PCM (22%), and galvanized steel (19%) and glass (13%) together account for more than 85% of total embodied emissions, confirming that the Solar-Still's footprint is materials-dominated. When benchmarked against conventional desalination, the system's carbon intensity lies above reverse osmosis but within the upper range of multi-stage flash distillation, with the advantage of zero operational emissions. Sensitivity analyses were performed to examine the influence of nano-enhanced PCM content, alumina concentration, and system lifespan on overall impacts. The novelty of this study lies in the hybrid-LCI approach adopted to provide a replicable framework for evaluating nanomaterial-enhanced renewable-energy systems in emerging regions. Key opportunities for improvement through bio-based or recyclable PCMs, low-impact nanomaterial synthesis, and design optimization to enhance productivity and material circularity were also highlighted in the study.

KEYWORDS: Life cycle assessment; solar still; nano-enhanced PCM; embodied carbon; global warming potential; sustainable desalination; IMPACT World+

1 Introduction

Freshwater is an indispensable but finite resource. Although water covers about 71% of the Earth's surface [1], roughly 97% of the planet's waters are saline, leaving less than 3% as freshwater, most of which are locked in ice or deep aquifers [2,3]. Population growth, industrialization, and climate change are placing unprecedented pressure on these limited reserves. The per-capita freshwater availability in many arid and semi-arid regions, including large parts of Africa, continues to decline each year, threatening food security, economic productivity, and public health [4,5].

Desalination, the process of converting saline water into potable freshwater, has therefore become an essential component of global water-supply strategies [6]. Commercial desalination is broadly classified according to its separation mechanism into thermal and membrane technologies [7,8]. Thermal desalination uses heat of evaporation to separate water and salt, and includes multi-stage flash (MSF) and multi-effect distillation (MED), while membrane processes, principally reverse osmosis (RO) and electrodialysis, rely on selective diffusion through semi-permeable membranes [9]. Modern desalination systems can produce water of high purity but are energy intensive. The electricity or steam that drives them is often fossil-based, resulting in carbon footprints ranging from 1.8–3.6 kg CO_2-eq m^{-3} for RO [10–12] to 9–25 kg CO_2-eq m^{-3} for MSF [13–16], depending on the energy mix. These operational emissions worsen global warming and increase operating costs.

In contrast, solar-driven desalination offers lower carbon-intensity pathway. Among its variants, the passive solar still is mechanically simple, requires no external energy supply, and is particularly suited to off-grid, rural settings with high solar irradiation such as Nigeria (5.5 kWh m^{-2} day^{-1}) [17]. Solar Stills harness solar energy to evaporate saline feedwater and condense freshwater on a cooled surface. Despite its environmental appeal, the technology suffers from low daily productivity, typically 3–6 L m^{-2} day^{-1} and a limited understanding of its embodied environmental burden [18]. To overcome low daily productivity due to the intermittency of solar radiation, thermal energy storage (TES) has emerged as a critical advancement in solar distillation. Latent Heat Storage (LHS) using Phase Change Materials (PCMs), such as paraffin wax, has shown to be particularly effective due to its high energy storage density and isothermal phase transition. However, conventional organic PCMs suffer from low thermal conductivity (~0.2 W m^{-1} K^{-1}), which retards the rate of heat charging and discharging, thereby limiting system efficiency.

Recent research has focused on overcoming this thermal bottleneck by dispersing high-conductivity nanoparticles (e.g., Al_2O_3, CuO, TiO_2) into the PCM matrix. These 'Nano-Enhanced PCMs' (NEPCMs) significantly improve thermal diffusivity, enabling faster energy transfer and higher daily yields. Studies, for example, [18–22] have reported increases in daily yield ranging from approximately 10% to over 120% when using PCMs and from 18% to 180% with the use of NEPCMs [19,23–25].

In particular, a study by Chaichan and Kazem [19] have shown that dispersing 3 wt.% Al_2O_3 into paraffin can increase water productivity by 60.53%. Dsilva Winfred Rufuss et al. [26] reported that TiO_2 and CuO nanoparticles improved productivity by 39.3% and 43.2%, respectively; this finding has also been discussed by other researchers [27]. Furthermore an 83.7% increase in productivity was achieved using graphene oxide [28]. These results highlight the pivotal role of nanoparticle integration in enhancing the nocturnal performance of solar stills.

Thus, while the operation of passive solar stills is emission-free and NEPCMs have shown promise in boosting daily distillate yield, the materials and fabrication of the Still, as well as the use of NEPCMs, may carry substantial hidden environmental impacts.

This study addresses this knowledge gap by:

i. Performing a cradle-to-grave Life-Cycle Assessment (LCA) of a locally fabricated double-effect, single-slope Solar Still equipped with Nano-Enhanced Phase Change Material (NEPCM) thermal storage.
ii. Quantifying the embodied carbon footprint (kg CO_2-eq per m^3 distillate) and related midpoint indicators such as energy use, ecotoxicity, and resource depletion.
iii. Identifying environmental hotspots within the Solar Still's material composition and life-cycle stages.
iv. Benchmarking environmental performance against conventional desalination technologies and identifying material or design pathways for impact reduction.

2 Methodology

2.1 Life-Cycle Assessment Framework

Life-Cycle Assessment (LCA) is a standardized method (ISO 14040/14044) for quantifying the environmental impacts of a product system from cradle-to-grave, encompassing resource extraction, manufacturing, use, and end-of-life. In this study, modeling was performed using openLCA v2.4.1 with the Australian Life-Cycle Inventory (OzLCI 2019) database as a proxy for Nigerian conditions, owing to the absence of a national LCI. Impact characterization employed IMPACT World+ v1.29 [29], which provides globally regionalized midpoint indicators including Global Warming Potential (GWP_{100}), energy-resource depletion, toxicity, and water-scarcity metrics. The functional unit (FU) for this system is set up as the delivery of 1 m^3 of purified distillate at the Still outlet. This specific FU provides a standardized metric, enabling a direct and meaningful comparison of the still's embodied impacts against other desalination and solar distillation technologies. A comprehensive cradle-to-grave methodology, assessing the complete life cycle of the Solar Still from raw material extraction through manufacturing, transportation, operational use, and end-of-life disposal was conducted. Sensitivity testing and data-quality transparency approaches emphasized in recent reviews of renewable-energy LCAs [30] were adopted here to ensure robustness.

In this study, we attempt to quantify the embodied carbon footprint and associated environmental impacts of a passive double-effect single-slope Solar Still, integrated with a nano-enhanced phase change material (NEPCM) for thermal energy storage as shown in Fig. 1. This Solar Still analysis is based on a full-scale double-effect, single-slope prototype previously fabricated and tested at the Federal University of Technology, Owerri, Nigeria (5.49°N, 7.02°E) (See Fig. 2). A detailed thermal and productivity analysis of this prototype when loaded with PCM (paraffin wax) was reported in [31] while its thermal and productivity analysis without PCM (Base Case) can be found in [32].

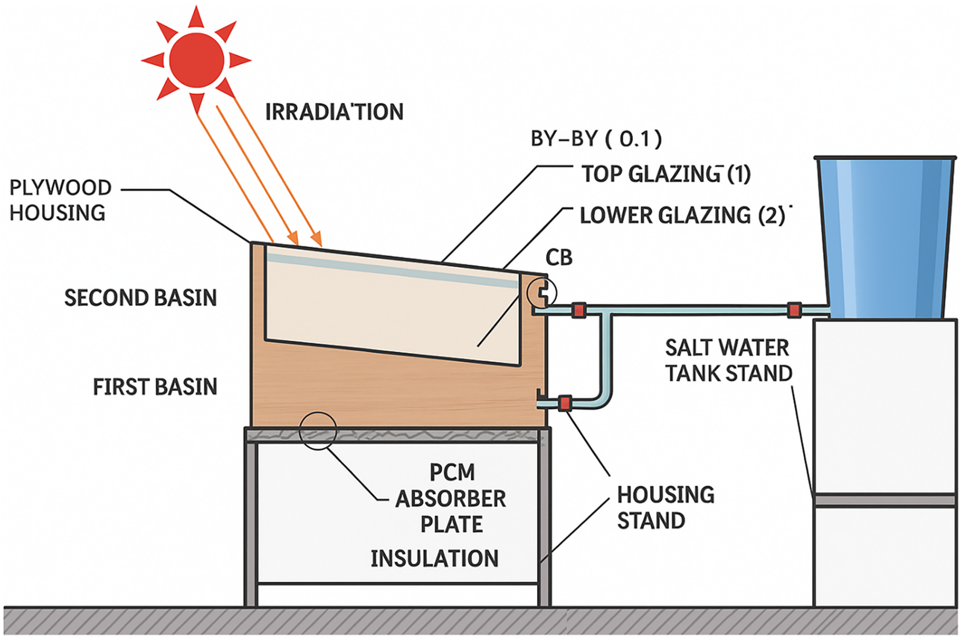

Figure 1: Schematics of fabricated solar still.

Figure 2: Actual fabricated solar still.

2.2 System Description

The experimental rig consists of a galvanized-steel absorber plate (2 mm thickness, 1.1 m^2 area) coated matte black, two shallow basins, double 3.2 mm glass glazing, and a thermal energy storage layer attached beneath the absorber. The basins and glazing share the same footprint (1.0 m × 1.1 m), with a front height of 0.56 m, back height of 0.74 m, and a 10° glazing tilt. The wooden casing is insulated at the base with 50 mm of rigid insulation. Fig. 1. shows a schematic diagram of the Solar Still, while Fig. 2. shows the actual rig.

The thermal storage component utilizes RT48 paraffin wax doped with 3 wt.% Al_2O_3 nanoparticles, forming a nano-enhanced PCM (NEPCM). This NEPCM integration is intended to improve heat storage by approximately 63% and release uniformity during continuous day-night operations.

The system operates on a passive double-effect distillation cycle enhanced by latent heat thermal energy storage. During insolation hours, short-wave solar radiation transmits through the double-glazing cover and is absorbed by the saline water and the mild steel absorber plate.

The double-effect mechanism relies on heat recovery: As water in the lower basin evaporates, it rises via buoyancy and diffusion to condense on the underside of the upper glazing. Crucially, the latent heat released during this condensation conducts through the glazing to heat the saline water in the upper (second) basin. This recovered energy drives a secondary evaporation cycle towards the top glazing, thereby increasing overall thermal efficiency compared to a single effect Still.

Simultaneously, the thermal energy storage layer, comprising RT48 Paraffin Wax enhanced with 3 wt.% Al_2O_3 nanoparticles, absorbs energy from the absorber plate via conduction. As the plate temperature exceeds the wax's melting point (48°C), the PCM undergoes a solid-to-liquid transition, storing energy as latent heat. After sunset, a reverse temperature gradient is established. The NEPCM re-solidifies, releasing its stored heat back through the absorber plate to the basin water. This sustains the evaporation process into the nocturnal hours, significantly extending the system's daily productivity.

2.3 Inventory Analysis

To accurately compute the carbon intensity of the Solar Still, foreground system data, which includes material quantities and process linkages, were derived directly from the experimental rig's bill of materials. All background processes, such as steel production, paraffin wax manufacturing, and the electricity mix, were sourced from the corresponding OzLCI datasets. An inventory of all the materials used to produce the Solar still is outlined in Table 1. The inventory includes 45.20 kg of paraffin wax (RT48) for the PCM and 1.36 kg of Al_2O_3 nanoparticles as the NEPCM additive and has a total gross mass of approximately 113.9 kg. The structural housing consists of 27.58 kg of structural marine plywood (FSC certified), while the basin and frame are made from 21.00 kg of galvanized steel (Z350, 3.6% PCR). The double-glazing component requires 18.53 kg of 6 mm clear flat glass, and the piping uses 0.27 kg of uPVC conduit. All material and process data, with the exception of the nanoparticles, were proxied using OzLCI datasets (e.g., 'Glass manufacture', 'Steel, cold rolled', 'Paraffin wax', 'Plywood, kiln dried', and 'PVC extrusion'). The inventory also includes inbound transport, modeled as 6.69 km of road freight.

Table 1: Material breakdown of the solar still.

Component/Flow	Description	Quantity (kg)	Data Source	Notes
6 mm Clear Flat Glass—AU	Upper and lower glazing	18.53	OzLCI	Includes 5% breakage allowance
C Z Purlin Cold Rolled Z350 Galvanised Steel—AU	Basin and frame	21.00	OzLCI	Includes 5% off cut
Paraffin Wax (RT48)—AU	PCM	45.20	OzLCI	Primary latent heat storage medium
Alumina Nanoparticles (Barberio LCI)	NEPCM additive	1.36	Literature dataset	3 wt.% of PCM mass
Structural Marine Plywood (FSC Hardwood)—AU	Casing and insulation	27.58	OzLCI	Includes 5% trimming
uPVC Conduit Tube—PAO	Piping network	0.27	OzLCI	6 ft, 0.14 $kg \cdot m^{-1}$, 5% scrap
Road Use (18–25 t Semi-Trailer)—AU	Freight transport	6.69 km	OzLCI	Weighted average of inbound distances

2.4 Hybrid Life-Cycle Inventory (LCI) Development

The background processes for conventional construction materials (glass, steel, plywood, PVC, paraffin wax) are available in major LCI databases (OzLCI, GaBi, ecoinvent), engineered nanomaterials such as Al_2O_3 nanoparticles are absent [33], mainly because they are typically produced at laboratory or pilot scale. Consequently, the environmental profile of the alumina nanoparticles used in this study was derived using a hybrid-LCI approach, i.e., combining database datasets for conventional materials with a literature-based inventory for the nano-additive.

Barberio et al. [34] report cradle-to-gate impacts for "BASE CASE—nanofluid of alumina (two-stage)", a system in which alumina nanoparticles are synthesized (stage 1) and subsequently dispersed into a liquid carrier (stage 2). The total Global Warming Potential (GWP_{100}) reported from their work for the production of 1000 kg of nanofluid was 7066.44 kg CO_2-eq. The nanofluid contained 9 wt.% Al_2O_3, therefore the resulting nanoparticle mass within this functional unit was 90 kg. Assuming that the reported GWP value reflects the combined burdens of nanoparticle synthesis + dispersion, the GWP per kilogram of alumina nanoparticles was obtained by dividing the total GWP (7066.44 kg CO_2-eq) by mass of Al_2O_3 (90 kg), resulting in an estimated 78.527 kg CO_2-eq per kg Al_2O_3.

This interpretation is consistent with the two-stage system boundary described by Barberio et al. [34], where nanoparticle synthesis energy dominates the environmental profile, and dispersion energy contributes a comparatively small share. To avoid double counting, the base PCM (RT48 paraffin wax) is modeled separately using OzLCI, and no additional mixing energy is added in openLCA, because the two-stage nanofluid dataset already includes the energy required to disperse nanoparticles into a carrier fluid. A custom process named "Alumina nanoparticles" was created in openLCA, and the derived emission factor (78.52 kg CO_2-eq kg^{-1}) was incorporated manually into the "Emissions to air" tab. This process was then linked to the solar-still manufacturing model as the upstream input for the 1.356 kg of nanoparticles (3 wt.%) used in the NEPCM formulation.

2.5 Operational Parameters of the Solar Still

A conservative design lifetime (L_t) of 10 years was adopted for this study. This assumption lies at the lower bound of the 10–20-year range commonly reported for passive solar distillation systems [35–38]. In addition, materials designed to withstand high humidity and UV exposure in Nigeria were selected and a sensitivity analysis was conducted on the system lifespan ensuring the environmental assessment does not underestimate long-term degradation. A temporal boundary of 365 days per year is adopted to model the continuous physical degradation of materials under ambient environmental exposure. However, to account for intermittency due to gloomy or cloudy weather, the effective productive period is adjusted using a Utilization Factor $(\boldsymbol{U})$ of 0.833 (83.3%) as detailed in Table 2.

Table 2: Operational parameters for the solar still.

Parameter	Symbol	Value	Unit	Source/Remark
Effective area	A	1.1	m^2	Modeled geometry
Lifetime	L_t	10	years	Design assumption
Days of operation	D	365	$days \cdot yr^{-1}$	Continuous
Utilization factor	U	0.833	—	Derived from seasonal availability
Specific yield	Y	4	$L \cdot m^{-2} \cdot day^{-1}$	Experimental average

No major component replacements were modeled, as the primary glass, PCM, and structural elements are expected to last the full design life. Cleaning is assumed to consist only of water-only rinsing (approximately 3 L/month), which is considered to have a negligible impact. The system has an effective area (A) of 1.1 m^2. The daily freshwater yield was derived using a two-step estimation approach. First, the baseline productivity was anchored to primary experimental data from the solar still when paraffin wax PCM was used and reported in [31]. To verify the functional unit (1 m^3 distillate) for the Nano-Enhanced (NEPCM) variant, the yield projection was validated against peer-reviewed experimental literature. While the base prototype produced an established baseline yield, the integration of Al_2O_3 nanoparticles is projected to increase productivity. A performance enhancement factor of 63% was applied to derive the daily yield of 4.0 L m^{-2} day^{-1}. This projection is conservative, lying at the lower bound of experimental results for Al_2O_3-enhanced paraffin storage, where reported improvements range from 55% [39], 60% [40] to over 116% [41]. By selecting a conservative enhancement factor, the study minimizes the risk of overestimating the 'environmental return on investment' of the nanomaterials. The Still is projected to produce a total lifetime distillate volume of 13.38 m^3, as summarized in Table 2.

The lifetime distillate yield ($V_{lifetime}$) was calculated using Eq. (1):

$$V_{lifetime} = \frac{A \times Y \times U \times 365 \times L}{1000} \tag{1}$$

where:

$V_{lifetime}$ = total lifetime distillate production (in m^3)

A = the solar aperture area of the still (in m^2)

Y = the average daily water yield (in $L/m^2/d$)

U = the utilisation factor, representing the fraction of operational days per year

L = the operational lifespan of the device (in years)

1000 = the conversion factor from Liters to m^3

From the lifetime production volume, a scaling factor (f_{alloc}) was derived to represent the fraction of a solar still's lifecycle consumed per cubic meter of distillate produced.

$$f_{alloc} = \frac{1}{V_{lifetime}} \tag{2}$$

This allocation was implemented in openLCA software using a two-process model. A primary process, representing the production of one solar still ('item'), was created to contain all cradle-to-grave material and energy flows from its Materials (given in Table 1). A secondary process was created to represent the functional unit (1 m^3 of distillate), which consumes the primary process as an input, scaled by the allocation factor f_{alloc}. Net quantities installed were derived from drawings/measurements and, where applicable, density-based calculations (e.g., glass mass from area × thickness × ρ). Manufacturing gross requirements account for scrap/breakage and are computed using Eq. (3):

$$\text{Gross} = \frac{\text{Net}}{1 - f_{\text{scrap}}}$$

$$\text{Scrap} = \text{Gross} - \text{Net} \tag{3}$$

where f_{scrap}—scrap fractions (5% for uPVC, glass, steel and wood).

Transportation of the manufactured unit from the factory to the installation site was modelled using a process for an 18–25 tonne semi-trailer. The environmental impact was calculated based on allocated vehicle-kilometers (vkm) rather than simple tonne-kilometres, as the logistics for such products are often constrained by volume or shared freight arrangements. The required vehicle-kilometres were calculated using Eq. (4):

$$vehicle\_km = M \times \left(\frac{C}{P \times f}\right) \times (1 + r) \tag{4}$$

where:

M = total mass to inputs to ship (kg)

C = vehicle payload capacity (kg per trip)

$(p * f)$ = fully loaded trip equivalents (FLE)

f = load-factor/fragmentation factor (often 1.0)

r = empty return fraction (0 = none, 1 = always empty return)

d = one-way distance (km).

It is important to clarify that the transport value listed in the inventory (6.69 km) represents the allocated burden, not the absolute geographic distance. Since the Solar Still (mass:114 kg) occupies only a fraction of the modeled 25-tonne truck's capacity, the actual geographic distances were scaled down to reflect the product's actual share of the vehicle's emissions. Consequently, this figure is not a fixed universal value but a weighted average specific to the supply chain scenario of this study.

2.6 Life Cycle Impact Assessment (LCIA)

To address uncertainties in waste management practices, the end-of-life (EoL) phase was modeled using a Landfill Scenario, a conservative baseline assumption in which 100% of the product's components are routed to landfill streams upon completion of their operational lifespan. The Life Cycle Impact Assessment (LCIA) was conducted using the IMPACT World+ (v1.29) characterization method at the midpoint level. The primary indicator selected for this analysis is Global Warming Potential (GWP_{100}), expressed in kg CO_2-equivalents. This primary focus is supported by a comprehensive suite of secondary indicators to ensure a thorough environmental profile. These include fossil and nuclear energy use (MJ deprived), freshwater ecotoxicity (CTUe), human toxicity (both cancer and non-cancer, CTUh), mineral resource use (kg deprived), eutrophication (marine and freshwater), photochemical oxidant formation (kg NMVOC), particulate matter formation (kg $PM_{2.5}$ eq), terrestrial acidification (kg SO_2 eq), ozone layer depletion (kg CFC-11 eq), and water scarcity (m^3 world eq). To maintain consistency with the functional unit, all impact assessment results are normalized to 1 m^3 of purified distillate output. The results of the analysis were expressed using several key metrics, including the total embodied GWP per Still (kg CO_2-eq $unit^{-1}$) and the GWP intensity per unit of distillate (kg CO_2-eq m^{-3}). The assessment also provides a process contribution breakdown, detailing the percentage share of each material, alongside normalized and aggregated midpoint impacts. Data quality was addressed through temporal representativeness (2019–2024) and completeness checks. Although Australian datasets were used as a regional proxy for Nigeria, the analysis focuses on relative contribution patterns, which are expected to remain robust across different datasets.

3 Results and Discussion

3.1 Life Cycle Impact Assessment Results

Processes excluded from this analysis, such as operator travel, minor maintenance, and cleaning consumables were deemed negligible, as they were estimated to contribute less than 1% of the total embodied impact. The midpoint environmental impact obtained for the functional unit of 1 m^3 of purified distillate is summarized by Table 3. The embodied Global Warming Potential (GWP_{100}) of the passive double-effect Solar Still was found to be 25.21 kg CO_2-eq m^{-3}, corresponding to a total cradle-to-grave footprint of 337.3 kg CO_2-eq per Still unit. Given the 10-year lifespan, aperture area of 1.1 m^2, average yield of 4 $L \cdot m^{-2} \cdot day^{-1}$, and a utilization factor of 0.83, the total freshwater output was calculated as 13.38 m^3 over the still's operational life. Dividing the total embodied emissions by this output yields a normalized footprint of 25.21 kg CO_2-eq m^{-3}, representing the final carbon intensity of the Still.

Table 3: Life cycle midpoint impact results per functional unit (1 m^3 of distillate).

Impact Category	Unit	Result	Main Contributor	Share (%)
Climate change (GWP_{100})	kg CO_2-eq	25.21	NEPCM (Al_2O_3 + RT48)	53
Fossil & nuclear energy use	MJ deprived	364.66	Paraffin wax & steel	(dominant but category-specific % not in LCIA export)
Freshwater ecotoxicity	CTUe	25.06	Al_2O_3 nanoparticles	—
Human toxicity (non-cancer)	CTUh	4.93×10^{-6}	Paraffin wax	—
Marine eutrophication	kg N-eq	0.0030	Plywood degradation	—
Mineral resource use	kg deprived	1.51	Steel & alumina	—
Photochemical oxidant formation	kg NMVOC eq	0.097	Steel manufacture	—
Ozone layer depletion	kg CFC-11 eq	2.4×10^{-8}	Glass manufacture	—

Although the numerical values derived from the modelling are specific to the prototype and database used, the hotspot hierarchy and relative contribution patterns are generalizable because they arise from material-inherent life-cycle burdens rather than local operating conditions. Sensitivity testing confirmed that the dominance of NEPCM, paraffin wax, steel, and glass remain structurally consistent across variations in lifetime, productivity, and background datasets, suggesting that the findings are broadly representative of solar stills incorporating PCM/NEPCM thermal storage.

Furthermore, this value is comparable to the results of Jijakli et al. [42] and other small-scale solar desalination systems, it is significantly higher than grid-powered reverse osmosis (RO) systems (1.8–3.6 kg CO_2-eq m^{-3}) and lies near the upper limit of multi-stage flash (MSF) distillation (9–25 kg CO_2-eq m^{-3}). This finding underscores that, despite being passive and emission-free in operation, the low lifetime yield of such small-scale systems amplifies their embodied carbon when normalized per cubic meter of product water.

In addition to GWP, notable environmental contributions were observed for fossil and nuclear energy use (364.7 MJ deprived m^{-3}), freshwater ecotoxicity (25.1 CTUe), and mineral resource use (1.51 kg deprived m^{-3}). Toxicity indicators (human cancer and non-cancer) and eutrophication potentials were comparatively minor.

3.2 Contribution Analysis

A detailed contribution (hotspot) analysis was conducted to decompose the still's total 337.3 kg CO_2-eq into material-level shares (Fig. 3). The analysis identified three clear hotspots: Alumina nanoparticles (31.5%), modeled using the custom "Alumina NPs (from Barberio et al. [34])" process, dominate the manufacturing-stage emissions due to the high energy intensity of nanoparticle synthesis. Paraffin wax (22%), the petroleum-derived PCM, represents the second-largest source, primarily from refining and end-of-life incineration. Steel and Glass (19% and 13%) contribute moderate shares through energy-intensive smelting and forming processes. Wood and other minor components (12% and 3%) account for residual contributions from the casing fabrication and transport.

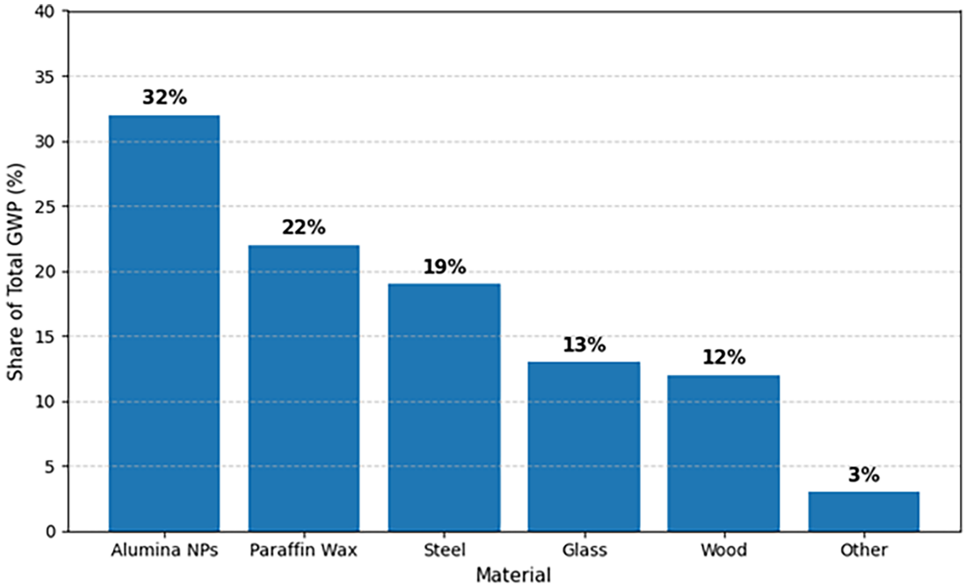

Figure 3: Embodied climate impact breakdown per 1 m^3 of distillate (Bar chart showing contributions from Al_2O_3 NPs, paraffin wax, galvanized steel, flat glass, plywood, freight, and uPVC).

Collectively, these four components account for over 85% of the total GWP, confirming that the Solar Still's environmental profile is materials-driven rather than dominated by use-phase or transport emissions.

This hierarchy mirrors findings from earlier LCA studies on solar desalination systems, where PCM manufacturing and metal components consistently represent the largest embodied energy sources. The large share of Al_2O_3 nanoparticles stems from energy-intensive synthesis processes, consistent with Barberio et al. [34], who reported cradle-to-gate GWP values exceeding 70 kg CO_2-eq kg^{-1} Al_2O_3. The paraffin wax, though lower in emission intensity, dominates by mass (45 kg per still). The embodied carbon associated with glass production (12% of total) primarily arises from high-temperature melting of silica feedstocks, while the plywood contribution (12%) reflects kiln-drying energy demand and resin-based binders. The very low PVC and freight shares (<3%) confirm the dominance of material production over logistics.

3.3 Life Cycle Energy and Resource Demand

Beyond its climate impacts, the Solar Still had a cumulative primary energy demand of approximately 365 MJ per cubic meter of distilled water. Approximately half of this embodied energy originates from the paraffin-based PCM production chain, followed by contributions from steel fabrication, glass manufacturing, and nanoparticle synthesis. These upstream processes collectively dominated the system's resource and energy requirements. To better understand the broader environmental profile, Fig. 4 presents a log-normalized radar plot of midpoint impact categories. Log-scaling was required due to differences spanning several orders of magnitude across categories. This transformation more clearly highlights the relative contributions across all impact pathways.

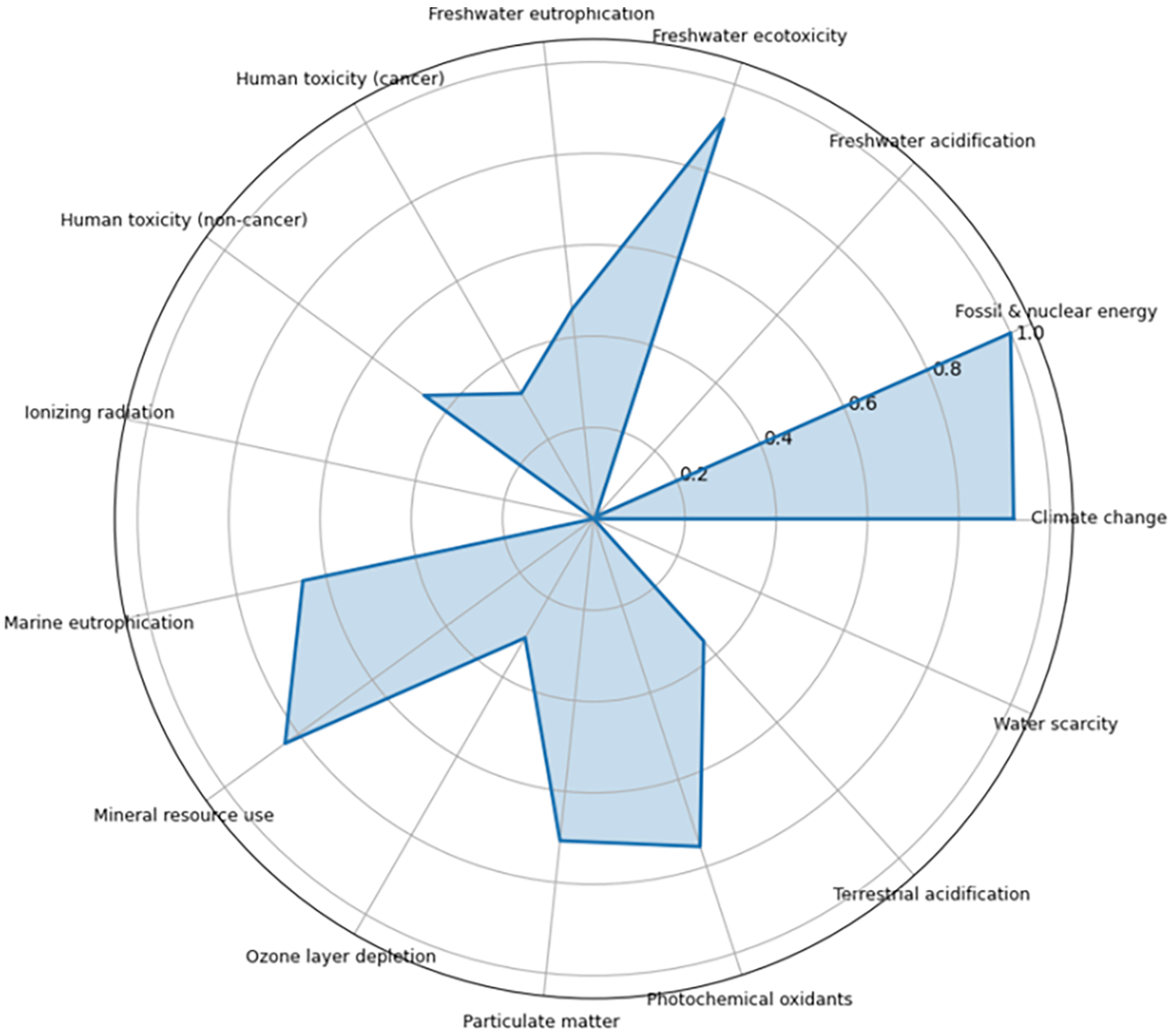

Figure 4: Log-normalized environmental impact profile of the NEPCM-integrated solar still (IMPACT World + midpoint).

The results reveal that fossil and nuclear energy use, freshwater ecotoxicity, climate change, and particulate matter formation are the most influential categories in the embodied footprint of the system. These impacts stem primarily from the energy and chemical-intensive production of paraffin wax and alumina nanoparticles, as well as metal processing for the structural frame. In contrast, categories such as eutrophication, acidification, ozone depletion, ionizing radiation, and water scarcity exhibit negligible contributions, even after log-scaling. This indicates that while the system is materially intensive, it does not impose significant burdens on nutrient-loading or atmospheric depletion pathways.

Overall, the expanded impact profile confirms that the incorporation of advanced materials particularly NEPCM introduces additional toxicity and resource-related burdens that do not appear in simpler Solar Still designs. These findings underscore the importance of material optimization and sustainable sourcing when integrating NEPCMs into thermal energy storage systems.

4 Benchmark against Other Desalination Technologies

Comparing embodied Carbon Intensity of the Solar still against those from major desalination technologies, we pooled the mean of literature-reported operational emissions for Reverse Osmosis (RO) [43–46] and Multistage Flash (MSF) [44,47] with the embodied greenhouse gas intensity of our fabricated NEPCM-integrated Solar Still. The result of this benchmark is given in Fig. 5. Reverse osmosis (RO) systems generally exhibit operational climate intensities in the range of 3–7 kg CO_2-eq m^{-3}, while multi-stage flash (MSF) technologies report considerably higher values, typically 8–15 kg CO_2-eq m^{-3}, depending on plant scale and energy source. In contrast, the Solar Still evaluated in this study exhibits an embodied cradle-to-grave climate intensity of 25.21 kg CO_2-eq m^{-3}. While this value lies above the operational intensities of RO and MSF, it reflects a fundamentally different emissions boundary: the Solar Still incurs almost no operational emissions, as water production is driven entirely by passive solar energy with no external electricity or thermal input.

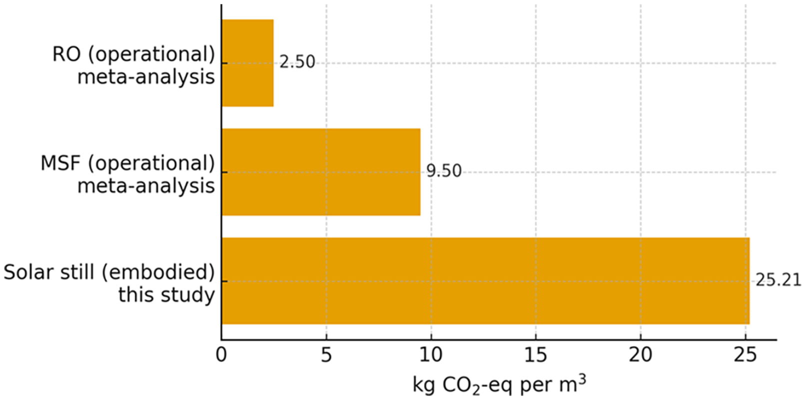

Figure 5: Comparative carbon intensity of desalination technologies.

Consequently, when considered in remote, off-grid, or fuel-constrained contexts, the Solar Still offers a distinct decarbonization pathway. Its total life-cycle carbon burden is fixed upfront, and unlike RO and MSF does not scale with throughput, grid carbon intensity, or energy price volatility. Over an extended service life, this results in a stable, low-maintenance, and emission-free operational profile, positioning the NEPCM-enhanced Solar Still as a viable complementary technology for sustainable small-scale desalination.

4.1 Scenario Analysis

To determine the environmental justification of integrating thermal storage materials, a comparative scenario analysis was conducted across three system configurations of the same still: Base Still (no PCM), PCM-only Still, and the Still with NEPCM added. The result of this analysis is presented in Fig. 6 which reveals the trade-off between embodied carbon intensity and lifetime distillate productivity.

The Base Still had the lowest carbon intensity due to minimal material use, but it also had the lowest productivity (45% less water) which makes it less desirable. The PCM-only variant exhibits the highest carbon intensity (28.75 kg CO_2-eq m^{-3}), indicating that the yield gains from plain paraffin wax are insufficient to offset its embodied emissions. Adding Alumina nanoparticles increases the total manufacturing emissions of the Still. However, the nanoparticles significantly improved the thermal conductivity and storage of the wax, leading to a massive increase in Lifetime Water Yield, thereby lowering the carbon intensity to 25.21 kg CO_2-eq m^{-3}. In context, the output of one NEPCM Still is equivalent to approximately two Base Stills, which would double the land area required. Therefore, the NEPCM Still represents the optimal configuration for users requiring nocturnal production, as it mitigates the environmental penalty of the

PCM by approximately 12% compared to the non-enhanced alternative. Furthermore, it is most suitable for space-constrained and high-demand applications.

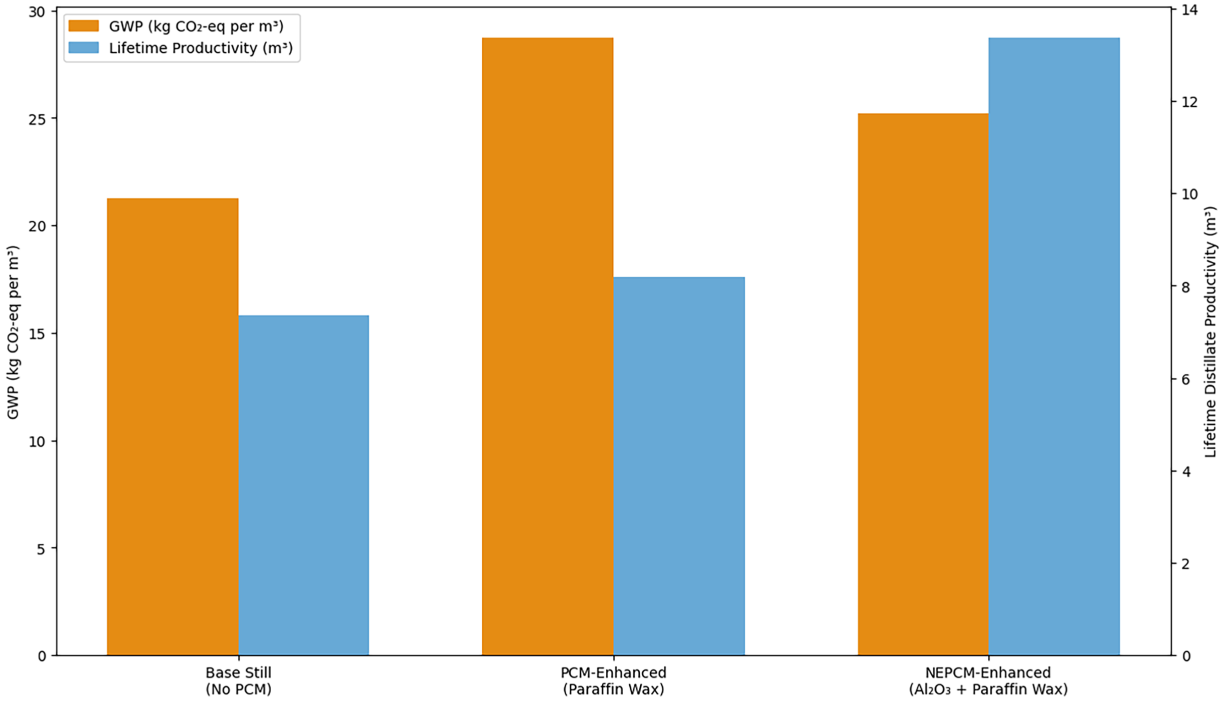

Figure 6: Comparative life-cycle performance of base, PCM-only, and NEPCM-enhanced solar stills.

4.2 Sensitivity Analysis: The Influence of System Lifespan (5 Years, 10 Years vs. 15 Years)

Given that the environmental impact of the NEPCM solar still is entirely embodied in its manufacturing phase, the functional lifespan of the system serves as the most critical determinant of its sustainability profile. A sensitivity analysis was conducted to evaluate how variations in operational longevity affect the normalized Global Warming Potential (GWP).

The results indicate a hyperbolic decay in carbon intensity as the lifespan extends as seen in Fig. 7. When the operational life was reduced to 5 years, the impact of premature failure or severe weather damage doubled the carbon intensity to 50.42 kg CO_2-eq m^{-3}, making the system environmentally uncompetitive compared to conventional desalination. Conversely, extending the lifespan to 15 years through durable material selection (e.g., galvanized steel, marine plywood) reduces the intensity to 16.81 kg CO_2-eq m^{-3}, a 33% reduction from the baseline. This finding underscores that mechanical durability and maintenance are not merely economic factors but are central to the environmental viability of passive solar desalination systems.

4.3 Optimization of Nanoparticle Concentration (0–5 wt.%)

To validate the selection of a 3 wt.% nanoparticle concentration, a sensitivity analysis was performed across a range of loading fractions (0–5 wt.%). The alumina concentration for each scenario in the analysis is given in Table 4. The results, presented in Fig. 8, reveal a non-linear optimization curve.

The PCM-only variant (0 wt.%) exhibited a high carbon intensity of 28.75 kg CO_2-eq m^{-3}, which indicates that without the thermal enhancement of nanoparticles, the paraffin wax is an environmentally inefficient storage medium. The introduction of 1 wt.% Al_2O_3 drastically improved performance, lowering the intensity to the theoretical minimum of 23.14 kg CO_2-eq m^{-3} as seen in Fig. 8.

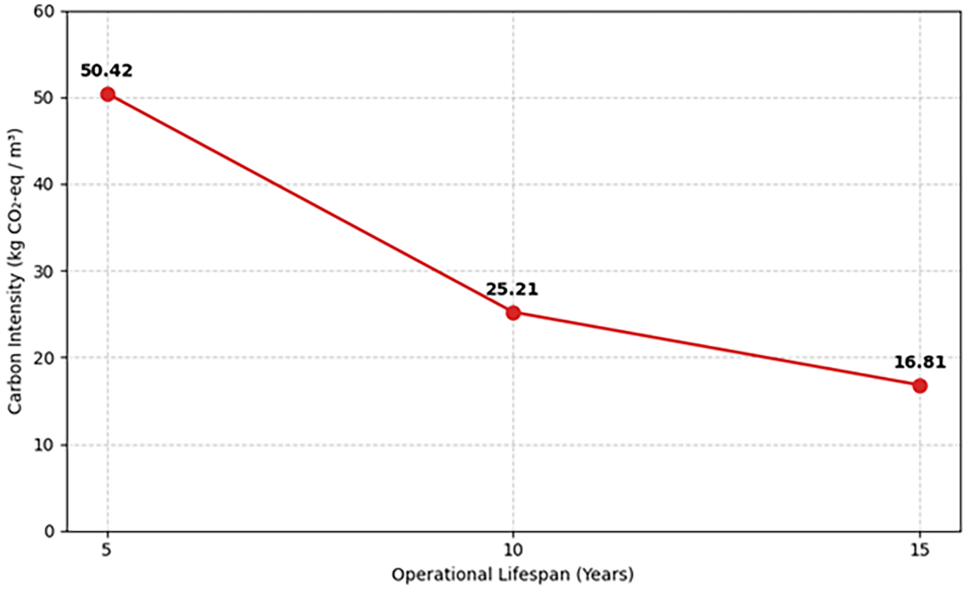

Figure 7: Effect of lifespan on carbon intensity.

Table 4: Nanoparticle concentration for each scenario.

Scenario	Alumina Conc.	Carbon Intensity ($kg\ CO_2/m^3$)	Status
PCM Only	0 wt.%	28.75	Inefficient (High wax impact, low yield)
Low Nano	1 wt.%	23.14	Eco-Optimal (Lowest Carbon)
Our Design	3 wt.%	25.21	Balanced (Max Yield, moderate carbon)
High Nano	5 wt.%	31.39	Diminishing Returns (High impact, agglomeration)

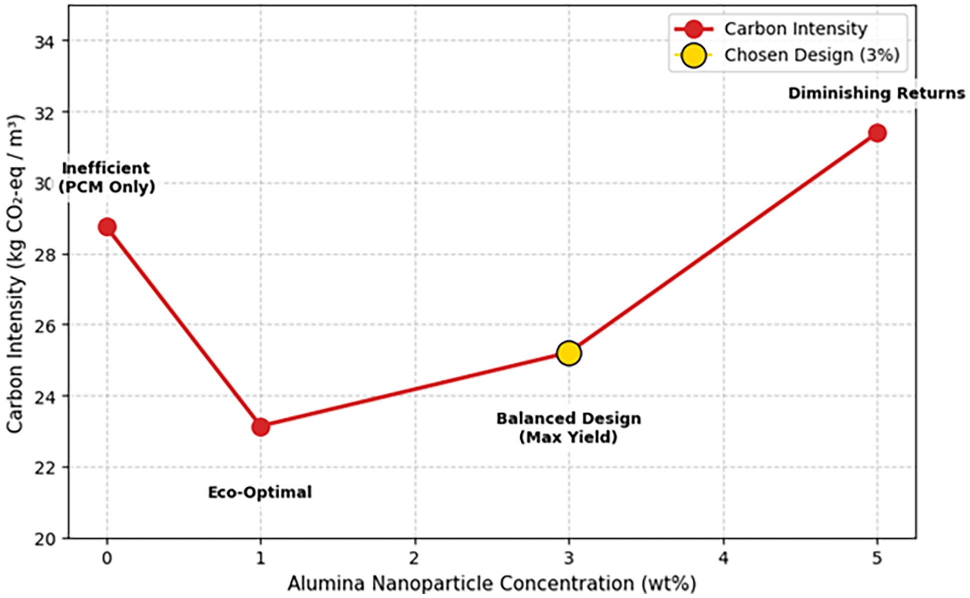

Figure 8: Optimization of nanoparticle concentration.

However, the 3 wt.% design (25.21 kg CO_2-eq m^{-3}) was selected as the optimal configuration. While slightly more carbon-intensive than the 1 wt.% case, it provides a higher total distillate yield (13.38 m^3), maximizing the utility of the fixed structural components (glass/steel). Conversely, increasing the concentration to 5 wt.% resulted in a sharp penalty, driving intensity up to 31.39 kg CO_2-eq m^{-3}. This aligns with findings by Samara et al. [48], who noted that higher concentrations lead to particle agglomeration and reduced latent heat capacity, thereby degrading system efficiency despite higher material costs.

5 Conclusion

This study conducted a cradle-to-grave Life Cycle Assessment (LCA) of a nano-enhanced, double-effect single-slope Solar Still fabricated in Nigeria to quantify its embodied environmental impacts and identify key design hotspots. The analysis, carried out in openLCA using the IMPACT World+ (v1.29) method and the OzLCI (2019) database, provides one of the first comprehensive assessments of a passive solar distillation system integrating Nano-Enhanced Phase Change Material (NEPCM) storage.

The total Global Warming Potential (GWP_{100}) associated with producing one Still was approximately 337.3 kg CO_2-eq, corresponding to a normalized carbon intensity of 25.21 kg CO_2-eq m^{-3} of freshwater over its ten-year lifetime and a total yield of 13.38 m^3. Although the system operates without external energy input, the results reveal that its environmental footprint is materials-dominated, driven largely by the manufacturing and end-of-life treatment of its components.

Hotspot analysis showed that Al_2O_3 nanoparticles (31.5%), paraffin wax PCM (22%), and structural steel and glass (19% and 13%) together contribute more than 85% of the total embodied carbon. In contrast, transport, PVC fittings, and other minor inputs had negligible influence (<3%). These findings confirm that the overall sustainability of Solar Stills is determined primarily by the choice and quantity of construction materials, rather than by operational factors.

The results highlight that material selection, particularly the choice of PCM and nanomaterials, exerts a dominant influence on total embodied impacts. Substituting high-impact Al_2O_3 nanoparticles with bio-derived or lower-energy synthesis routes could significantly improve environmental performance. Similarly, increasing yield through geometric optimization or reflective coatings can proportionally reduce the GWP intensity. Recycling of metals and glass at end-of-life presents another low-cost mitigation route. Overall, this LCA demonstrates that the carbon intensity of passive solar distillation can be maintained within the range of active desalination systems while eliminating operational energy demand.

When benchmarked against industrial desalination technologies, the NEPCM-integrated still's carbon intensity lies above grid-powered reverse osmosis (1.8–3.6 kg CO_2-eq m^{-3}) and within the upper range of multi-stage flash distillation (9–25 kg CO_2-eq m^{-3}). However, unlike these energy-intensive systems, the passive Still operates solely on solar radiation, yielding zero operational emissions and offering an attractive low-maintenance solution for decentralized or off-grid communities.

From a design perspective, the study underscores the need to:

i. Reduce nanomaterial content or adopt lower-impact synthesis routes for Al_2O_3.
ii. Explore bio-based or recyclable PCMs as substitutes for petroleum-derived paraffins.
iii. Employ recyclable alloys and modular construction for end-of-life recovery; and
iv. Increase Still productivity through geometric and thermal optimization to dilute embodied impacts over greater water output.

The hybrid LCI approach adopted—integrating literature-based nanomaterial inventories with standard LCA datasets—proved effective for capturing the environmental significance of advanced materials absent from conventional databases. This methodology can serve as a template for future sustainability assessments of nanomaterial-enhanced renewable energy systems.

In conclusion, while the present NEPCM-integrated Solar Still demonstrates a moderate embodied carbon footprint relative to its operational benefits, its environmental performance can be markedly improved through informed material selection, recycling strategies, and performance scaling. The findings provide an evidence base for guiding eco-design, local manufacturing, and policy decisions aimed at achieving sustainable water production in resource-constrained and solar-rich regions.

Several assumptions and limitations were defined to maintain model simplicity and transparency. Minor components, including sealants, gaskets, fasteners, and coatings, were excluded from the inventory, as their small mass fractions (<1%) were assumed to contribute negligibly to the overall impacts. Insulation was considered an embedded component of the plywood structural layer. The baseline scenario assumes all materials are landfilled. Furthermore, while cleaning water and brine disposal are discussed qualitatively, they are excluded from quantitative assessment. This is justified by the operational model, which assumes brine evaporates naturally within the basin, consistent with passive Solar Still operation.

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Nomenclature

LCI	Life Cyle Inventory
LCIA	Life-Cycle Impact Assessment
NEPCM	Nano-Enhanced Phase Change Material
PCM	Phase Change Material
GWP_{100}	Global Warming Potential (100-year)
OzLCI	Australian Life-Cycle Inventory
FSC	Forest Stewardship Council
PCR	Post-Consumer Recycled
PVC	Polyvinyl Chloride
RT48	Paraffin wax (melting temperature ~48°C)

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