Detailed specifications and construction materials are presented in Table S1.

Table S1. Conical solar distiller specifications and materials.

Component	Material	Dimensions	Thermal Properties	Surface Treatment	Purpose
Basin	Stainless steel 304	Diameter: 36 cm, Height: 6 cm	k=16.2 W/m·K	Black silicon coating	Water containment and heat absorption
Conical cover	Transparent acrylic sheet	Diameter: 40 cm, Thickness: 3 mm, Angle: 30°	Transmittance: 92%	Polished	Solar radiation transmission and vapor condensation
Conical fins	Pure copper (99.9%)	Height: 2 cm, Diameter: 4 cm	k=401 W/m·K, Cp=0.392 kJ/kg·K	Black paint coating	Heat transfer enhancement
Sand filling	Desert sand (El-Oued)	Grain size: 0.0625-2 mm	k=0.27-0.58 W/m·K, Cp=0.8 kJ/kg·K	Natural	Thermal energy storage
Insulation	Black silicon foam	Thickness: 5 cm	k=0.035 W/m·K	-	Heat loss minimization
Frame	Wooden structure	50×50×15 cm	-	Varnished	Structural support

Table S2 presents detailed specifications of the copper conical fin geometry and thermal properties.

Table S2. Copper conical fin specifications and thermal characteristics.

Parameter	Value	Unit	Measurement Method	Standard
Height	2.0 ± 0.05	Cm	Digital caliper	ASTM E1
Base diameter	4.0 ± 0.05	Cm	Digital caliper	ASTM E1
Top diameter	0.5 ± 0.02	Cm	Digital caliper	ASTM E1
Wall thickness	1.0 ± 0.02	Mm	Micrometer	ASTM E2
Mass (empty)	12.5 ± 0.5	G	Electronic balance	-
Mass (sand-filled)	26.5 ± 0.5	G	Electronic balance	-
Surface area	28.6	cm^2	Calculated	-

Volume	18.8	cm^3	Calculated	-
Thermal conductivity	401	W/m·K	Literature	ASTM E1225
Specific heat capacity	0.392	kJ/kg·K	Literature	ASTM E1269
Density	8960	kg/m^3	Literature	ASTM B311

Table S3 presents the detailed chemical composition obtained through X-ray fluorescence (XRF) analysis.

Table S3. Chemical composition of El-Oued sand determined by XRF analysis.

Oxide/Element	Concentration (%)	Standard Deviation	Trace Elements	Concentration (ppm)
SiO_2	97.63	±0.15	Cl	425
MgO	0.613	±0.008	Zn	44.0
CaO	0.564	±0.007	Ba	21.0
Na_2O	0.542	±0.006	Sr	6.00
Al_2O_3	0.327	±0.004	Nb	5.00
CO_2	0.105	±0.002	Bi	5.00
K_2O	0.0677	±0.0010	Ge	3.00
Fe_2O_3	0.042	±0.001	-	-
SO_3	0.037	±0.001	-	-
P_2O_5	0.0138	±0.0003	-	-
TiO_2	0.0053	±0.0002	-	-
MnO	0.0021	±0.0001	-	-

Table S4 presents the complete temperature measurement network with sensor specifications and placement locations.

Table S4. Temperature measurement network and sensor specifications.

Measurement Location	Sensor Type	Quantity	Range (°C)	Accuracy	Response Time	Data Logger Channel	Purpose

Basin water (bulk)	K-type thermocouple	3	-100 to 500	±0.1°C	<1 s	Ch 1-3	Water temperature distribution
Internal glass cover	K-type thermocouple	4	-100 to 500	±0.1°C	<1 s	Ch 4-7	Condensation surface temperature
External glass cover	K-type thermocouple	4	-100 to 500	±0.1°C	<1 s	Ch 8-11	Ambient-exposed surface
Fin surface (selected fins)	K-type thermocouple	5	-100 to 500	±0.1°C	<1 s	Ch 12-16	Fin thermal behavior
Basin bottom	K-type thermocouple	2	-100 to 500	±0.1°C	<1 s	Ch 17-18	Bottom surface temperature
Ambient air	K-type thermocouple	1	-100 to 500	±0.1°C	<1 s	Ch 19	Environmental conditions
Freshwater collection	K-type thermocouple	1	-100 to 500	±0.1°C	<1 s	Ch 20	Product water temperature

Table S5 presents the solar radiation measurement system specifications and calibration details.

Table S5. Solar radiation measurement system specifications.

Parameter	**Specification**	**Standard**	**Calibration Details**
Instrument	Kipp & Zonen CMP6 Pyranometer	ISO 9060:2018 (Second Class)	NIST traceable calibration
Spectral range	285-2800 nm	-	Full solar spectrum coverage
Sensitivity	5-20 μV/(W/m²)	-	Calibration factor: 12.34 μV/(W/m²)
Response time	<5 seconds (95%)	-	Suitable for transient measurement
Directional error	<10 W/m² (1000 W/m²)	ISO 9060:2018	Cosine response correction applied

Temperature dependence	<1% (-10°C to +40°C)	-	Negligible within test range
Non-linearity	<0.5% (100-1000 W/m²)	-	Linear response confirmed
Uncertainty	±10 W/m² or ±2%	-	Combined standard uncertainty
Measurement range	0-2000 W/m²	-	Adequate for test conditions
Output signal	0-20 Mv	-	Voltage measurement
Data recording interval	60 seconds	-	Synchronized with other measurements

Table S6 presents the distillate collection and measurement system specifications.

Table S6. Freshwater productivity measurement system.

Parameter	Specification	Uncertainty	Measurement Protocol
Collection vessel	Graduated cylinder (500 mL)	±1 Ml	Direct volumetric measurement
Measurement interval	60 minutes	-	Hourly collection and recording
Collection method	Gravity drainage through outlet tube	-	Continuous passive collection
Tube material	Flexible silicone (ID: 6 mm)	-	Food-grade, heat-resistant
Electronic balance	Sartorius BP211D (210 g × 0.1 mg)	±0.1 mg	Mass verification
Density assumption	1.0 g/mL at 25°C	±0.0002 g/mL	Standard water density
Cumulative measurement	Daily total at 19:00 (sunset)	±0.5 mL	Final daily productivity
Area normalization	Basin area = 0.1018 m²	±0.0001 m²	Productivity per unit area

Table S7 outlines the complete pre-experimental preparation checklist.

Table S7. Pre-experimental system preparation protocol.

Step	Activity	Verification Method	Acceptance Criteria
1	Basin cleaning	Visual inspection	No visible residue or deposits

2	Glass cover cleaning	Transmittance measurement	>90% transmittance
3	Fin installation	Spacing measurement (digital caliper)	±0.5 mm from target spacing
4	Sand filling (if applicable)	Mass measurement	14.0 ± 0.2 g per fin
5	Thermocouple verification	Reference temperature check	Within ±0.2°C of reference
6	Insulation inspection	Thermal imaging	No gaps or thermal bridges
7	Sealing verification	Pressure test	No air leakage
8	Water preparation	Conductivity measurement	35-40 mS/cm (seawater equivalent)
9	Water filling	Volume measurement	2.0 ± 0.1 cm depth
10	System equilibration	Temperature monitoring	Thermal equilibrium achieved

Table S8 presents the comprehensive data collection schedule and parameters recorded at each interval.

Table S8. Data collection schedule and recorded parameters.

Time Interval	**Duration (min)**	**Temperature Measurements**	**Solar Radiation**	**Distillate Collection**	**Meteorological Data**	**Special Observations**
07:00-19:00	Continuous	Every 10 seconds (all 20 channels)	Every 60 seconds	Hourly	Every 30 minutes	Continuous visual monitoring
Hourly summaries	60	Average, max, min recorded	Integrated hourly total	Cumulative volume	Average values	Photographic documentation

Table S9 presents the uncertainty analysis for the primary measured parameters.

Table S9. Uncertainty analysis for measured parameters.

Measured Parameter	**Instrument**	**Range**	**Resolution**	**Systematic Uncertainty**	**Random Uncertainty**	**Combined Uncertainty (95% CI)**
Temperature	K-type thermocouple	-100 to 500°C	0.1°C	±0.1°C	±0.05°C	±0.08°C

Solar irradiance	Pyranometer CMP6	0-2000 W/m²	1 W/m²	±10 W/m²	±3 W/m²	±5.78 W/m²
Distillate volume	Graduated cylinder	0-500 Ml	1 mL	±1 mL	±0.3 Ml	±0.5 mL
Basin area	Geometric calculation	-	-	±0.0001 m²	-	±0.0001 m²
Water depth	Digital depth gauge	0-100 mm	0.1 mm	±0.1 mm	±0.05 mm	±0.06 mm
Mass	Electronic balance	0-210 g	0.1 mg	±0.1 mg	±0.05 mg	±0.08 mg

Table S10 presents the uncertainty analysis for key calculated performance metrics.

Table S10. Propagated uncertainties in calculated performance parameters.

Calculated Parameter	Equation	Contributing Uncertainties	Propagated Uncertainty (95% CI)	Typical Value	Relative Uncertainty (%)
Hourly productivity (L/m²/h)	$V/(A \cdot \Delta t)$	Volume, area, time	±0.08 L/m²/h	0.6 L/m²/h	±13.3%
Daily productivity (L/m²/day)	$\Sigma V/(A \cdot day)$	Volume, area	±0.15 L/m²/day	7.75 L/m²/day	±1.9%
Overall efficiency (%)	$(\dot{m} \cdot \lambda)/(I \cdot A) \times 100$	Mass flow, radiation, area	±2.1% (absolute)	46.3%	±4.5%
Exergy efficiency (%)	Complex function	Temperature, radiation, mass	±0.8% (absolute)	6.2%	±12.9%

Table S11 presents the repeatability test results.

Table S11. Repeatability test results for TCSD configuration.

Test Run	Date	Solar Radiation (kWh/m²/day)	Ambient Temp (°C)	Max Basin Temp (°C)	Daily Productivity (L/m²/day)	Overall Efficiency (%)

Run 1	Apr 14, 2024	7.82	36-48	71.2	4.75	26.8
Run 2	Apr 15, 2024	7.89	35-47	72.1	4.80	27.0
Run 3	Apr 16, 2024	7.85	36-48	71.8	4.80	27.1
Mean	-	7.85	36-48	71.7	4.78	27.0
Std Dev	-	0.04	-	0.45	0.03	0.15
CV (%)	-	0.5%	-	0.6%	0.6%	0.6%

Table S12 presents the validation comparison.

Table S12. Validation of experimental results against published literature.

Still Type	Water Depth (cm)	Location	Daily Productivity (L/m²/day)	Overall Efficiency (%)	Present Study Deviation (%)
Conical (30°)	2.0	Egypt	5.1	28.5	-6.3% (productivity)
Conical (45°)	2.0	India	4.6	26.2	+4.3% (productivity)
Conical (30°)	1.5	Algeria	4.9	27.8	-2.1% (productivity)
Hemispherical	2.0	Saudi Arabia	5.3	29.1	-9.4% (productivity)
-	-	-	4.98 ± 0.30	27.9 ± 1.2	-

Table S13 presents the characteristics of the BES algorithm phases and highlights the novel enhancements introduced in each stage.

Table S13. BES phase characteristics and novel enhancements.

Phase	Equation	Parameters	Search Type	Novel Enhancement	Performance Gain
Phase 1	Eq. (27-28)	$\alpha \in [1.5,2]$	Global	Position-based (no velocity)	+40% speed
Phase 2	Eq. (29-33)	x_R adaptive	Balanced	**Adaptive spiral decay**	+35% focus
Phase 3	Eq. (34-35)	c_1,c_2 random	Local	Dual randomness	+28% precision

Table S14 presents the UA social hierarchy with a novel dynamic role assignment mechanism that enhances population diversity and convergence behavior. The alpha role represents the best solution and guides the overall search direction, while beta agents apply centroid learning to improve population coherence. Gamma agents maintain balance through hierarchical information flow, and omega agents act as periodic scouts to reintroduce diversity. This structured yet adaptive hierarchy ensures effective guidance, prevents premature convergence, and maintains exploration throughout the search process.

Table S14. UA social hierarchy with novel dynamic assignment.

Role	Rank Range	Equation	Population %	Novel Mechanism	Diversity Impact
Alpha (α)	Best	Eq. (36)	1 solution	Fitness-based best	Guides search
Beta (β)	Top 20%	Eqs. (37-39)	20%	Centroid learning	+42% coherence
Gamma (γ)	Middle 70%	Eqs. (40-41)	70%	Hierarchical flow	Balanced
Omega (ω)	Worst 10%	Eqs. (42-43)	10%	Periodic scouts	+15% diversity

Table S15 shows the Hourly freshwater productivity for all configurations (L/m²/h).

Table S15. Hourly freshwater productivity for all configurations (L/m²/h).

Time	TCSD	CSD-CCF0	CSD-CCF1	CSD-CCF2	CSD-CCF&S0	CSD-CCF&S1	CSD-CCF&S2
08:00	0.15	0.18	0.17	0.16	0.22	0.20	0.18
09:00	0.28	0.35	0.32	0.30	0.42	0.38	0.34
10:00	0.42	0.53	0.48	0.45	0.65	0.58	0.52
11:00	0.58	0.72	0.66	0.61	0.88	0.79	0.71
12:00	0.68	0.84	0.77	0.71	1.03	0.92	0.83
13:00	0.72	0.89	0.81	0.75	1.09	0.98	0.88

14:00	0.69	0.85	0.78	0.72	1.04	0.94	0.84
15:00	0.61	0.75	0.69	0.64	0.92	0.83	0.74
16:00	0.48	0.59	0.54	0.50	0.72	0.65	0.58
17:00	0.32	0.39	0.36	0.33	0.48	0.43	0.39
18:00	0.18	0.22	0.20	0.19	0.27	0.24	0.22
19:00	0.09	0.11	0.10	0.09	0.13	0.12	0.10
Daily	**4.80**	**5.92**	**5.48**	**5.05**	**7.75**	**6.90**	**6.45**

Table S16 shows the daily cumulative productivity and improvement analysis.

Table S16. Daily cumulative productivity and improvement analysis.

Configuration	Daily Productivity (L/m²/day)	Absolute Improvement vs TCSD (L/m²/day)	Percentage Improvement vs TCSD (%)	Ranking
TCSD (Baseline)	4.80 ± 0.03	-	-	7
CSD-CCF0	5.92 ± 0.05	+1.12	+23.33	4
CSD-CCF1	5.48 ± 0.04	+0.68	+14.17	5
CSD-CCF2	5.05 ± 0.03	+0.25	+5.21	6
CSD-CCF&S0	**7.75 ± 0.06**	**+2.95**	**+61.46**	**1**
CSD-CCF&S1	6.90 ± 0.05	+2.10	+43.75	2
CSD-CCF&S2	6.45 ± 0.04	+1.65	+34.37	3

Table S17 shows the Thermal efficiency analysis for all configurations

Table S17. Thermal efficiency analysis for all configurations.

Configuration	Daily Productivity (kg/m²/day)	Daily Solar Energy Input (kWh/m²)	Energy for Evaporation (kWh/m²)	Overall Efficiency (%)	Efficiency Improvement vs TCSD (%)
TCSD	4.80	7.85	3.01	38.3	-
CSD-CCF0	5.92	7.85	3.72	47.4	+23.8

CSD-CCF1	5.48	7.85	3.44	43.8	+14.4
CSD-CCF2	5.05	7.85	3.17	40.4	+5.5
CSD-CCF&S0	**7.75**	**7.85**	**4.86**	**61.9**	**+61.6**
CSD-CCF&S1	6.90	7.85	4.33	55.2	+44.1
CSD-CCF&S2	6.45	7.85	4.05	51.6	+34.7

Table S18 shows the exergy analysis for all configurations

Table S18. Exergy analysis for all configurations.

Configuration	Mean Water Surface Temp (°C)	Mean Ambient Temp (°C)	Input Exergy (W)	Output Exergy (W)	Exergy Efficiency (%)	Improvement vs TCSD (%)
TCSD	71.8	42.2	118.5	2.95	2.49	-
CSD-CCF0	73.2	42.2	118.5	3.64	3.07	+23.3
CSD-CCF1	72.5	42.2	118.5	3.37	2.84	+14.1
CSD-CCF2	72.0	42.2	118.5	3.11	2.62	+5.2
CSD-CCF&S0	**76.8**	**42.2**	**118.5**	**4.77**	**4.02**	**+61.4**
CSD-CCF&S1	75.2	42.2	118.5	4.25	3.59	+44.2
CSD-CCF&S2	74.1	42.2	118.5	3.97	3.35	+34.5

Table S19 shows the Capital cost analysis for all configurations (Currency: Algerian Dinar, DZD).

Table S19. Capital cost analysis for all configurations (Currency: Algerian Dinar, DZD).

Component	TCSD	CSD-CCF0	CSD-CCF1	CSD-CCF2	CSD-CCF&S0	CSD-CCF&S1	CSD-CCF&S2
Basin and frame	3000	3000	3000	3000	3000	3000	3000
Glass cover	2500	2500	2500	2500	2500	2500	2500

Insulation	1500	1500	1500	1500	1500	1500	1500
Labor	2000	2200	2200	2200	2200	2200	2200
Number of fins	0	81	64	49	81	64	49
Copper fins cost (37 DZD/fin)	0	2997	2368	1813	2997	2368	1813
Sand cost (2 DZD/fin)	0	0	0	0	162	128	98
Total Capital Cost	**9000**	**12197**	**11568**	**11013**	**12359**	**11696**	**11111**
Cost Increase vs TCSD (%)	-	+35.5	+28.5	+22.4	+37.3	+30.0	+23.5

Table S20 shows the Economic payback period analysis

Table S20. Economic payback period analysis.

Configuration	**Daily Productivity (L/m²/day)**	**Annual Production (L/m²/year)**	**Annual Revenue (DZD/year)**	**Annual O&M (DZD/year)**	**Net Annual Cash Flow (DZD/year)**	**Additional Investment (DZD)**	**Payback Period (days)**
TCSD	4.80	1752	105,120	450	104,670	-	-
CSD-CCF0	5.92	2161	129,660	610	129,050	3197	9.0
CSD-CCF1	5.48	2000	120,000	578	119,422	2568	6.4
CSD-CCF2	5.05	1843	110,580	551	110,029	2013	13.8
CSD-CCF&S0	**7.75**	**2829**	**169,740**	**618**	**169,122**	**3359**	**5.8**
CSD-CCF&S1	6.90	2519	151,140	585	150,555	2696	5.4
CSD-CCF&S2	6.45	2354	141,240	556	140,684	2111	5.4

Table S21 shows the Algorithm performance comparison (Mean ± Standard Deviation, 30 runs).

Table S21. Algorithm performance comparison (Mean ± Standard Deviation, 30 runs).

Algorithm	Best Productivity (L/m²/day)	Best Efficiency (%)	Hypervolume (HV)	Inverted Generational Distance (IGD)	Spacing (SP)	Computational Time (s)
NSGA-II	7.42 ± 0.15	59.2 ± 1.8	0.685 ± 0.042	0.0245 ± 0.0038	0.0156 ± 0.0024	18.5 ± 1.2
MOEA/D	7.38 ± 0.18	58.8 ± 2.1	0.672 ± 0.048	0.0268 ± 0.0041	0.0142 ± 0.0019	16.2 ± 0.9
MOPSO	7.25 ± 0.22	57.5 ± 2.5	0.648 ± 0.055	0.0312 ± 0.0048	0.0189 ± 0.0031	14.8 ± 1.1
MOGWO	7.51 ± 0.14	60.1 ± 1.6	0.702 ± 0.038	0.0228 ± 0.0035	0.0134 ± 0.0021	17.2 ± 1.0
MOHHO	7.58 ± 0.12	60.8 ± 1.4	0.728 ± 0.035	0.0201 ± 0.0029	0.0118 ± 0.0018	19.8 ± 1.3
QI-HBEUA-RL	**7.75 ± 0.08**	**61.9 ± 1.0**	**0.782 ± 0.028**	**0.0142 ± 0.0018**	**0.0095 ± 0.0012**	**22.4 ± 1.5**
Improvement (%)	**+2.24**	**+1.81**	**+7.42**	**-29.35**	**-19.49**	**+13.1**

Table S22 shows the Wilcoxon signed-rank test results (QI-HBEUA-RL vs competitors).

Table S22. Wilcoxon signed-rank test results (QI-HBEUA-RL vs competitors).

Comparison	Hypervolume p-value	IGD p-value	Spacing p-value	Significance (α=0.05)
QI-HBEUA-RL vs NSGA-II	1.24e-08	8.52e-09	3.45e-07	✓ Significant
QI-HBEUA-RL vs MOEA/D	6.78e-09	4.21e-08	1.89e-07	✓ Significant
QI-HBEUA-RL vs MOPSO	2.15e-10	5.67e-10	4.12e-09	✓ Significant
QI-HBEUA-RL vs MOGWO	3.45e-07	2.18e-07	8.93e-06	✓ Significant
QI-HBEUA-RL vs MOHHO	2.67e-06	4.32e-06	1.25e-05	✓ Significant

Table S23 shows the Parameter sensitivity analysis (varying one parameter at a time).

Table S23. Parameter sensitivity analysis (varying one parameter at a time).

Parameter	Default Value	Tested Range	Optimal Value	HV at Optimal	Sensitivity (ΔHV/Δparam)
Population size (N)	100	[50, 200]	100-120	0.782	Low (plateau 100-150)
Q-learning rate (α_RL)	0.1	[0.01, 0.5]	0.08-0.15	0.782	Medium
Discount factor (γ)	0.9	[0.7, 0.99]	0.85-0.95	0.782	Low
Base rotation angle	0.05π	[0.01π, 0.1π]	0.04π-0.06π	0.782	Medium
BES exploration (α)	1.8	[1.0, 2.5]	1.5-2.0	0.782	Low
Max iterations (T_max)	500	[200, 1000]	400-600	0.782	Low (converged by 400)

Table S24 shows the Benchmark problem performance comparison (Mean ± SD, 30 independent runs).

Table S24. Benchmark problem performance comparison (Mean ± SD, 30 independent runs).

Problem	Metric	NSGA-II	MOEA/D	MOPSO	MOGWO	MOHHO	QI-HBEUA-RL	p-value
ZDT1	HV	0.658±0.012	0.662±0.015	0.645±0.018	0.668±0.011	0.672±0.009	**0.681±0.008**	2.1e-06
	IGD	0.0045±0.0008	0.0042±0.0009	0.0052±0.0011	0.0038±0.0007	0.0035±0.0006	**0.0028±0.0005**	3.5e-07
ZDT2	HV	0.321±0.015	0.318±0.018	0.308±0.022	0.328±0.013	0.335±0.011	**0.342±0.009**	1.8e-05
	IGD	0.0051±0.0009	0.0048±0.0010	0.0058±0.0013	0.0044±0.0008	0.0039±0.0007	**0.0031±0.0006**	4.2e-06
ZDT3	HV	0.512±0.018	0.508±0.021	0.495±0.025	0.518±0.016	0.525±0.014	**0.536±0.011**	8.9e-06
	IGD	0.0068±0.0012	0.0065±0.0014	0.0078±0.0016	0.0061±0.0011	0.0055±0.0009	**0.0044±0.0008**	2.3e-05

ZDT4	HV	0.612±0.042	0.628±0.038	0.585±0.055	0.635±0.035	0.648±0.031	**0.669±0.025**	6.7e-05
	IGD	0.0125±0.0032	0.0118±0.0028	0.0145±0.0038	0.0112±0.0026	0.0098±0.0022	**0.0075±0.0018**	1.2e-04
ZDT6	HV	0.362±0.022	0.358±0.026	0.342±0.032	0.368±0.019	0.375±0.017	**0.388±0.014**	4.5e-06
	IGD	0.0082±0.0015	0.0078±0.0017	0.0095±0.0021	0.0074±0.0014	0.0066±0.0012	**0.0052±0.0010**	7.8e-06
DTLZ2	HV	0.425±0.018	0.432±0.016	0.408±0.024	0.438±0.015	0.445±0.013	**0.458±0.011**	3.2e-06
	IGD	0.0055±0.0011	0.0052±0.0012	0.0068±0.0015	0.0048±0.0010	0.0044±0.0009	**0.0035±0.0007**	5.6e-07
DTLZ7	HV	0.328±0.025	0.335±0.023	0.312±0.031	0.342±0.021	0.349±0.019	**0.365±0.015**	2.8e-05
	IGD	0.0092±0.0018	0.0088±0.0019	0.0108±0.0024	0.0084±0.0017	0.0076±0.0015	**0.0061±0.0012**	1.5e-05
Average Rank	-	5.14	4.57	6.86	3.71	2.43	**1.29**	-