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Enhanced Performance of Humidification-Dehumidification Desalination Systems through PCM Integration: An Experimental and Numerical Review.

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Abstract

This review systematically examines various Humidification-Dehumidification desalination systems, focusing on their essential components and operational efficiencies. Our study confirms the viability of seawater desalination using these systems, particularly for decentralized applications. Among humidifiers, the packed bed type is predominantly utilized due to its effectiveness. Direct dehumidifiers are shown to enhance system performance significantly compared to indirect types. Hybrid energy systems demonstrate superior efficiency, achieving the highest gain output ratios, while solely thermal-based systems are less efficient. Comparatively, systems incorporating solar water heating surpass those using solar air heating in output. Optimization of system productivity and economic efficiency is achievable through integration with a heat pump, maintaining low costs while enhancing the gain output ratio. Critical design parameters influencing freshwater production include the feed water flow rate, air flow rate, and the designs of the evaporator and condenser. A notable increase in productivity is linked to the expanded surface areas of these components. The study also explores the economic aspects of these systems, comparing costs in scenarios with and without the integration of phase change materials (PCMs), which are extensively used as packing media to improve thermal performance.

Keywords*:* Humidification; Dehumidification; Desalination; Distillation; System; water productivity.

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Nomenclature

Symbols

$\dot{Q}_{in}$	Total energy input (Joules)	*GOR*	Gain output ratio
m_{FW}	Mass flow rate of freshwater (kg/s)	*A*	Surface area (m²)
λ	Latent heat of vaporization (J/kg)	*T*	Temperature (°C)

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Abbreviations

HDH	Humidification-Dehumidification	HDD	Humidification-Dehumidification Desalination
PCM	Phase Change Material	CAOW WH	Closed air Open water / Water Heating
MEH	Multiple Effect Humidifier	CACW WH	Closed air Closed Water / Water Heating
WDS	Water Desalination System	CAOW AH/WH	Closed air Open water Air Heating / Water Heating
GOR	Gain Output Ratio	OAOW AH/WH	Open air Open Water Air Heating / Water Heating
MSF	Multi-Stage Flash	HDH-HP	Humidification-Dehumidification Desalination- Heat Pump
MED	Multi-Effect Distillation	ASHPLTES	air source heat pump system combined with latent thermal energy storage
VC	Vapor Compression	QTASHP	quasi-two-stage air source heat pumps
HDHWDSs	Humidification-Dehumidification Water Desalination Systems	AC	air conditioning
CAOW	Closed air Open water	PF	pin fins heat sink
CWOA	Closed Water Open-air	SWF:	black steel mesh fibers
OAOW	Open air Open Water	HDH-RO	humidification dehumidification reverse osmosis
CACW	Closed air Closed Water	HDH SAHPD	humidification dehumidification (solar assisted heat pump desalination)
N.A	not applicable or value not directly available, * $L/m^2.h$	Hybrid HDH ROD	Hybrid Humidification-Dehumidification Desalination (reverse osmosis Desalination)
PV	Photovoltaic	SBH-DH	solar-based humidification-dehumidification
ETC	Evacuated Tube Collector		
FPC	Flat Plate Collector		
COP	Coefficient of Performance		

Terms

Desalination The process of removing salt and other minerals from saline water to produce freshwater suitable for human consumption and use.
Humidifier A component that increases humidity (moisture) in the air by adding water vapor.
Dehumidifier A component that reduces humidity (moisture) in the air, typically by cooling air to remove moisture via condensation.
Phase Change Material (PCM) Substances that absorb and release thermal energy during the process of melting and freezing, used in energy storage.
Solar Thermal Energy Heat energy derived from solar radiation, used in heating and powering processes such as desalination.
Evaporator A device used to turn the liquid form of a chemical substance such as water into its gaseous-form/vapor.
Condenser A device used to condense a gaseous substance into liquid form, typically by cooling it.
Economic Analysis The systematic approach to determining the optimum use of scarce resources, involving comparison of two or more alternatives in achieving a specific objective under the given assumptions and constraints.

1. Introduction

A Global growth is significantly hindered by a scarcity of freshwater resources. Water desalination systems (WDS) are continuously being developed, enhanced, and modified to tackle this critical challenge. Traditionally, desalination plants have relied on non-renewable energy sources, primarily fossil fuels, rendering them costly and energy-intensive. Consequently, it is crucial to shift towards renewable energy sources to power these systems. Recently, renewable and sustainable resources, including geothermal and solar energy, have been increasingly utilized to supply the entire thermal energy required for operating humidification-dehumidification (HDH) desalination systems. Among various desalination methods, HDH is particularly effective in addressing the acute problem of drinking water scarcity. Desalination technologies are categorized into two main groups: thermal and membrane. The thermal category emulates natural distillation processes and includes techniques such as Solar Still, HDH, Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression (VC) distillation. Conversely, the principal aim of membrane processes is to purify saline seawater through filtration.

2. Humidification–dehumidification (HDH) desalination system.

The HDH (Humidification-Dehumidification) desalination process begins by converting seawater into water vapor in the humidifier, then condensing this vapor on the coils of the dehumidifier at temperatures below the dew point. In the humidification step, sprayers saturate the air with saltwater, which is pre-heated using solar energy, before moving to the dehumidification section where the moisture in the air condenses on the cooler surfaces of the condenser, collecting as distilled water. The majority of the thermal energy released during condensation is transferred back to the cool seawater. HDH systems offer several advantages including scalability, simplicity in design, low-temperature operation, and cost-effectiveness in both setup and operation. These systems effectively integrate renewable energy sources such as solar power. The thermal performance of HDH systems is typically assessed by calculating the Gain Output Ratio (GOR), defined as the ratio of the latent heat of vaporization of the produced freshwater to the total energy input

$$GOR=\frac{\dot{m}_{FW}\times\lambda}{\dot{Q}_{in}} \qquad \text{Equation (1)}$$

Fundamentally, HDH water desalination systems comprise two critical components: the humidifier (evaporator) and the dehumidifier (condenser), alongside the necessary heating source for heating water, air, or both. The evaporator aims to maximize air humidity using devices such as spray towers, bubble columns, wetted-wall towers, and packed bed towers, which employ various packing materials to enhance moisture retention and thereby increase the air humidity ratio. The dehumidifier, or condenser, plays a crucial role in water production by condensing the humid air. Different types of heat exchangers, direct and indirect, are used in dehumidification, with indirect units achieving higher heat recovery by using the hot, moist air to preheat incoming seawater. HDH systems are categorized based on energy source (solar, thermal, geothermal, hybrid), cycle configuration (closed air/open water,

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closed water, or open-air/open water), and the flow dynamics (forced or natural). Additionally, they are differentiated by the stream being heated, distinguishing between air-heated and water-heated systems, which provides insights into the specific heating mechanisms employed.

Summary of HDH desalination systems based on cycle configuration.

The efficiency of water desalination systems (WDS) can be enhanced by heating water, air, or both. Comprehensive reviews of numerous studies on Humidification-Dehumidification Water Desalination Systems (HDHWDSs), categorized by cycle configuration, are summarized in Tables 1 and 2. These tables detail the components of each system—humidifiers, dehumidifiers, packing materials, and heating sources—for different configurations such as CAOW, OACW, OAOW, and CACW. Figures 1 and 2 further illustrate comparisons of cost and productivity across these studies. These visual and tabular summaries showcase key performance metrics, including the Gain Output Ratio (GOR) and production costs, contingent on data availability. The analyses reveal that the CAOW configuration achieves the highest GOR, whereas the OACW configuration records the lowest. Moreover, OACW systems incur the highest costs, while CACW systems are the most cost-effective.

Table 1: Summary of previous works on CAOW cycle for HDH desalination systems.

Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Abu El Nasr et al[4]	Water heating	Spray type	Shell and a coil of copper tube	Solar energy, FPC	N.A	N.A	-Increasing the inlet water temperature improved the system productivity. -The maximum productivity was achieved at 59°C inlet water temperature and 33°C ambient temperature.
Kabeel et al[5]	Water heating	Packed-bed	Shell and a coil of copper tube with corrugated fins	Solar energy, ETC (A = 2 m^2)	Cellulose paper, a = 2800 m^2/m^3	N.A	-The modified condenser enhanced the effectiveness from 0.49 to 0.71. -The maximum productivity was maintained at the ratio of cold water to hot water twice. -Forced-air down circulation maintained higher system performance than those of natural-air, forced-air up, and forced-air up–down circulations.
Wu et al[6]	Water heating	Three-stages of packed-bed	Three-fined tube heat exchanger, 5 m^2	Thermal energy and electrical heater simulate a solar energy	Porous plastic balls	2.65 at 85°C heating temperature	-The highest system output achieved was 182.47 kg when the feed water rate was set at 2 t/h..
Amer et al[7]	Water heating	Packed-bed	Shell and a coil of copper tube with fins, (A = 6 m^2)	Thermal energy, electrical heater (6 kw)	Wooden slate, Gunny bag cloth, PVC sheets	N.A	-The system productivity improved by 5%, 15%, and 50% at water flow rate 2.8, 2.3, and 1.8 kg/min, respectively.
Zubair et al[8]	Water heating	Packed-bed	N.A	Solar energy, ETC with heat pipes	N.A	1.6	-The highest productivity was maintained in June then September and March, and the lowest in December.
Wang et al[9]	Water heating	Packed-bed	N.A	Solar energy, photovoltaic panel, (A = 9.16 m^2)	N.A	N.A	-The highest daily productivity of 0.873 L/m^2 was maintained at 64.3°C evaporative temperature. -Cost of fresh water from solar power—HDH process was similar to that of traditional treatment plants.
He et al. [10]	Water heating	Packed-bed	Packed-bed	Waste heat recovery exchanger	Polypropylene, Sulzer Mellapak 250 Y	1.44	-Increasing the flow rate of dry air from 0.1 to 0.5 kg/s increased the total cost of heat transfer area from $470.81 to $701.46.
Wu et al[11]	Water heating	Three stages of packed-bed	Three finned–tube heat exchanger, (A = 5 m^2)	Thermal energy and electrical heater simulate a solar energy	Porous plastic balls	2.65	-The system yield decreased with increasing the supplement water flow rate and the condenser drainage.
Narayan et al[12]	Water heating	Packed-bed	Four polypropylene plate and tube, (A = 8 m^2)	Thermal energy, electric heater	Polypropylene, CF1200 MA a = 226 m^2/m^3	4	-The maximum GOR without mass extractions can be ensured at higher brine temperature. -The extractions of mass from humidifier toward dehumidifier enhanced the GOR up to 55%.
Zamen et al[13]	Water heating	Two-stage of packed-bed	Finned-tube heat exchanger, (A = 30 m^2)	Solar energy, FPC (A = 80 m^2)	Polypropylene, a = 240 m^2/m^3	N.A	-The productivity of two-stage unit improved by 20% compared with that of a single-stage unit. -The summer total production was double compared to winter production.
Zhani[14]	Water heating	Packed-bed	Polypropylene plate type of condenser.	Solar energy, FPC (A = 7.2 m^2)	Thorn trees	3	-The gas-to-liquid ratio (GOR) was improved by elevating the water flow rate to the humidifier, whereas it was reduced by raising the water flow rate in the dehumidifier.
Hermosillo et al[15]	Water heating	Packed-bed	Shell and heat exchanger of liquid gas type, (A = 3.5 m^2).	Solar energy, ETC	Cellulose paper, a = 300 m^2/m^3	0.91	-The proposed system enhanced the productivity by 50-70% than a solar still system.

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Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Hamed et al[16]	Water heating	Packed-bed	Shell and a coil of copper tube with corrugated fins.	Solar energy, ETC (A = 2 m^2)	Cellulose paper	2.2	-The cost of distillate water per liter was 0.0578$. -The productivity enhanced with raising the water temperature inlet to humidifier. -Operating the system from 13 to 17 PM maintained the best performance.
He et al[17]	Water heating	Packed-bed	Plate-type heat exchanger	Waste heat recovery exchanger	Polypropylene, Sulzer Mellapak 250Y	1.51	-The GOR increased from 1.28 to 1.85 with increasing the dehumidification effectiveness from 0.8 to 0.9. -The unit cost of water production reduced with humidification effectiveness.
Thiel et al [18]	Water heating	Packed-bed	Very simple tube-in-tube device, (A = 4.88 m^2)	N.A	CF-1900SB/MA	5.65	-The optimal extraction flow was about 40% of the total flow. -Doubling the dehumidifier area enhanced the GOR by two or three times, while the water production increased insignificantly.
Sharqawy et al[19]	Water heating	Packed-bed	Finned-tube heat exchanger, (A = 11.7 m^2).	Solar energy or waste heat.	Cross-fluted film fill media.	1.93	-The optimum flow rate ratio was greater than unity. -Higher GOR was maintained with decreasing the maximum water temperature and/or by raising the minimum water temperature.
	Air heating	Packed-bed	Finned-tube heat exchanger, (A = 47.1 m^2).			2.19	-The optimum flow rate ratio was less than unity.
He et al [20]	Air heating	Packed-bed	Plate-type heat exchanger	Waste heat recovery exchanger	Polypropylene, Sulzer Mellapak 250Y	3.06	-The higher waste heat temperature increased both water production and the total investment of the air-heated system; however, it decreased the GOR and the cost of water production.
Giwa et al [21]	Air heating	Packed-bed	Shell and a coil of copper tube, (A = 6 m^2)	Solar energy air cooled PV	Wooden slate sheet	N.A	-The PV-RO desalination system reduced the environmental impacts by 83.6%.
Houcine et al [22]	Air heating	Packed-bed	Finned-tube heat exchanger	Solar energy, FPC (A = 44.1 m^2)	Cellulose paper	N.A	-The cost of water derived from the suggested multiple-effect humidification process was greater in comparison to alternative enhanced systems.

Table 2: Review of previous researches on the OACW cycle for HDH desalination systems.

Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Dai and Zhang [23]	Water heating	Packed-bed	Finned-tube heat exchanger	Hot steam from boiler instead of solar energy, solar collector	Honeycomb paper	0.85	- At the optimum operating conditions, the thermal efficiency of this system was 0.85%.
Elminshawy et al [24]	Water heating	Solar still with reflectors	Shell and tube heat exchanger	Hybrid energy, solar energy, and thermal energy, electric heater	N.A	0.77	- The productivity of the HDH system improved by 210%, 312%, and 366% at 1, 10, and 15 April by using water heaters and reflectors
Mohamed et al [25]	Water heating	Packed-bed	Finned-tube heat exchanger	Solar energy, ETC	Cellulose paper	0.55	-The air flow rate, flow rate ratio, and water flow rate were measured at 0.81, 4.5, and 4 kg/min, respectively.
Huang et al [26]	Water heating	Packed-bed	Finned-tube heat exchanger, (A = 27.43 m^2)	Hot steam from shell and tube heat exchanger, (6.91 m^2)	N.A	N.A	- The air mass flow rate should be as small as possible.in order to minimize the specific total energy consumption,
Zubair et al [27]	Water heating	Packed-bed	Shell and three of fined tube heat exchanger	Thermal energy, four electrical heaters	Cellulose paper	0.7	-The modified cycle improved energy performance over the basic cycle by 100%. -The inlet water temperature had an inconsiderable effect on the product cost.
Tariq et al [28]	Water heating	The cycle-based air saturator	Shell and tube heat exchanger, (A = 1.5 m^2)	Solar energy, FPC	N.A	0.8	-The proposed system enhanced the fresh water productivity, recovery ratio, and gain-output ratio by 30%, 46%, and 11%, respectively, while it reduced -The cost by 14% compared to the conventional system with a direct-contact humidifier.
Khalil et al [29]	Water heating	Bubble column	Shell and tube heat exchanger	Solar energy, ETC	N.A	0.53	-Air bubbling humidification technique operated efficiently in HD systems than the conventional one. -The maximum productivity was maintained with one millimeter hole diameter.
El-Agouz [30]	Water heating	Bubble column	Shell and tube heat exchangers, (A = 4.6 m^2)	Thermal energy, three electric heaters	N.A	0.8	-The system productivity was affected moderately by water temperature and air flow rate, whereas it was influenced slightly by water level.

Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
							-The maximum productivity was maintained at water temperature of 86°C and air flow rate of 14 kg/h.
Enayatollahi et al [31]	Water heating	Spray type	Shell and tube heat exchanger	Solar energy, FPC (A = 2 m^2)	N.A	N.A	-Raising the water flow rate reduced the system production. -The productivity increased with increasing the air flow rate to a specified value beyond that, the production decreased.
Huang et al [32]	Water heating	Spray type	Four stages dehumidifier with indirect heat exchanger	Heater	Direct contact between saline water and air	2.89 - 3.43	-The maximum GOR reduced by 11.44% with increasing the salinity from 4% to 20%. -The evaporation rate and the system productivity decreased by almost 0.66% and 0.75% per 1% increase in water salinity.
Huang et al [33]	Water heating	Spray type	Shell and tube heat exchanger	Using steam	Corrugated metal sheet packing	N.A	-The electrical energy consumption had a remarkable effect on overall energy system efficiency. -The minimum specific energy consumption was 222.0 kJ/kg.
Shalaby et al[34]	Water heating	Packed-bed	Shell and tube condenser type	Evacuated tube solar water heater	16 layers of wick were	N.A	-Wick packing material increased the daily system productivity by 28.28%. -Increasing the flow rate of brackish water, and its temperature improved the system productivity.
Srithar et al[35]	Air heating	Packed-bed	Shell and copper coil	Condenser of refrigerator	Gunny bag	N.A	-The COP of the conventional refrigeration system was 2.6, and it was improved up to 4.61 with integrating HDH system. -The COP of the modified refrigerator system reached 7.6 using turbulator in condenser and dehumidifier covered with gunny bag 33
Sachdev et al[36]	Air heating	Wind tower	Shell and tube heat exchanger	Solar energy (absorber plate with double-glass cover)	Clay conduit column	N.A	-The optimum air mass flow rate increased the productivity by 354% compared with the minimum flow rate. -The high value of inlet air temperature was preferred for the maximum productivity of 6.7 kg/day.
Li et al [37]	Air heating	Packed-bed	Shell and long tubes of copper with fins	Solar energy, solar air heater with evacuated tubes (A = 14 m^2)	Cellulose paper	N.A	- Raising the inlet water temperature to the humidifier from 9 to 27°C resulted in a significant improvement in the air relative humidity, increasing it from 89% to 97%, along with an increase in the outlet air temperature from 35 to 42°C. 2. -Improving both the outlet air temperature and air relative humidity led to a noticeable increase in the system's production efficiency.

* L/h.m^2

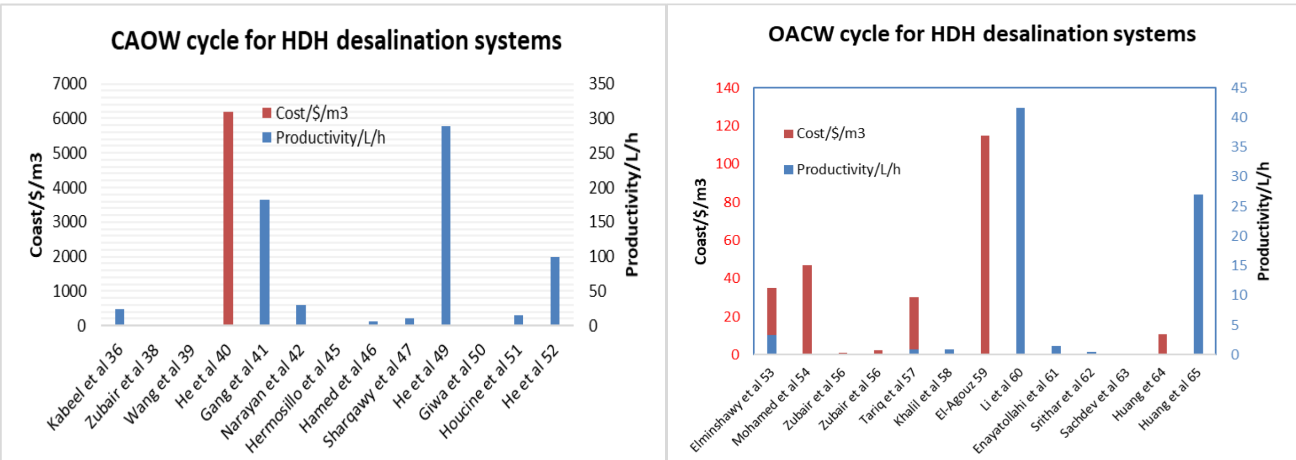

Figure 1: Cost versus productivity of previous works on (a) CAOW cycle and (b) OACW for HDHWDSs.

Table 3 Review of previous research on the OAOW cycle for HDH desalination systems.

Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Zhang et al [38]	Water heating	Packed-bed	Two finned-tube heat exchangers (A = 28,21 m^2)	Condenser of heat pump cycle	Polypropyl-ene a = 400 m^2/m^3	2.052	-The seawater temperature had a considerable effect on productivity, whereas the effect of air temperature was inconsiderable.
Zubair et al [27]	Water heating	Packed-bed	Three finned-tube heat exchangers	Thermal energy, four electrical heaters	Cellulose paper	0.35	-The GOR increased with increasing the water-to-air mass ratio; however, further increase of mass ratio reduced the GOR.
He et al [20]	Water heating	Packed-bed	Packed-bed	Condenser of heat pump cycle	Polypropylene, Sulzer Mellapak 250 Y	4.17	-The dehumidification effectiveness had an inconsiderable impact on the heat pump performance. -Lowering the inlet air wet-bulb temperature improved the water production and the gained-output ratio.

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Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Faegh and Shafii [39]	Water heating	Packed-bed	Evaporator of heat pump cycle	Condenser of heat pump cycle	CF1200MA Cross Fluted Film Fill Media	2.476	-Increasing the evaporator saturation temperature enhanced the COP and the system GOR. -Increasing the condenser saturation temperature reduced the GOR.
Zhang et al [40]	Water heating	Packed-bed	Two finned-tube heat exchangers (A = 28,21 m^2)	Condenser of heat pump cycle	Polypropylene	2.532	-The system yield was minimally impacted by changes in air temperature. -The system productivity significantly improved with higher air humidity ratio and seawater flow rate.
Okati et al [41]	Water heating	Solar still	Subsurface condenser chamber	Solar energy, FPC	N.A	N.A	-Increasing the inlet air velocity from 0.1 to 0.3 m/s enhanced the system productivity by 77.28%. -The augmentation in water production was noted following the increase in the number of condenser pipes from 1 to 8.. -Increasing the inlet water temperature from 30°C to 50°C enhanced the system productivity by 70.70%.
Dehghani et al [2]	Water heating	Packed-bed	Packed-bed	Gas burner heater	Polypropylene a = 240 m^2/m^3	0.65	- Increasing the recirculation brine from 10% to 30% improved the system overall recovery ratio from 66% to 86%, while it decreased the GOR from 0.65 to 0.45. -Increasing the salinity of the water from 10% to 20% and 30% led to a rise in heat load by 8% and 16%, respectively. -Increasing the water salinity reduced the production.
Lawal et al[42]	Water heating	Packed-bed	Four pieces of fin-tube heat exchangers	Condenser of heat pump cycle	Corrugated cellulose pads of honeycomb	4.07	-The system provided cooling load of 3.07 kW -The COP of heat pump ranged from 3.06 to 4.86.
Lawal et al [43]	Water heating	Packed-bed	Four pieces of fin-tube heat exchangers	Condenser of heat pump cycle	Cellulose pads packing material	Variable	-Increasing the humidifier effectiveness and decreasing seawater flow rate enhanced the GOR.
Rajaseenivasan and Srithar [44]	Air heating	Bubble column	Shell and coil type of heat exchanger	Biomass stove with sawdust briquettes as fuel	N.A	1	-The performance of the humidifier was greatly influenced by the temperature of the water. -High specific humidity was achieved with a bubble humidifier with one-millimeter pipe hole diameter, 170 mm water depth, and 60°C water temperature.
Shafii et al [45]	Air heating	Packed-bed	Evaporator of heat pump cycle	Condenser of heat pump cycle	Cellulose paper	2.08	-Increasing the air relative humidity and its flow rate passing through the dehumidifier enhanced the system GOR. -Raising the ambient temperature reduced the GOR.

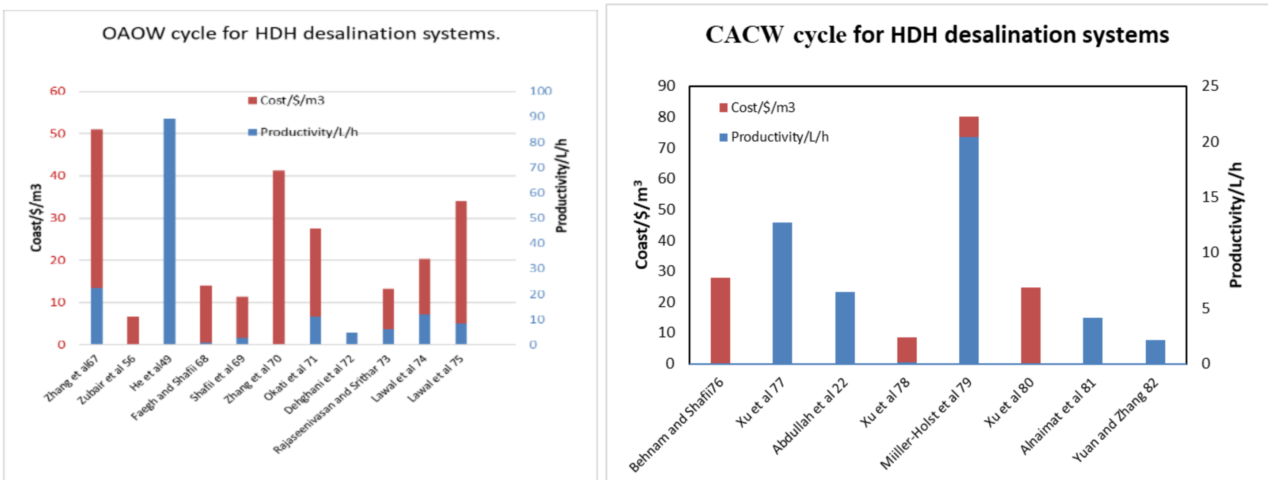

Figure 2: Cost versus productivity of previous works on (a) OAOW cycle and on (b) CACw -WH cycle for HDHWDSs.

Table 4: Synopsis of previous research for HDH desalination systems that follows the CACW cycle.

Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
Behnam and Shafii [46]	Water heating	Bubble column	Shell and coil of copper tube	Solar energy, ETC with heat pipe	N.A	0.65	-Adding oil between the evacuated tube collector and heat pipes enhanced the freshwater production and the performance. -Eliminating water pump and water circulation through collectors increased the daily production rate and reduced the cost per liter.
Xu et al [47]	Water heating	Packed-bed	Finned-tube heat	Hybrid energy, thermal energy, and condenser	Honeycomb paper	1.24	-The productivity of this system decreased with increasing the cooling seawater flow rate.

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Reference	Purpose	Humidifier	Dehumidifier	Heating source	Packing material	GOR	Important remarks
			exchanger, (A = 0.49 m^2)	of heat pump cycle			-A high ratio of remaining water flow rate from the humidifier to the total water flow rate enhanced the system performance.
Abdullah et al[48]	Water heating	Packed-bed	Shell and two twisted copper coils	Solar energy, PTC	Aspen pad, thorn trees	2.5-4.5	-The type of packing materials has a clear effect on the productivity.
Xu et al[49]	Water heating	N.A	N.A	Solar energy, solar collector	N.A	12.24	-The enhancement in system performance was achieved through an increase in the temperature of the seawater being sprayed.
Miiller-Holst et al[50]	Water heating	Packed-bed	Flat-plate heat exchanger	Solar energy, soar collector (A = 38 m^2)	Hanging fleeces made of polypropylen e	3-4.5	-The improved distillation unit reduced the average value of the specific thermal energy required to distillate production from 90 to 110 kWh/m^3.
Xu et al [51]	Water heating	Two stages of packed beds	Finned-tube heat exchanger	Hybrid energy, solar collectors (A = 15 m^2) and condenser of heat pump cycle	Honeycomb paper, a = 396 m^2/m^3 Plastic polyhedron empty balls, a = 500 m^2/m^3	1.93	-The two-stage WDS exhibited a reduced water-production cost of approximately 17.4% in comparison to the single-stage method. -the productivity was improved by about 15.5%, and GOR was increased by 55.6%.
Alnaimat et al [52]	Water heating	Packed-bed	N.A	Solar energy, FPC (A = 16 m^2)	Polypropylen e	N.A	-The diffusion-driven desalination system with low cost of installation and energy consumption is more competitive with other WDS.
Yuan and Zhang [53]	Water heating	Two stages of packed-beds	Plate heat exchanger	Solar energy, solar collector (A = 10 m^2)	Honeycomb paper	N.A	- Productivity decreases with increasing feed-water flow rate. - The maximum water production could be maintained by optimizing the flow rate of cooling water with collector area.

3. Comparison of Economic Cost versus Productivity.

The development of desalination technology is significantly influenced by economic considerations. Consequently, comprehensive financial analyses have been undertaken in this field. The subsequent section, referenced in Table 5, evaluates various cost analysis studies pertaining to humidification, dehumidification, and desalination processes. Voivontas et al. [54] conducted a cost-benefit analysis of renewable energy desalination systems, while Goosen et al. [55] explored the cost-effectiveness and efficiency of solar desalination plant designs. These researchers identified that the most critical factors in the economic analysis of Humidification-Dehumidification Desalination (HDD) systems are the operating and maintenance costs of condensers and pumps. Moreover, integrating HDD systems with waste heat recovery and regeneration cycles has the potential to enhance both economic and thermodynamic efficiencies.

Shatat et al. [56] reported that the cost of producing freshwater from solar-powered desalination systems is approximately \$11/m³. This assessment was specific to systems deployed in dry and semi-dry remote areas. The study highlighted that increases in the lifespan of desalination plants lead to reduced production costs. Additionally, as system capacity expands, the cost per unit of freshwater decreases. The economic parameters assessed in this study included plant lifespan, solar collector area, and interest rates.

Table 5: Various cost analysis investigation studies in the field of HDH desalination

Author	Study category	System description	Productivity (L/day)	Cost (\$/m^3)
Zubair et al.[57]	Theo.	CAOW WH	45 - 53.3	3.2 - 3.8
Ariyanfar et al.[58]	Exp.	CAOW WH	7836.48	0.86
Wang et al.[9]	Exp.	CAOW WH	0.873 *	21.8
Xu et al.[49]	Theo.	CACW WH	3.36	8.59
Behnam et al.[46]	Exp.	CACW WH	6.275 *	28
He et al.[17]	Theo.	CAOW	2377.2	20
He et al.[10]	Theo.	CAOW WH	2030.4	6200-13400
Rahimi-Ahar et al.[59]	Theo.	CAOW	48 - 52.2	2- 41
Wu et al.[11]	Exp. & Theo.	CAOW	4368	2.5
Narayan et al.[12]	Exp.	CAOW	700	-
Sayyaadi et al.[60]	Theo.	CAOW AH/WH	23280	0.66
Rahimi-Ahar et al.[61]	Exp.	CAOW AH/WH	25.68 *	4.1
Zhani et al.[62]	Exp.	CAOW AH/WH	20	0.08 €l
Okati et al.[41]	Theo.	OAOW WH	264.8	2.76
Rajaseenivasan et al.[44]	Exp.	OAOW	146.4	13.3
Elminshawy et al.[63]	Exp. & Theo.	OAOW	104 **	3
El-Agouz et al.[64]	Theo.	OAOW AH/WH	0.46 kg_w/kg_a	-
El-Agouz et al.[65]	Exp.	-	9 **	29
Dayem et al[66]	Exp.	-	9 *	500
Zubair et al.[27]	Exp. & Theo.	OAOW	-	4.10 - 6.55
Zubair et al.[27]	Exp. & Theo.	OACW		0.79 - 2.25
Deniz et al.[67]	Exp. & Theo.	OACW A/WH Solar HDH	26.88	98.1

Author	Study category	System description	Productivity (L/day)	Cost ($/m^3)
Tariq et al.[28]	Theo.	OACW-WH	21	30
El-Agouz[30]	Exp. & Theo.	OACW WH	197.28	115
Elminshawy et al.[24]	Exp. & Theo.	OACW WH	30.3 *	35
Ahmed et al.[68]	Exp.	OACW A/WH	360	10
Rajaseenivasan et al.[69]	Exp.	OACW AH/WH	15.23 *	25.7
He et al.[70]	Theo.	Heat pump	1717.44	18
Zhang et al.[40]	Theo.	Heat pump	1021.2	41.2
Rostamzadeh et al.[71]	Theo.	Heat pump	932.16	2217 - 7130
Faegh et al.[72]	Theo.	Heat pump	287.8	14
Zhang et al [73]	Exp.	Heat pump	534.24	51
Lawal et al.[42]	Exp.	Heat pump	287.8	10.68
Hamed et al.[16]	Exp. & Theo.	Solar HDH	22	57.8
Ayati et al.[74]	Theo.	HDH	25.2	3.4
		HDH-HP	32.16	3.42
		HC-HP	32.4	5.12
		VPHDH-HP	43.92	4.68
Elsafi[75]	Theo.	HDH-CPVT AH	33	10
Jamil et al.[76]	Theo.	Hybrid HDH ROD	-	0.13
Rajaseenivasan et al.[77]	Exp.	HDH SAH	16.32 *	32
		HDH SAH /Turbulators	20.61 *	26
		HDH DPC/Turbulators	23.92 *	19
Yuan et al.[78]	Exp.	HDH-EVT WH	1200	2.9
sharshir et al.[79]	Exp.	HDH-Solar Still EVT WH	20.49	34
Xu et al.[47]	Exp.	HDH SAHPD	306	30-42
Xu et al.[51]	Exp.	HDH SAHPD	418.8	25 -30
Shafii et al.[45]	Exp.	HDH AH	66.96	11.4
Muthusamy et al.[80]	Exp.	HDH AH	6.8	1250
Faegh et al.[81]	Theo.	HDH WH	21.84	14
Ali et al.[82]	Exp.	HDH WH	42	14.4
Farsad et al.[83]	Theo.	HDH AH/WH	22	57.8
Zubair et al. [84]	Exp.	HDH WH	224.304 -72.24	21-34
Kabeel et al.[85]	Theo.	HDH-FE	96	8.6 for hybrid
				9.7 for separate
Kabeel et al.[86]	Theo.	HDH-FE	96 88 77 89	12.53 13.08 17.71 14.23
Habeebullah[87]	Exp.	HDH HP	2230	13.5
El-Said et al.[88]	Theo.	MSH SSF	112.5	6.43
Abdel-Hady et al.[89]	Exp.	-	130.18	43
Lawal et al. [90]	Exp.	MSF-HDH	30,549,000	1.068
Easa et al [91]	Exp.	solar humidification dehumidification	32.6 ****	41

* L/day·m^2, ** L·m^{-2}, *** US$/L·h, ****kg/day

4. Comprehensive Review of Phase Change Materials (PCM).

This section offers a detailed review of the literature on phase change materials (PCMs), encompassing a wide range of PCMs suitable for thermal storage across various operating temperatures. It also addresses challenges associated with the application of these materials in practical energy storage systems. Thermal energy storage systems are primarily categorized into two types: sensible and latent heat storage systems, with the latter exhibiting superior efficiency. This enhanced performance is attributed to their significant thermal storage capacity, the ability to undergo isothermal phase changes, and minimal volume changes during the melting and solidification phases [25].

4.1. Concept of Phase Change Energy Storage.

Phase change materials function as thermal storage media, capable of storing thermal energy through a phase transition from solid to liquid and vice versa. This phase change occurs isothermally, whether during melting for heat storage or during solidification for crystallization recovery. The thermal energy is stored as latent heat, emerging from the endothermic breakdown of PCM chemical bonds during the transition from solid to liquid. Conversely, this stored energy is exothermally released when the PCM reverts to its solid state, maintaining a consistent temperature throughout the process [92]-[94]. The ability of PCMs to absorb and retain a significant amount of heat without temperature fluctuation categorizes them as effective thermal storage solutions.

The melting point varies across different types of PCMs. Typically, PCMs serve as thermal storage units during the day, releasing stored energy at night to enhance system efficiency. The stored energy, known as latent heat or heat of fusion, is critical during phase transitions. Latent heat storage can take various forms, including solid-solid, solid-liquid-vapor, and solid-liquid phase changes. Selection criteria for PCMs, detailed in Table 6, include thermal stability, phase transition temperature, and heat storage capacity [96]-[100].

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Property	Characteristics
Thermodynamics	Suitable phase change temperature, High latent heat of transition, High specific heat, High thermal conductivity, Homogenous melting.
Kinetics	No super cooling, High crystallization rate, High nucleation rate
Physical	Favorable phase equilibrium, High density, Small to no change in volume, Low vapor pressure, No phase segregation.
Chemical	Chemical stability, Compatibility with container materials, Nontoxic, Nonflammable, Nonexplosive, Noncorrosive, No degradation.
Economic	Available, Low price, Easy recycling and treatment, Good environmental performance.

4.2. Classification of Phase Change Materials.

As depicted in Figure 3, phase change materials (PCMs) are classified into three main categories based on their chemical composition: organic, inorganic, and eutectic substances. Key thermal properties of these PCMs, such as the range of phase change temperatures and the enthalpy of transformation, are critical in defining their heat storage capacity and potential applications. During a phase transition, PCMs exhibit a considerably higher specific heat capacity compared to conventional fluids. For example, paraffin is particularly advantageous due to its minor density fluctuations between its solid and liquid states, making it an excellent choice for PCM applications.

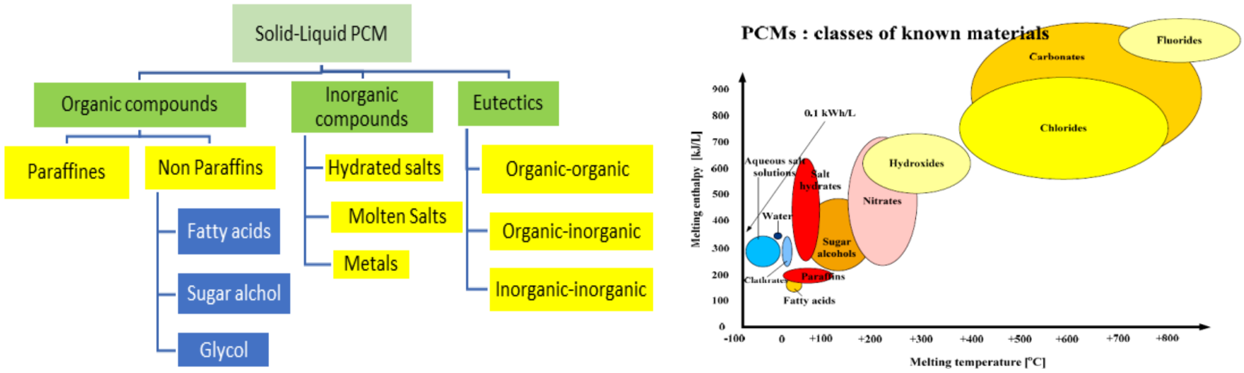

Figure 3: (a) Phase change materials (PCMs) classification and (b) name of PCM materials [101].

4.2.1. Organic Phase Change Materials

Paraffins: These are among the most popular and user-friendly organic PCMs, with melting points ranging from -20°C to 120°C. Paraffins are chemically inert, non-toxic, and environmentally benign, thus they do not contribute to corrosion in energy storage systems. Typically derived from mineral oil, paraffins are saturated hydrocarbons exhibiting similar properties. Paraffins with carbon chain lengths from C5 to C15 remain in a liquid state at room temperature, whereas those outside this range are solid waxes. The melting temperatures of these paraffins, influenced by the length of their carbon chains, range from 23 to 67°C, with longer chains resulting in higher melting temperatures and greater heat of fusion. Extensive research indicates that paraffin waxes possess many ideal characteristics for heat storage applications.

Non-paraffins: This group includes various other organic compounds such as esters, fatty acids, stearic acid, palmitic acid, alcohols, and glycols, all utilized for latent heat storage. Non-paraffin organics form the largest category of phase change materials, offering a broad spectrum of melting points and heat of fusion values.

4.2.2 Inorganic Phase Change Materials

Salt Hydrates: These compounds generally follow the chemical formula MnH2O, where 'M' represents an inorganic base. Salt hydrates are critical in heat storage applications due to their significant volumetric latent heat capacity. Their melting points vary between 15 and 117°C. Salt hydrates can melt in three different ways: congruent, incongruent, and semi-congruent, each affecting the stability and repeatability of their thermal storage properties [102].

4.2.3 Eutectics

Eutectics are complex mixtures of two or more salts that solidify at a specific melting/freezing point. They can be categorized into organic, inorganic, and organic-inorganic based on their composition. Eutectics behave similarly to congruent melting salt hydrates and are promising for thermal energy storage applications due to their ability to melt and solidify without segregation. This property ensures that they form a homogeneous crystal blend upon solidification, thereby minimizing the chances of component separation and enhancing the stability of the storage medium.

5. Summary review of using PCM in HDH system.

Faegh et al. [39] proposed a novel method for harnessing the latent heat from condensing vapor in solar stills by utilizing phase change materials (PCMs) as a thermal storage medium. During daylight hours, solar-generated water vapor is funneled to an external condenser filled with PCM, where it condenses, allowing the PCM to absorb and store latent heat that would otherwise be lost. Notably, the PCM and the salty water do not come into direct contact, preventing immediate solar energy storage in the PCM. Instead, the stored energy is gradually transferred to the saline water in the evening, facilitating continued desalination after sunset. Test results indicated that incorporating an external condenser equipped with heat pipes into solar stills with evacuated tube collectors significantly enhances nighttime desalination efficiency without reducing daytime yield. With PCM, the yield improved by 86%, achieving a productivity of 6.555 kg/m² per day at 50% efficiency.

Yu et al. [103] introduced an air source heat pump system combined with latent thermal energy storage (ASHPLTES) designed to enhance heating performance in cold climates. A comprehensive techno-economic evaluation of ASHPLTES was performed in four representative cities in China, comparing it with conventional systems such as quasi-two-stage air source heat pumps (QTASHP), coal-fueled boilers, wall-hanging gas boilers, and direct electric heating systems. The study utilized mathematical models to evaluate the energy, environmental, and economic performance, revealing that heat pump systems like QTASHP and ASHPLTES offer significant energy conservation and environmental benefits, despite their higher initial and operational costs. Potential reductions in these costs could be achieved through increased productivity and government subsidies.

Nada et al. [104] explored a low-energy Humidification-Dehumidification (HDH) and air conditioning (AC) hybrid system incorporating an efficiently designed dehumidifier and innovative packing pad materials. An empirical study assessed the system's effectiveness over various operational parameters, such as air and water flow rates, temperature settings, and packing pad thickness. The results showed that the hybrid system could produce fresh water while simultaneously reducing the cooling load, thus maintaining optimal indoor comfort levels. The study also found that increasing the flow rates and temperatures improved the system's overall performance and fresh water production rate, although this also led to higher production costs. However, increasing the thickness of the cooling pads reduced the cost per kilogram of fresh water produced. System performance metrics, including fresh water productivity, cooling load capacity, and efficiency, demonstrated the system's capacity to achieve a cost as low as 0.7 ¢/kg FW, with productivity reaching 17.42 kg/h, a cooling load of 3.9 kW, and an air supply temperature of 16°C at a coefficient of performance of 4.35.

Table 8: Previous research using PCM for HDH and solar still systems.

Author	Year	Study type	System description	PCM	GOR	Productivity	Cost	Result
Nan Wang et al. [105]	2020	Theo.	Solar-based desiccant AC system with HDH	RT-44 Melting point of 41 − 44 ° C	For an air mass flow rate of 0.78 kg/s. from 0.113 to 0.104.	4.9 L/h	-	- Before entering the desiccant wheel, the regeneration air was preheated by a photovoltaic/thermal sun collector device. - The PCM enhanced the solar system to meet the heating demands of the air conditioning system at night. - For an air mass flow rate of 0.78 kg/s, the maximum COP=0.411 heat capacity =3.39 kWh efficiency =65%. - The photovoltaic collector's maximum electrical power generation capacity and electrical efficiency were 0.72 kWh and 13.7 percent, respectively. - The PCM's maximum thermal energy was around 0.89 kWh.
Zhang et al.[106]	2018	Exp. & Theo.	HDH	- PCM (I) is the common paraffin. - PCM (II) is the mixture with volume fraction 50% of expanded graphite, 1% of oleic acid triethanolamine, and 49% of ordinary paraffin.	13.37	the water capacity is 0.2 L/h.	23.47 Yuan/t	Increased 84.4% compared with the dehumidifier without using PCM. and the water production ratio is 13.37.
Wang et al.[107]	2013	Exp. & Theo.	Condensers packed with PCM spheres.	HS 34 PCM that has an about 2˚C melting temperature interval around 34˚C.				Heat and mass transfer between gas and water and get about 16.3 % more fresh water productivity in 4 h than the same condenser with co-current flow arrangement under given conditions.
Ketut et al [108].	2020	Exp.	Double slope solar distillation	Myristic acid	-	not effective during daytime	-	-The use of myristic acid for increasing the productivity of solar distillation in is not effective because the melting point of it is higher than water temperature in the basin. Material with a phase change temperature below 42.5 °C is more appropriate to use in these conditions.
Yousef et al [109].	2019	Exp.	Solar still incorporated with PCM storage unit for solar	Paraffin wax. And pin fins heat sink (PF) is embedded inside the	-	-	-	-The findings indicate that the overall daily cumulative production of distilled water from the still with PCM, still with PCM-PF, and still with PCM-SWF surpasses that of the traditional still by 9.5%, 16.8%, and 13%, respectively.

Author	Year	Study type	System description	PCM	GOR	Productivity	Cost	Result
			distillation system.	PCM and, black steel mesh fibers (SWF) are employed in basin with PCM.				
Tiwari et al [110].	2024	Exp.	SBH-DH system that incorporates a solar air heater (4.687 m^2) based on phase change material (PCM)	-	-	15.9 L/day	41$/$m^3$	increases the operating time by 3 h. But the yield of the system with PCM does not change significantly in comparison to the system without PCM
Vijayakumar et al [111].	2021	Exp.	solar stills equipped with HDH	paraffin wax	-	-	-	The experiments revealed that by adding phase change materials to stepped solar still with HDH, the production of distilled water is increased by around 84.4% compared to stepped solar still equipped with HDH alone.
Mohanasund-aram et al. [112].	2023	Exp. & Theo.	solar desalination	–	-	6.273 kg per square meter per day in the winter and 9.715 kg per square meter per day in the summer.	-	As a result, the hybrid effort increased both the yield of fresh water and the drinking water's quality.
Reyes et al [113].	2023	Exp. & Theo.	passive solar desalinator.	paraffin wax.	-	ranged from 1120 to 1313 liter/m^2	between 0.0165 and 0.0593 $/liter.	1)PCM had no yield impact since exposed area is shared between absorber plate and tubes. 2) Freshwater production costs increased with the PCM incorporation.
Bozorgi et al. [114].	2023	Theo.	heat pump Hybridized with phase change Material-based solar desiccant cooling system	-	-	-	-	the PSDC system provides thermal comfort conditions in Vancouver and Toronto with COP of 1.05 and 1.44, respectively. While in Doha and Bangkok, the innovative system that is HP-PSDC system has better performance when the COP (Coefficient of Performance) of the former is 4.98 and the latter is 4.5.

Wang et al.[107] reported that condensers serve as important components for humidification–dehumidification (HDH) desalination plants. It was validated against the experimental data from a small scale HDH desalination system. The comparisons of productivities and temperature profiles among gas, liquid, and solid phases exhibit a high level of consistency with the recorded data. Phase change material (PCM) melting processes do not significantly impact the water production rate in a co-current flow arrangement. However, a condenser filled with PCM capsules demonstrates higher water production rates compared to one filled with air capsules under specific conditions.

Hu et al [115] conducted a study on a solar HDH desalination system utilizing a condenser packed with PCM material in a spherical form. The performance of PCM as a packed bed was examined. The results indicated that the productivity of WDS was affected by several factors such as condenser geometrical aspect ratio, size of packing material, water to air flow ratio, and PCM thermal properties. The results revealed that the water to air flow ratio recorded 1.5 as an optimum value. In addition, using a small size of PCM as packing material with high heat conductivity maintained maximum values of the productivity.

Hassabou et al [116] discussed the results of experimental studies on a phase change material (PCM) supported humidification-dehumidification (HDH) system. The system consists of an evaporator and condenser comprised by two cylindrical packed beds with phase change materials encapsulated in spherical plastic shells. The primary aim of employing PCM packing is to attain a variety of heating/humidification and cooling/dehumidification effects as air traverses through the consecutive PCM layers in the evaporator and condenser, respectively. The study delves into the examination of the effectiveness and feasibility of incorporating PCM components in HDH solar desalination plants, specifically under stable operating conditions. Since the multiple-effects phenomena of interest have a profound impact on the system performance under steady state conditions. Experiments, not only on laboratory scale but also as a prototype, were designed and performed to measure fundamental time dependent variables and critical parameters affecting the system performance.

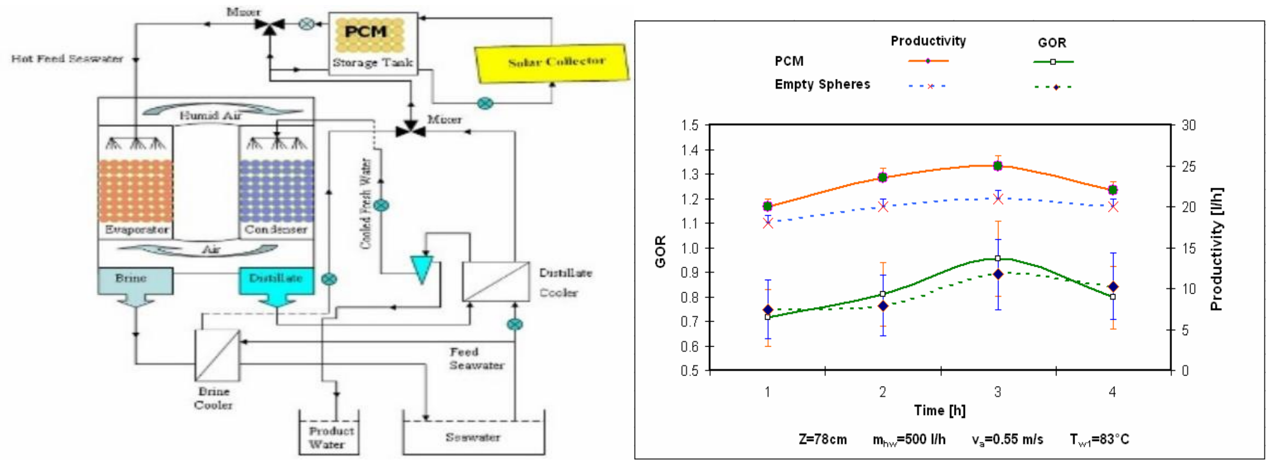

Figure 4: (a) Schematic diagram of PCM based HDH desalination unit. (b) Evolution of productivity and GOR for PCM and Empty balls packing elements [116].

Adil A. M. Omara [118] The research paper discusses the utilization of phase change materials (PCMs) as latent heat storage systems to enhance the efficiency of solar stills. Previous research on boosting the efficiency of both active and passive solar stills using PCM is also outlined. The findings reveal that a passive solar still integrated with PCM can lead to a productivity enhancement of up to 120% compared to a solar still lacking PCM. On the other hand, an active solar still combined with PCM has the potential to achieve a productivity increase of up to 700%. These outcomes suggest that productivity rises with an increase in PCM mass and a decrease in saline water mass. Moreover, it is noted that the effectiveness of PCM is lower during the daytime compared to nighttime. Furthermore, the study highlights that organic PCMs, such as paraffin, have been predominantly utilized in research on productivity enhancement, while there has been limited exploration on the impacts of inorganic and eutectic PCM types.

6. Conclusions

- Technology Potential: Humidification-Dehumidification (HDH) technology is highly promising for decentralized, small-scale water production, though further research is required to enhance system efficiency and reduce costs.
- System Components:
    i. Humidifiers: Packed bed humidifiers are preferred over other types due to their superior performance in HDH desalination systems.
    ii. Dehumidifiers: Direct dehumidifiers significantly outperform indirect dehumidifiers, improving the overall system performance.
- Energy Systems:
    i. Hybrid Energy Systems: Achieve the highest gain output ratios, demonstrating superior efficiency.
    ii. Thermal Energy Systems: Show the lowest gain output ratios, indicating areas for potential improvement.
- Heating Methods: Solar water heating substantially enhances system output compared to solar air heating, highlighting its effectiveness in HDH applications.
- System Optimization:
    i. Integration with Heat Pumps: Enhances productivity and cost-effectiveness, maintaining low costs while improving gain output ratios.

ii. Design Parameters: Feed water flow rate, air flow rate, and the design of evaporator, condenser, and packing material are critical in boosting freshwater output. Optimizing the Multiple Effect Humidifier (MEH) unit's component size is essential.

- Economic Analysis: Conducted comparisons reveal that increasing the surface areas of the evaporator and condenser leads to a significant increase in productivity. The use of Phase Change Materials (PCMs) as packing media in all key components enhances thermal performance and system efficiency.

- Future Directions: Continued development of PCM technologies and further economic assessments are recommended to validate cost-effectiveness and improve scalability of HDH systems.

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