Chapter 2

LITERATURE REVIEW

2.1 Introduction

The previous chapter covers all the essential components related to the current investigation in great detail. The current chapter is dedicated to reviewing the previous investigations in various domains of experimental studies, such as design, materials, and other aspects, to identify the research gap. It has emphasized recent developments and a glimpse of previous research works in this field.

The desalination process is broadly divided into “Direct” and “Indirect” ways based on solar energy management, as shown in Figure 2.1. In Direct mode, solar radiation collecting and desalination occur at the exact location. Whereas, in Indirect mode, the desalination unit is divided into two parts: the solar collector and the desalination. Various techniques are summarised under these modes, which serve as the foundation for further modification and development.

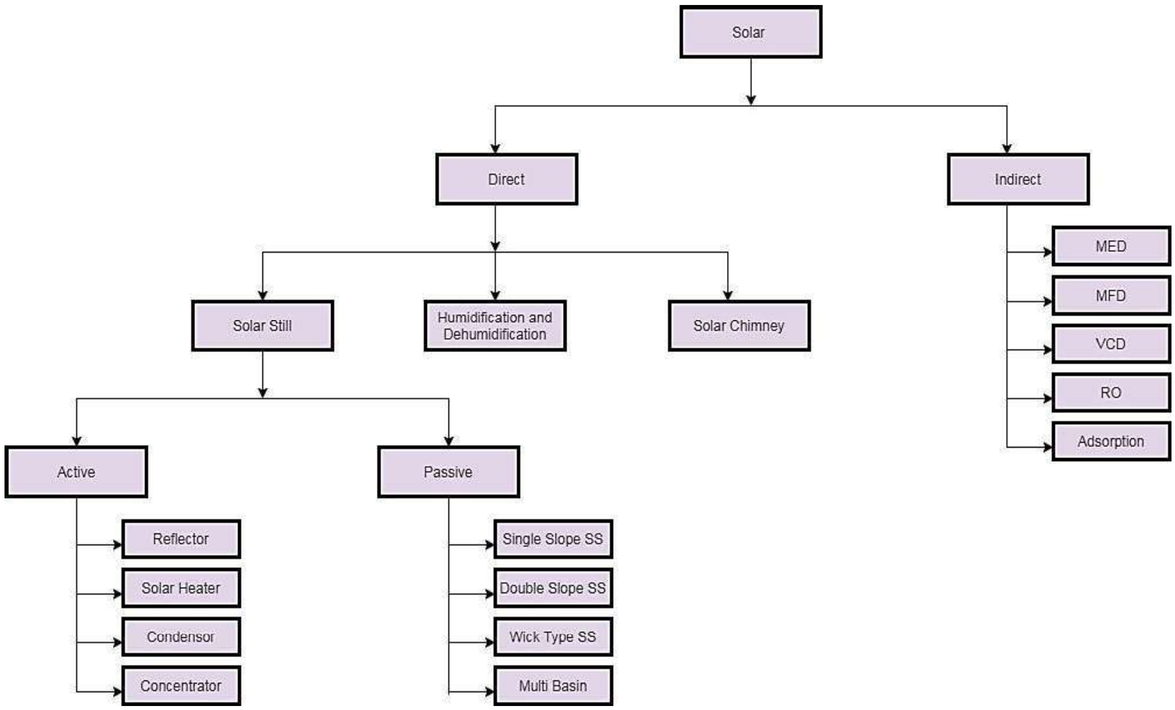

Figure 2. 1 Solar desalination techniques

2.2 Direct solar desalination

The direct use of solar energy for desalination has increased the popularity of "Solar stills" and "Humidification-Dehumidification" (HDH) methods that rely on indigenous mechanisms rather than sophisticated integrations.

2.2.1 Passive Solar stills

A conventional passive solar still with in which heat interactions are very simple in construction and cost effective. The study shows that maximum yield obtained with it reached up to 2-4 l/m^{2}day at different depth of basin water.

I. Single slope solar still

Single slope solar stills (SSSS) are the most common and have the basic design of a typical solar still, as shown in Figure 2.2, providing a platform for further development with numerous variations. The basic principle has been discussed in previous chapter, although it has many issues to fix. The tilted glass cover facilitates condensation process and also prevents outgoing radiation from the still, which causes the warming effect within. Tilt angle is one of the main aspects that has gained much attention. Many investigations have been conducted to find the influence of cover tilt angle on productivity in various designs, seasons and latitude angles [17]. Although, results showed inconsistent conclusions about the optimum tilt angle. Many researchers interpret it as the angle of latitude of the location where the experiment was conducted [18–20]. Some findings shows tilt angle greater than latitude angle [21–23]. Whereas some results shows tilt angle less than latitude angel will be more productive [24–26].It also noticed that without tracking solar still's cover direction is crucial for high performance of SS.

I. Double slope solar still

In case of double slope solar stills, usually setups are oriented in east-west direction since it extends the duration of solar irradiation each day. Further to improve the rate of evaporation nanomaterials are incorporated. Nanomaterials are important because of their distinctive qualities, including adsorption, a high surface-to-volume ratio, catalytic activities, and reactivities. The [27] investigated the performance of the DSSS system with nanoparticle. The experiment was performed on two different masses of base fluid (water) viz. 35 kg and 80 kg. Moreover, this base fluid is mixed with Al_2O_3 nanoparticle. Results showed that there is a significant increase in the yield up to 12.2% and 8.4% respectively as compared to without nanoparticle system.

2.2.2 Active Solar Still

When passive solar stills were unable to produce the adequate amount of freshwater then active solar stills comes into arena in which additional accessories like solar flat plate collectors [28], solar concentrator [29], Reflectors, condensers and mechanical agitators are used. Some accessories intercepts additional solar energy to heat the basin water and some provide more conducive surface for condensation that lies at lower temperature than conventional still.

I. Solar Still integrated with reflectors

These types of accessories extend the insolation trapping area that has excellent utility in winter season when insolation is minimum. Based on the location of reflectors it can be categorized as internal reflectors (IR) [30–32], and external reflectors (ER). The [33] performed the experimental work on SSSS with internal reflector that results 34% yield improvement. Similarly, the [34] included cooling system with external reflectors that results increase in efficiency up to 37.8%. The [35] used both IR and ER (top) (10° from vertical) with the same dimension as basin area (355×343 mm) and glass cover at tilt angle of 20°. The results revealed that the daily output improved by 70% to 100% as compared to simple solar still moreover.

II. Integrated with condenser

Extended condenser surface area improves the condensate quantity. Depending upon their arrangement, it can be of three types, *Internal condensers, External condensers, and Built-*

in condensers [36]. The [37] performed an experiment on solar still combined with an external condenser and a toothed shaft agitator that encourage contact between air and water by breaking the boundary layer of water. An exhaust fan was used to direct the vapor to the external condenser. The results showed that the productivity and efficiency of the system improved to around 40% and 31%, respectively, compared to conventional solar still.

III. Integrated with solar concentrator

Depending on the formation of optical image of the source, two types of concentrators are known viz. Imaging and Non-imaging concentrator. Imaging concentrators are formed the image of source onto the receiver unlike non-Imaging concentrator that do not form the optical image of source of radiation. The [38] conducted an experiment with parabolic trough concentrator (PTC) associated with and without tracking system. Results illustrate that tracked PTC produces maximum fresh water as compared to without tracking with conventional unit.

2.3 Modifications in Design of SS

The main shortcoming associated with direct solar desalination was its low yield and efficiency [39]. Among other attempts, solar still design modification related domain explored. Like, the shape of the cover plate [40], the design of the absorber area [41] and material selection for fabrication are interesting areas where work has been extended.

2.3.1 Design of cover plate

The cover plate design considerations are focused on maximizing insolation absorption and providing an enhanced surface for condensation. Various designs and materials for the cover plate have been investigated under different climatic conditions. The top cover of solar still must possess distinctive properties like high transmissivity coefficient, low absorption coefficient, procurable, cheap, and pathogens free. Generally, the cover plate of solar still made from tempered glass, which has high solar transmissivity value. [42]. Some designs of cover plates. Due to its fragile nature, the cost and precaution required for handling focus diverted toward transparent polymers like **Acrylic Sheets** (PMMA). Although various studies revealed that using acrylic material decreases the yield compared to glass, and it happens due to the low transmissivity of Acrylics.

I. Flat plate solar still

Traditionally, so many researchers worked on flat cover plate for solar still to improve the productivity. Numerous modifications have been done with flat plate solar still till date to improve its productivity and efficiency. Surface modifications can improve the efficiency of solar stills such as to enhance the transmissivity, Magnesium Chloride (MgF_2) antireflective coating can be done on outer side of the glass [43]. For the last few decades, researchers have started to explore new dimensions of the design for the cover. The nonconventional designs are coming into intense research work. But the overall result showed that the flat cover plate is more beneficial than other shapes because it provides less resistance (area) for solar insolation to get reflected back.

II. Hemispherical solar still

Among non-conventional solar stills, hemispherical solar stills performance was studied by the [44]. Based on computational modeling, solar still with hemispherical acrylic cover and conical shaped absorber investigated moreover a two-dimensional three-phase system was made for condensation and evaporation simulation on ANSYS-CFD.

Experimental outcomes provide good consent with simulation results. Although from geometrical point of view an efficient solar insolation trapping was not plausible with conical type of absorber area. ANSYS-CFD simulation bestowed an effective and potent tool for designing and comparing new ideas.

III. Pyramid shaped solar still

The [45] has performed a numerical and experimental study on single sloped (tilt angle 30º), double sloped (tilt angle 45º), and pyramidal-shaped (tilt angle 65º) solar stills. Variation in the design of still affects the productivity significantly because of change in the angle of incidence of solar radiation and also result revealed that SSSS performed well as compared to others if all stills placed in the same climatic conditions. The yield of pyramidal shaped solar still was not satisfactory in any season.

Similarly, the [46] demonstrated an experiment on the integration of two stills. In the first case, inclined solar still has performed alone and in the second case, it gets integrated with the pyramidal solar still where water fed directly into it that combination helps to raise the temperature difference between water and condensing surface temperature and eventually enhance the productivity. Integration of solar stills with different water depths (0.08 m, 0.06 m, 0.04 m) in basin revealed the optimum water depth of 0.02 m with a flow rate of 8.33 kg/hr. and also productivity increased up to 79% as compared to work alone. The [47] has performed its experiment with Phase change material (PCM) used in pyramidal-shaped solar still. The experimental results showed that an overall increase in productivity from 3.5 kg/m^2 to 5.5 kg/m^2 per day which was 35% higher than pyramidal solar still without PCM when water mass was 20 kg in the basin. The detailed mathematical analysis of square pyramidal SS has been done by [48] and found the correlation of water depth and tilt angle with productivity and top losses of SS. The results yields 4.43 kg/m^2 per day with tilt angle variation from 10º to 60º on the other hand productivity decreases from 3.88 to 1.52 kg/m^2 with depth variation from 0.01 to 0.03 m.

2.3.2 Absorber Area Augmentation

The design of the basin area referred to the design of the basin absorber area of still. A large absorber area implies trapping a large amount of solar energy that further heats up the basin water and enhances the evaporation rate that ultimately improves productivity of solar still. This area enhancement can be done with the help of fins (rectangular or circular shaped), corrugated surfaces, and spreading metal scraps.

I. Fins on absorber surface.

The [49] performed experimental analysis on improved solar still with fins and external condenser. Pin finned solar still showed significant improvement in efficiency up to 34.9% as compared to conventional solar still. Although, Solar still with pin finned and condenser showed about 9% higher gain as compared to pin finned absorber SS.

The [50] investigated the performance of combined effect of fins and PCM (paraffin wax). They fabricated SSSS with hollow fins at the absorber surface and PCM placed beneath the basin and inside the fins. The results showed that the energy efficiency of conventional solar still and modified solar still (mere fins) were 55% and 64%. Further, energy efficiency improved by using fins and PCM together.

I. Corrugation of absorber surface

The [51] have performed several research works on the corrugated surface. One of which study was performed on corrugated absorber covered with double wick and assisted with ER in the Egyptian climate. The experimental results revealed that both efficiency and productivity get improved. The productivity and efficiency of the double wicked SS improved up to 145% and 59% respectively as compared to conventional solar stills having 33% efficiency.

2.4 Solar Desalination with Heat Storage

Solar desalination has shown great potential to cope with the demand at the domestic level. Although it has many advantages, the intermittent nature of solar flux during day time causes irregularity in the freshwater production rate. Also, at nighttime, the absence of solar energy causes zero yields. To fix this issue, phase change heat storage material can be employed.

The [52] apply the latent heat storage material (PCM) that improves the heat storage capacity to further heat the water. The unprecedented biodegradable LHS materials like honey bee wax, cow dung, Gallus gallus domesticus cascara [53], and other biomass-derived material, along with nonbiodegradable materials like plasmonic materials that have shown a significant increase in efficiency up to 96% in solar based desalination processes; use of multi PCM and emulsion of PCM broadened the scope of TES system; metal composites; coupling of latent and sensible heat storage material; multi-dimensional heat storage medium, thermoelectric modules with photovoltaic panels, metal composites etc. Some of the required properties of sensible heat storage and latent heat storage materials are listed in Table 2.1, and common sensible heat storage materials are listed in Table 2.2.

Table 2. 1 Required properties for thermal energy storage materials [54,55]

S. No.	Thermophysical property	Preferred High/Low	Significance

1.	Energy Density	High	Preferred to have high density which results less volume occupation
2.	Specific heat capacity	High	Preferred to have high which stores large amount of heat
3.	Thermal conductivity	High	To improve rate of charging and discharging it should be high
4.	Latent heat of fusion	High	To store large amount of heat it should be high
5.	Melting point	Depends	It depends upon application (operating temperature range) which can be low/high
6.	Super cooling	Low	It should be lower through freezing process.
7.	Thermal stability	High	It should be high for large number of cycles
8.	Chemical stability	High	PCM should be chemically inert
9.	Vapor pressure	Low	It should be small for safety and ease of keeping
10.	Change in volume	Low	It must be low to avoid large allowance
11.	Toxicity	Low	Preferred zero toxicity
12.	Flammability	Low	Must be zero for safety purpose

Table 2. 2 Comprising the sensible heat storage materials and its properties [56–58]

S.N.	Material	Specific Heat (J/kgK)	Density× 10^3 (kg/m^3)	Thermal Conductivity (W/mK)	Thermal Diffusivity× 10^6 (m^2/s)	Heat Capacity (J/m^3K)

1.	Marble	800	2.6-2.8	2.07-2.94	0.995-1.413	2.08
2.	Sandstone	710	2.1-2.4	1.83	1.172	1.56
3.	Sand (dry)	830	1.4-1.6	0.15-0.25	-	-
4.	Aluminum	896	2.70	204 @ 293 K	84.10	2.42
5.	Cast iron	837	7.90	29	4.43	6.61
6.	Copper	383	8.90	385 @ 293 K	112.3	3.42
7.	Potassium chloride	670	1.98	6.53 @ 322 K	-	1.32
8.	Therminol 55 oil	872	1.91	0.13@ 293 K	-	2400
9.	Isobutanol	2303	0.80	0.13@293 K	-	3000
10.	Ethylene glycol	2433	1.11	0.256@293K	-	2382
11.	Jute cloth	324	1.50	0.427	-	-

2.4.1 SHS with Passive SS

The [59] performed the initial investigation on various heat absorbing material on single basin double slope solar still having basin area of 3 m^2 with complete insulation. The results showed the improvement in productivity about 60%, 45% and 38% with the use of black dye, black ink, and black rubber respectively. Hence, black dye is one of the best materials to store the solar energy for further use.

The [60] conducted an experiment on convention SS with jute clothe as heat storage medium. It was found that from earlier investigations, depreciation in performance of solar still due to heat accumulation in the region of raw water to glass surface of basin. The [61] performed the experimental work on three model namely; conventional SS, SS with blue marble, and SS with cow dung cake with absorber area of 1 m^2. The results showed that blue marble performs better than cow dung cake referring to increase in daily yield up to 35% and 20%.

2.4.2 SHS with Active SS

The [62] investigated the performance of triple basin solar still with sensible heat storage medium (pebbles, black granite) in conjugation with evacuated heat pump (EHP). It is found that after months of data conventional solar still with granite gravel and EHP produced 19 kg/m^2 as compared to conventional triple basin yield of 6.5 kg/m^2 in a day.

The [63] have done a theoretical study on low-temperature desalination systems. The results showed that 100 kg/day could be withdrawn from two different models with 15 m^2 and 18 m^2 solar collector areas that capture and transfer the thermal energy to the sensible heat storage unit of 1 m^3 and 3 m^3, respectively. Daily, freshwater of 6.5-7 kg/m^2 can be obtained with a 1m^2 solar collector showing average evaporation efficiency of 75%, average exergy efficiency of 60%, and TES volume of 0.1m^3.

2.4.3 LHS with Passive SS

Sensible heat storage materials can only hold heat briefly due to their poor thermal heat capacity. Hence, latent heat storage capability is explored in this domain to supply heat at night. The [64] performed an experiment on stepped solar still with latent heat storage material viz. Paraffine. Greenhouse effect chamber was created outside the still that supply the hot air into the solar still and after heating and humidification of air it get back to greenhouse chamber. The observation revealed that with uniform supply of hot air inside solar still create conducive environment to increase the rate of freshwater production that is seen in number as efficiency get improved by 57% and daily productivity reached at 4.6 kg/m^2. The [65] investigated the performance of low-temperature salt hydrates (m.p. 28 ºC) PCM with single slope transparent solar still having set of three-stage trough channels for condensate. Three sets of the experiment were performed viz. without PCM, 3 kg PCM, 6 kg PCM. It was revealed that overall yield improved by 30.3% and efficiency by 36.42%.The [66] theoretically investigated the effect of the mass of PCM on the yield of solar still. Sodium thiosulfate pentahydrate was used as PCM and its mass to water mass ratio variation from 10% to 100% decreases the yield by up to 30%.

I. LHS with nanoparticle

Nanoparticle materials have shown a promising role in the field of desalination. *Thermal conductivity* is a critical thermophysical property that governs the heat transfer rate from LHS material to basin water. To enhance the desalting process (evaporation and condensation) metallic and semiconducting nanoparticles were used with good reliability and durability [36]. The [67] conducted the experimental investigations on range of nanoparticle material embedded in PCM (paraffin wax) on solar still working and performance. Three types of nanoparticles are investigated viz. TiO_2, CuO and GO at 0.3% weight in PCM to form NPCM-1, NPCM-2 and NPCM-3 respectively. Each solar still has basin area of 0.5 m^2. The result shows that the highest yield of freshwater in the order of 5.28, 4.94, 3.92 kg/m^2 in a day in case of NPCM-3, NPCM-2, and NPCM-1 respectively.

Some metal and metal oxide nanoparticle viz. gold (Au), silver (Ag) have shown plasmonic effect that intensifies the light absorption capacity of the material. The plasmonic materials shows surface plasmon resonance in which conduction band electron undergoes collective oscillation in the exposure of light that shows enhanced absorption and scattering. For desalination several plasmonic materials are investigated like porous CuS/PE for 20 cycles [68], Nitrides of metals as TiN, ZrN, HfN have good efficiency for 5-10 cycles [69], plasmonic graphene polyurethane embedded with Au/Ag has shown 63%, 88%, 96.5% at 1, 5, 8 Sun illumination [70], TiN based photothermal membrane produces 1.34 $kg/m^2/hr$ with 84.5% efficiency [71], Au/Ag based plasmonic functionalized cotton showed 86.3% and 94% under 1 Sun and 8 Sun illuminance with 1.4 and 11 $kg/m^2/hr$. evaporation rate [72], Al-based absorber performed decently under 4 Sun and 6 Sun illuminance [73].

II. LHS with fins

Fins are used to increase surface area so that solar flux interception can be increased. For this purpose, various arrangements, shapes, and size are tested under different climatic condition. Like, circular/annular [74], longitudinal [75], plate [76], and pin fins are considered for good rate of heat transfer from TES to basin water with significant thermal conductivity like aluminum [77], copper [78], and iron. Another important aspect is fin location which is usually decided by relative heat transfer coefficient of the surrounding [79]. The [80] investigated the performance of Y shaped double bifurcated fins that improves the discharge rate by 24%.The [81] performed an study in which "V" shaped corrugated absorber with added wick. Paraffin wax [mass of PCM (m_{PCM}) = 25 kg] was used as a heat storage medium. It was found that efficiency gets enhanced by 11.7% of solar still with corrugated absorber, PCM, and wick.

2.4.4 LHS with Active SS

The [82] investigated the performance of solar still equipped with paraffin wax at the bottom of the absorber and parabolic solar concentrator. The findings revealed that enhancement in productivity of solar still reached 55%-65% in summer season and 35%-45% in winter season as compared to conventional solar still. Moreover, salinity of fresh water obtained by this process was 550-500 ppm whereas impure water has 3000-5000 ppm salinity level. The [83] performed an experimental study on single slope solar still with hemispherical absorber surface at the bottom getting reflected radiation from parabolic concentrator with PCM (paraffin wax; M.P. 60 °C) in spherical balls. The results show that with PCM the daily average yield reached up to 4.46 kg/m^2 as compared to 3.52 kg/m^2 in case of without PCM. Some other investigations have been reported in the tabulated form in Table 2.3.

Table 2. 3 Synopsis of investigations performed on solar still with TES

S. No.	Modification	Location	Thermal storage material	Reference	Yield (kg/m^2day)	Efficiency	Conclusive remarks
Latent heat storage							
1.	Conventional SS	India	Myristic acid	[84]	5.71	-	Effect of mass of raw water and PCM investigated.

2.	Weir type cascade SS	Iran	Paraffin wax	[85]	3.40	-	Forced flow and increased residence time facilitates the evaporation .
3.	Single stage SS with emulsion of PCM	Egypt	Paraffin wax, oil, water, and Al	[86]	4.50	36.2%	Saline water concentrati on has negative impact on efficacy.
4.	Single slope SS with PCM embedded with Al_2O_3	India	Paraffin wax	[87]	4.20	40%	With nano composite daily efficiency reached 45%.
5.	SS with GO dispersed in PCM	Vietn am	Paraffin	[88]0	6.25	-	Increase in Nusselt no. reflect the increase in HTC; 25% more efficient than PCM alone.
6.	SS with concentrator	India	Paraffin	[89]	1.60	-	Incorporati on of mild still billets can also improve the

							performance.
7.	SS with concentrator	India	Paraffin	[90]	1.62	-	Mild steel scraps also improve the performance of SS.
8.	SS with double pass hot air injection	Egypt	Paraffin	[91]	9.40	-	Forced hot air bubble generate turbulence that boost the evaporation.
9.	Single slope SS	Saudi Arabia	Stearic Acid	[92]	5	85%	Transient analysis; It is recommended to use wick type solar still in winter season.
10.	SS with PCM	India	Lauric Acid	[93]	-	40%	Least water depth reduces the loss of heat flux into ambient.
11.	SS with PCM	India	Lauric acid (L) and Myristic acid (M)	[94]	L=2.41 M= 1.90	-	Lauric acid better than myristic acid.

12.	SS with film cooling	China, Egypt	Paraffin	[95]	0.85	-	With graphite flakes yield boosts up to 74%.
13.	Passive SS with PCM	Morocco	Paraffin	[96]	5.70	-	Maximum temp of brackish water decides the selection of PCM.
14.	Modified SS	Oman	Tricosane (candle wax)	[97]	-	-	Amount of freshwater yield is inversely proportional in day and directly proportional to night.
Sensible heat storage							
15.	Active single basin SS	Saudi Arabia	Salt	[98]	4	37.8%	Basin liner conductivity has negative effect on daily yield and efficiency.
16.	Single basin SS	India	Black granite gravel	[99]	3.90	52%	Depth of the gravel layer affect the function

							of SS also result improved with no cost.
17.	Plastic Solar still	Italy	Greenhouse effect	[100]	1.80	16%	Develop the co relation between yield and solar intensity; y = 0.065(x-0.225).
18.	Conventional SS	India	Sand	[101]	6	-	Cumulative productivity with day (5.1) and night (0.9) gives 6 kg/m^{2}.
19.	Passive SS	India	Pumice stone (5kg)	[102]	1.75	29.3%	Overall productivity deceases with sensible heat storage stone.
20.	V-type SS	India	Charcoal	[103]	3.22	30%	The floating charcoal enhance the rate of evaporation.

21.	Multi-effect SS	India	Aluminum sheet	[104]	6.70	62%	Unique mechanism of heat storage below the Al sheet during day time.
22.	Passive SS	India	Pumice Stone (10kg)	[102]	1.61	28.8%	Without heat storage medium yield was higher as 1.95 kg/m^2.
23.	Conventional SS	India	Sand bags (30 kg)	[105]	3.50	28.6%	100 no. of sand bags charged with 30 kg are more effective than 40 kg sand bags collection.
			Sand bags (40 kg)		3.14	31%	

2.5 Economic Analysis of solar stills

Economic point of view is very important especially when these kinds of alternative would be crucial source of freshwater for developing countries. The Table 2.4 consist of some typical cost ($) value incurred in freshwater production during solar desalination. From these data we can confer that around expenses comes out for per liter of fresh water around 0.01-0.02 $ for most of the cases, which can be further mitigate on the larger scale production.

Table 2. 4 Cost of distilled water in previous studies

S. No.	Desalination method/Reference	Productivity (l/day)	Cost of water ($)/ day/l	Daylight hour
1.	Double effect SS; [106]	20	0.0026	-
2.	Solar still using shape stabilized PCM; [107]	3.41	0.243	-
3.	SS with thermoelectric cooling and nanofluid;[108]	-	0.0252	9-17
5.	Tubular SS with parabolic concentrator; [109]	3.53	0.024	5-19
6.	SS with PCM and heat pipe; [110]	6.55	0.0153	9-21
7.	Inverted absorber SS; [111]	6.30	0.0121	7-19
8.	Solar still with solar heater; [112]	63	0.012	8-17
9.	SS with parabolic solar collector; [113]	3.5	0.0058	9-17
10.	Tilted wick type SS; [114]	3.6	0.020	9-17
11.	Dual effect tubular SS; [115]	10.4	0.0322	-

2.6 Research gap

The above literature reviews reveal extensive research work has been carried out by researchers in the present domain. Although researchers have explored many aspects of solar still system design for decades. However, solar still performance depends on more than just the models presented by the above researchers. The solar still performance can also be predicated by the optimum tilt angle of the solar still and the selection of peculiar materials to enhance the thermal performance. The need for unique solar still designs with good heat-retaining capacity is the focus of this work, in turn, the inspiration for the present objectives.

2.7 Objectives

- To determine the ideal tilt angle for solar stills during the tropical zone's winter.
- Passive solar stills underperformed due to incompetency to trap the broad range of solar radiation. So come up with a novel material which can absorb extended spectrum of solar radiation that will accelerate the evaporation process and eventually boost the yield and efficiency of solar still.
- To design and construct a novel solar still model and analyze the system's ability to retain heat at night. Additionally, to compare the results with traditional solar still.
- Uncertainty analysis of measured quantity and its impact on derived quantity to analyze the propagation of error.
- Theoretical modeling of solar still (using the MATLAB program) to measure yield and efficiency with practical data validation.