

1.1 History

Water and air are the two most essential ingredients of life. However, rapid industrialization and modernization create the issue of concern related to both. The quest for water has been running since ancient times, especially in remote locations where freshwater is not readily available. On the way to tackle the water shortage and excessive demand for potable water leads to evolve the various techniques that can produce freshwater from raw/useless water. Earth is known as a blue planet because nearly 71 % of the Earth's surface is covered with water; still, humanity will have to go through a crisis because 96.5% of this water is in the ocean, i.e., saline. Besides this, icecaps and glaciers contain more than 68% of the fresh water on Earth, and groundwater makes up a little over 30% [1]. Therefore, a technique called Desalination was developed to convert saline water into a useful form. Aristotle (B.C. 384-322) gave an idea in his Meteorology that "seawater can be made drinkable by vaporization; other liquids behave in the same way". In the same way, thousands of years ago, Greek sailors used to extract fresh water from salt water by evaporation, and Romans used clay filters to trap salt in saline water. The first modern desalination unit was installed in Chile in 1872 [2]. Today, around the world, more than 17,000 desalination facilities generate 107 million cubic meters of desalinated water daily.

1.2 Water Scarcity

The agricultural sector has significant withdrawal (self-supplied) of water, nearly 70%, whereas industrial and municipalities withdrawals are reached up to 20% and 10%, respectively, in recent times. Therefore, a significant disparity between water demand and supply leads to water scarcity. That is evident in even developed nations like South Africa, Australia, Southern Europe, Middle-East Asia, and developing nations [3–5]. Water scarcity, water stress, and water crisis conditions are categorized by organizations like UN-Water, Human Development Report (HDR), etc., considering the severity of the situation and other aspects. The HDR data analysis reveals that nearly 4 billion people will face at least a month of severe water scarcity problems, especially those hailing from the Asian continent. The UN-Water Development report highlights the conjugation of climate change and water scarcity. It reveals that the global water consumption rate rose 6-fold from the last century, increasing at a pace of 1% each year [6].

In the wake of these facts and figures, it becomes of utmost importance to develop a mechanism that can fulfill humankind's demand for fresh water without compromising sustainable development.

1.2.1 Saline water

In broader terms, water with salts termed as saline water which is available in abundant on earth surface. Theoretically, amount of chloride concentration decides the salinity of water which is measured in ppm (parts per million) or ppt (parts per thousand) while Total dissolved solids (TDS) signify the all-salt content viz. sulphate and chloride of sodium and magnesium as shown in Figure 1.1. The concentration level (by weight) of these salts decides

the quality of water with other factors like pH, electrical conductivity, etc. Depending on TDS value, water bodies can be categorized according to WHO-Water quality [7].

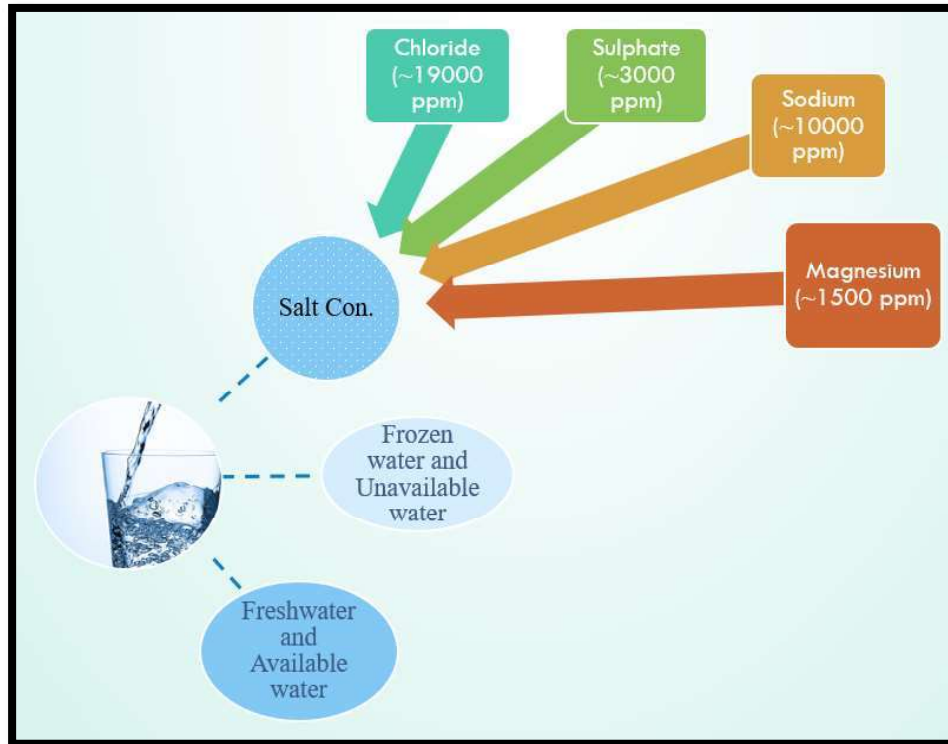


Figure 1. 1 Composition of salts in saline water

- ❖ **Fresh water** - Less than 600 ppm (Ex. Aquifers, Ponds, Rivers, etc.)
- ❖ **Brackish water** - From 600 ppm to 30,000 ppm (Ex. Estuaries, Mangrove swamps, Chilka Lake, Pulicat Lake, Baltic Sea, Black Sea etc.)
- ❖ **Saline water** - From 30,000 ppm to 50,000 ppm (Ex. Sea water, Salt Lake (Sambhar Lake, Red Sea, Mediterranean Sea) etc.)
- ❖ **Briny water** – Above 50,000 ppm (Ex. Brine pools etc.)

1.3 Desalination

A process that separates the salty component from the solvent (water, soil, etc.) is called desalination. Different methods can achieve this process, like membrane-based, thermal-based, adsorption-based, etc., to remove the salt component from the saline water. Sea water contains various types of minerals and their concentration. *Desalination* is an energy-intensive process that is being fulfilled by fossil fuels. Especially in Middle East Asia, Australia, and Southern Europe, like developed nations, can afford fossil fuels to run these desalination plants. However, it also leaves a large carbon footprint and is not everlasting. Desalination is the most feasible solution to get rid of water scarcity. Two broad categories are conceived based on the technology used to desalinate the water.

- ❖ Membrane desalination
- ❖ Thermal Energy desalination

1.3.1 Membrane Desalination

Essentially, a membrane serves as a barrier to keep two phases apart by limiting the passage of specific components. The invention of membranes dates back to the 18th century. The reverse osmosis (RO) technique is the most popular to obtain fresh water from saline water. In an osmosis process, lower solute concentration tends to go into higher solute concentration to balance the concentration of solute on both sides through a semipermeable membrane. In contrast to the reverse osmosis process, with the application of pressure, the solution passes from higher concentration fluid to lower solute concentration fluid through a semipermeable membrane, illustrated in Figure 1.2. Most of the desalinated volume is produced by fossil fuel-driven plants like Jubail plant (Saudi Arabia), producing 1,401,000 m³ (370,1045 US gal) on a daily basis, working on reverse osmosis technique and mainly based on fossil fuel recognized as the world's largest desalination plant which is verified by International

Desalination Association (IDA) and placed in Guinness book of world record as of Jan 14, 2019 [8]. This technique's primary flaw and restriction is that it needs a lot of energy, 80% of which is used by the pump, which is powered by fossil fuels. Second, the volume of highly salinized wastewater is generated and dumped into the oceans, which disturbs the regional ecosystem. Additionally, a complete desalination plant needs routine maintenance because salt or suspended particles have plugged the membrane pores.

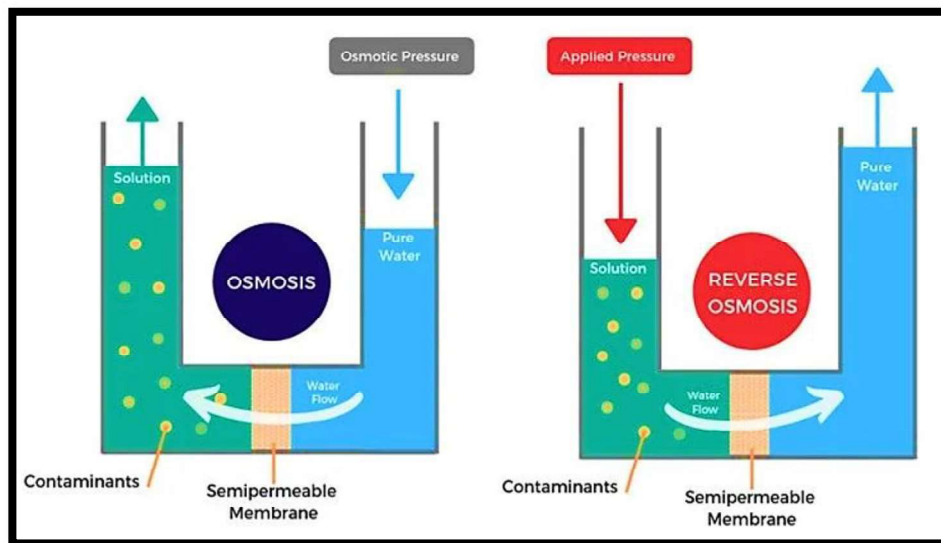


Figure 1. 2 Osmosis and Reverse Osmosis Process [9]

1.3.2 Thermal Desalination

The evaporation and condensation phenomenon is the foundation of the thermal desalination process. Using heat energy, the salt water (solution) evaporates more quickly, and the resulting vapor condenses on a cooled surface. This method is less expensive in many respects than membrane-based plants since it does not require a large pump or semipermeable membrane as required in RO techniques. Multi-Effect Distillation (MED)

and Multi-Stage Flash (MSF) distillation are two commonly utilized processes based on this technique.

MSF distillation process mainly uses thermal energy to run the process apart from electrical energy. In this process, several stages are made successively, decreasing pressure conditions. The feed water gets preheated in the heat exchanger, which reduces the primary load of heating. Primary heating is done via fossil fuels, waste heat plants, renewable energy, nuclear reactor, etc., where the temperature is raised to 90 to 110 °C. After heating, saline water keeps flashing to vapor in each stage before getting discharged from the last stage, as shown in Figure 1.3. These units can produce fresh water up to 35000 m³/day with up to 40 stages. It is the second most widely accepted process to obtain fresh water after Reverse Osmosis worldwide. The massive Ras Al-Khair desalination project, widely regarded as the world's Desalination heavyweight, is a hybrid project-based MSF and RO distillation process.

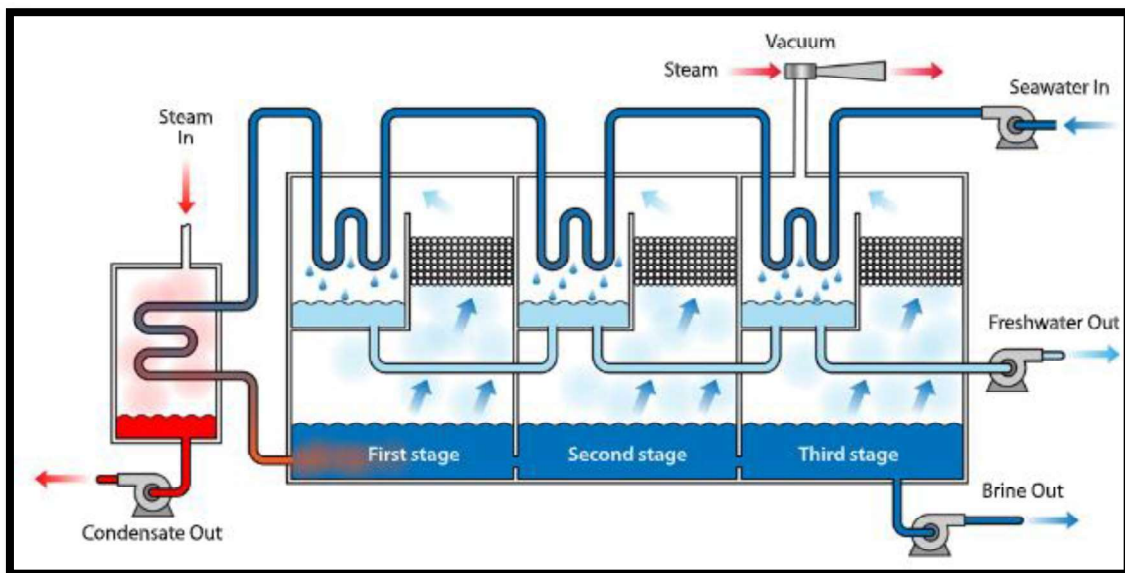


Figure 1. 3 Schematic diagram of Multi-Stage Flash distillation [10]

MED is a multistage process that consists of 2-16 stages. Every successive stage has reduced pressure conditions similar to MSF, but the process is quite different. In this process, steam (in tubes) is used as a heat source to evaporate the feedwater shower at the first stage. This evaporated water transfers heat to evaporate feed water shower at the second stage and get condensed back into fresh water and collected. Similarly, evaporated water from the second stage becomes a heat source for the third stage and goes on, as illustrated in Figure 1.4. In this process brine temperature reached up to 70 °C. These are capable to produce up to 30,000 m³/day. Nowadays, MSF replaces MED since it is more affordable and easier to maintain.

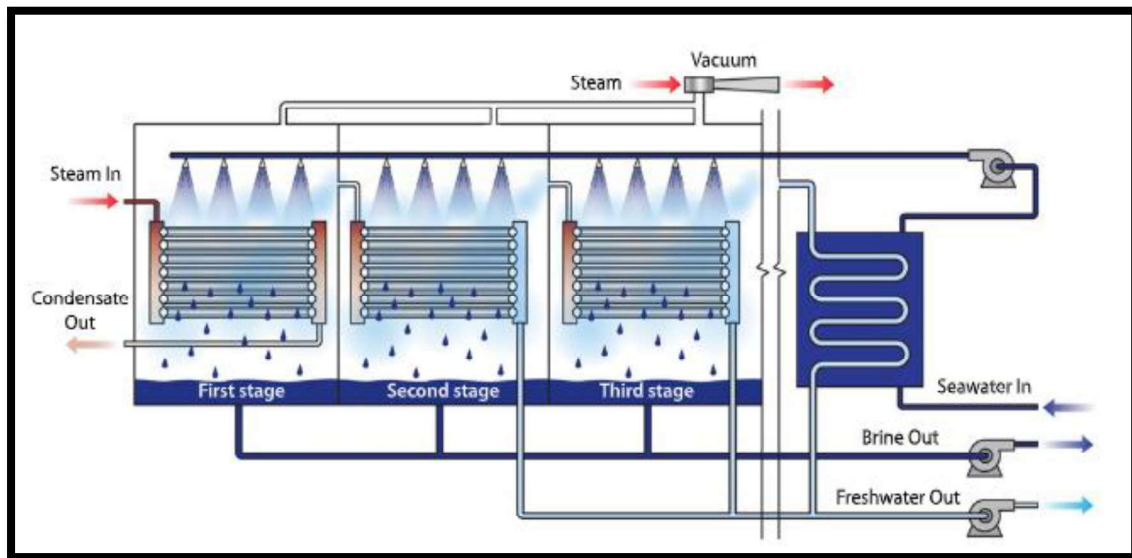


Figure 1. 4 Schematic diagram of Multi-effect distillation [10]

1.4 Solar Energy

Solar radiation falling onto the earth's surface can be divided into two categories. Beam radiation is a part of solar radiation from the sun without being scattered by the atmosphere. (Beam radiation is often referred to as direct solar radiation). Diffuse Radiation is the solar radiation received from the sun after its directional change due to scattering and collision

with gas particles in the atmosphere. Hence, total solar radiation is the sum of the **Beam** and the **Diffuse** solar radiation on a surface. India, stretched from 8°4' N to 37°6' N, receives above 5 kWh/m²/day global radiation in most of the parts, as shown in Figure 1.5.

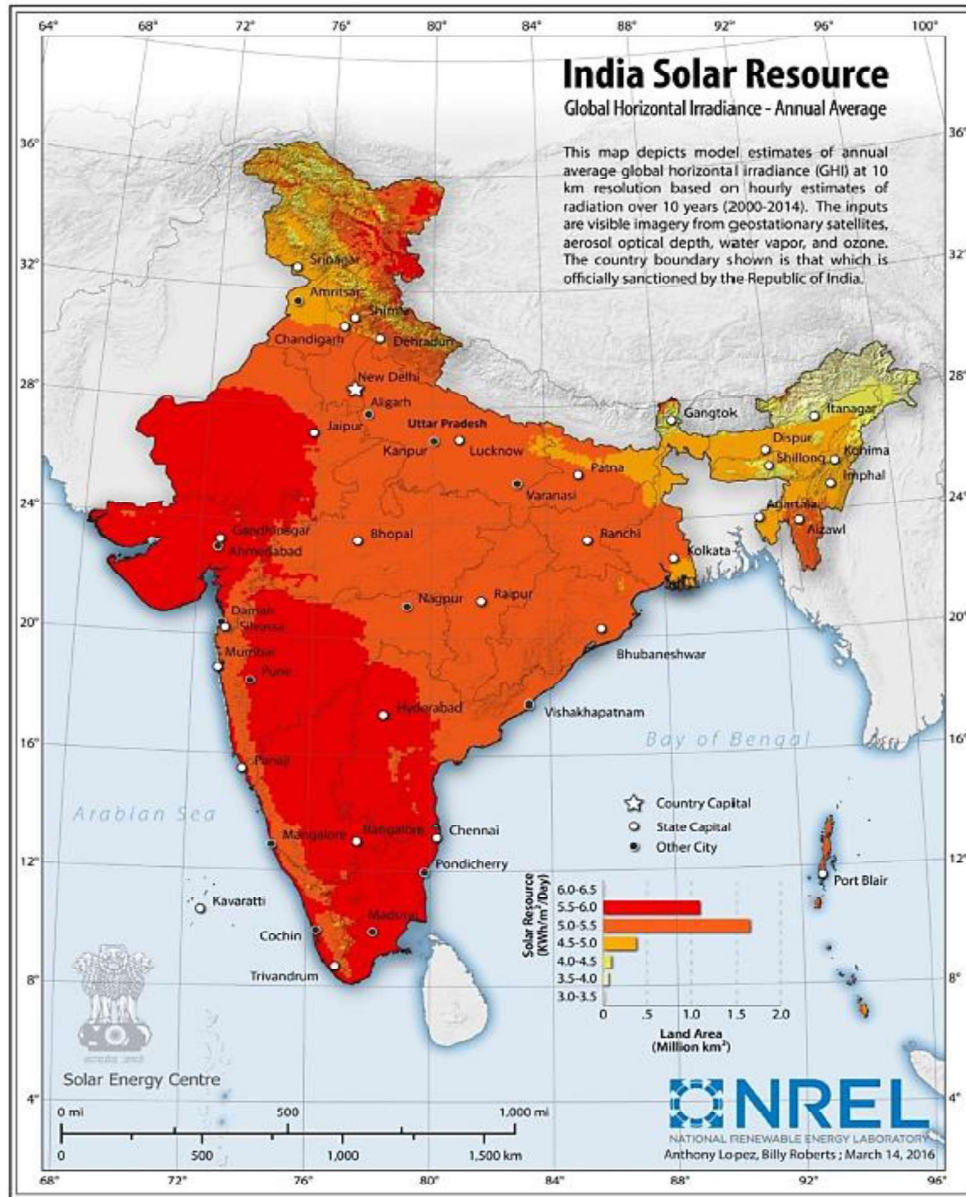


Figure 1. 5 Annual average global solar insolation on India [11]

The solar radiation consists 55% Infrared (A, B, C), 42% Visible spectrum, and rest Ultraviolet (A, B, C) as shown in Figure 1.6. Infrared spectrum mostly used for heating

purpose due to its large wavelength however visible and Ultraviolet range skipped due to insufficiency of material.

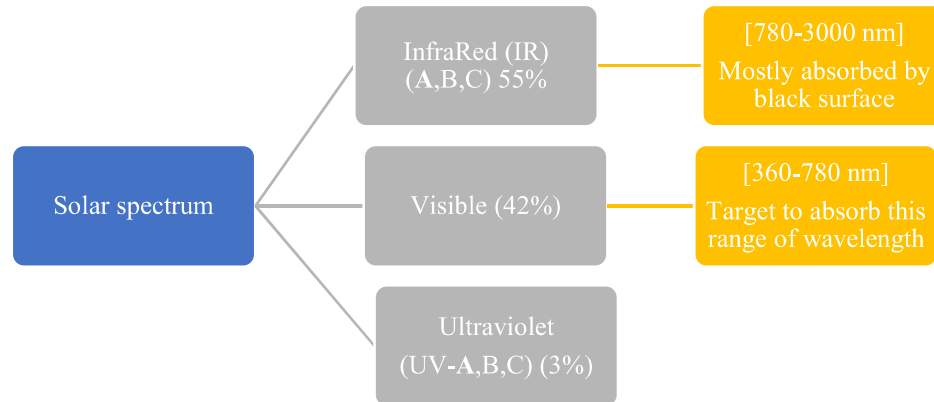


Figure 1. 6 Proportion of solar spectrum wavelength in IR, Visible, and UV range

1.5 Solar Desalination

In nature, evaporation causes rain when solar irradiation receives by water bodies which is a part of “Hydrological Cycle” similarly all man-made solar desalination units worked. Solar desalination can be grouped into *Direct Solar desalination* and *Indirect Solar desalination* based on technique to use solar energy. Direct utilization of solar energy to obtain fresh water viz. solar still, humidification-dehumidification technique otherwise termed as Indirect solar desalination process.

1.5.1 Solar Still

Solar still is an essential device that utilizes solar energy to evaporate the basin water. A relatively cooled surface facilitates the condensation and, eventually, condensate collected in a water collector. Inside solar still, all three modes of heat transfer take place along with evaporative heat transfer. Solar radiation (I) directly falls on the transparent glass surface and gets transmitted due to the short wavelength of incoming radiation (I) and the high

transmissivity of glass material. After passing through the glass, surface radiation (I_2) gets absorbed by basin water and basin liner (absorber and wall surface area). Due to the low heat capacity of the basin liner, it achieved a higher temperature than basin water in the same time and radiation condition. Simultaneously, basin water starts evaporating and releasing the heat in convective (Q_{cw}), radiative (Q_{rw}), and evaporative (Q_{ew}) modes. The inside of the solar still is not affected by ambient wind velocity. So, natural convection heat transfer prevails here, and buoyancy initiates heat transfer. The evaporative heat transfer accommodates the water vapor originating from basin water due to heating and condensing on the inner glass surface with favorable conditions. Here, the latent heat of condensate is liberated into the ambient through the glass surface, which external agents like wind velocity and ambient temperature will facilitate. From the glass surface to the ambient, convection heat transfer (Q_{cg}) occurs, and the sky acts as a radiative (Q_{rg}) surface for heat exchange. The evaporation and condensation phenomenon continues due to distilled water from a solar still. The mass transfer (water vapor) rate is further increased by convective ($Q_{conv,b-w}$) heating of basin water by basin liner. If available, some amount of radiation (I_3) passes through the thickness of the basin water and is absorbed by material beneath the basin water. A schematic diagram of solar still with heat transfer is shown in Figure 1.7.

Additionally, some fraction of heat (Q_{loss}) is lost through the conducting media (insulating wall) to the ambient. Due to the small thickness of the glass cover, a zero-temperature gradient can be assumed. As a result, a uniform temperature of the glass cover is taken.

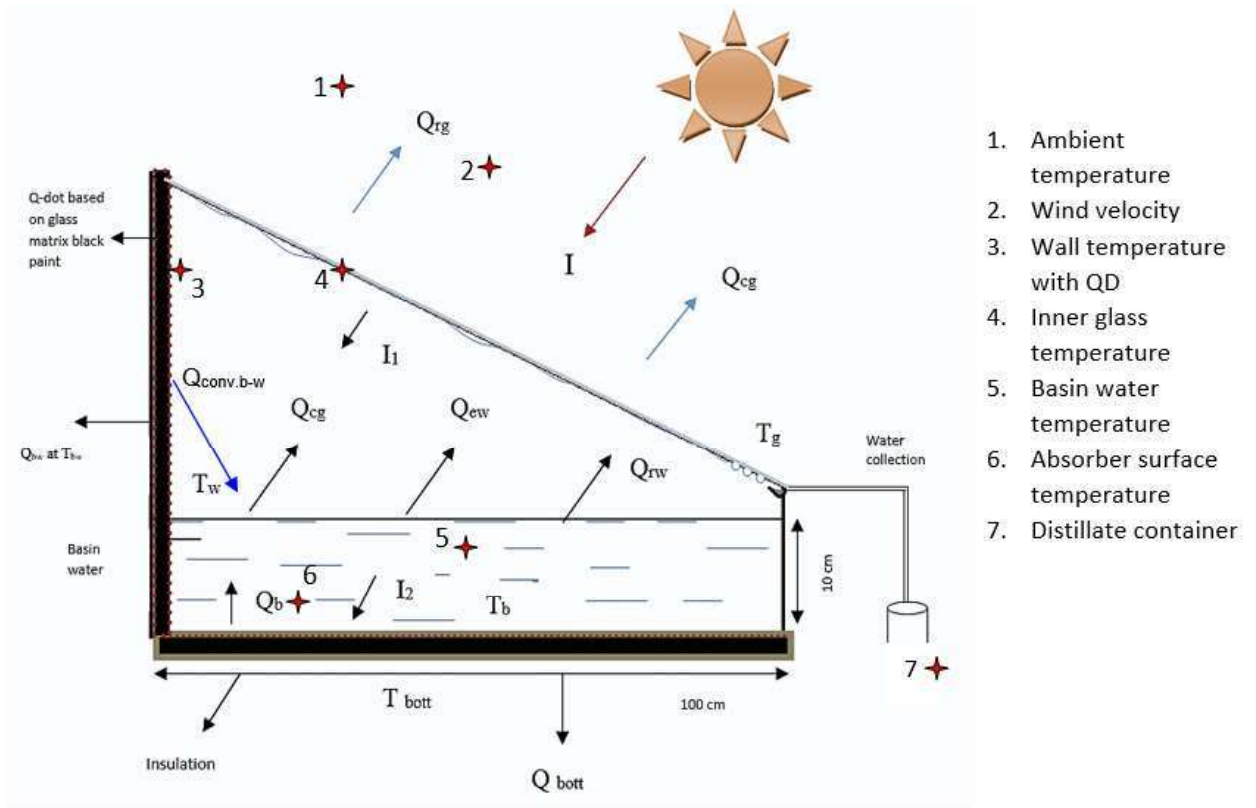


Figure 1. 7 Various modes of heat transfer and physical variables in solar still

1.6 Phase Change Material

Sensible heat storage materials fail to function continuously at night for longer due to low specific heat capacity. However, Latent heat storage materials can store both sensible and latent heat, as phase change materials (PCMs) work well with solar desalination systems. PCMs are used to sustain the operation of solar stills during periods of insufficient sunlight and to address intermittent solar irradiation. Solar energy is absorbed while it is sunny and released when it is not. PCMs are divided into three classes based on their chemical makeup, as depicted in Figure 1.8.

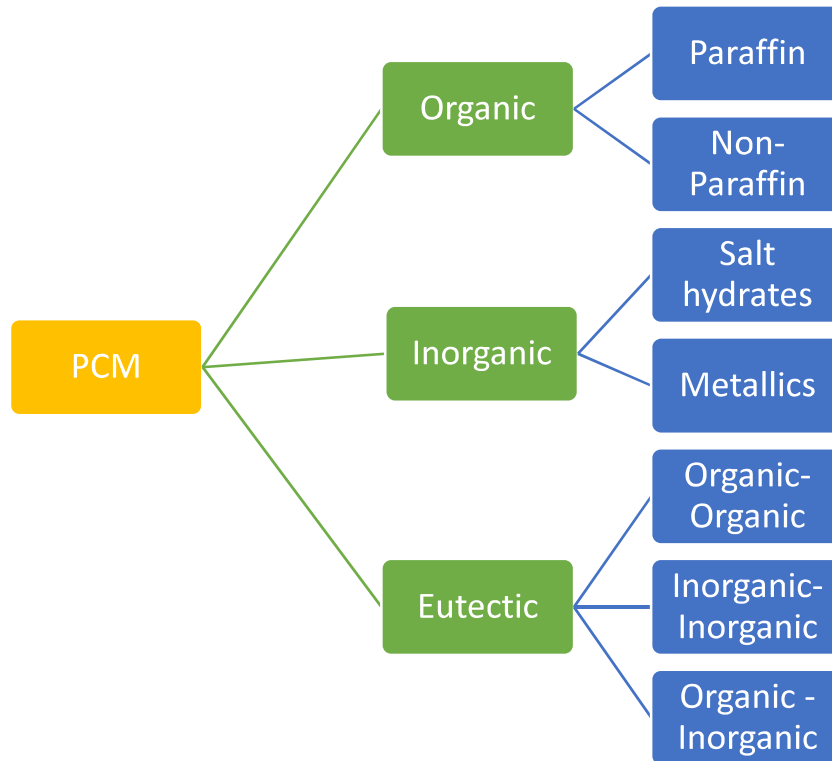


Figure 1. 8 Classification of PCM [12]

In present work, Lauric acid (20 kg) is used underneath of basin's absorber surface to store the excess solar energy as depicted in Figure 1.9. Selection of this PCM is based on its non-toxic nature, easy accessibility and economic viability. Additionally, it offers congruent melting, thermal and chemical stability with good reliability. The thermophysical property viz. latent heat of fusion, melting point, thermal conductivity, specific heat and density are listed in Table 1.1.

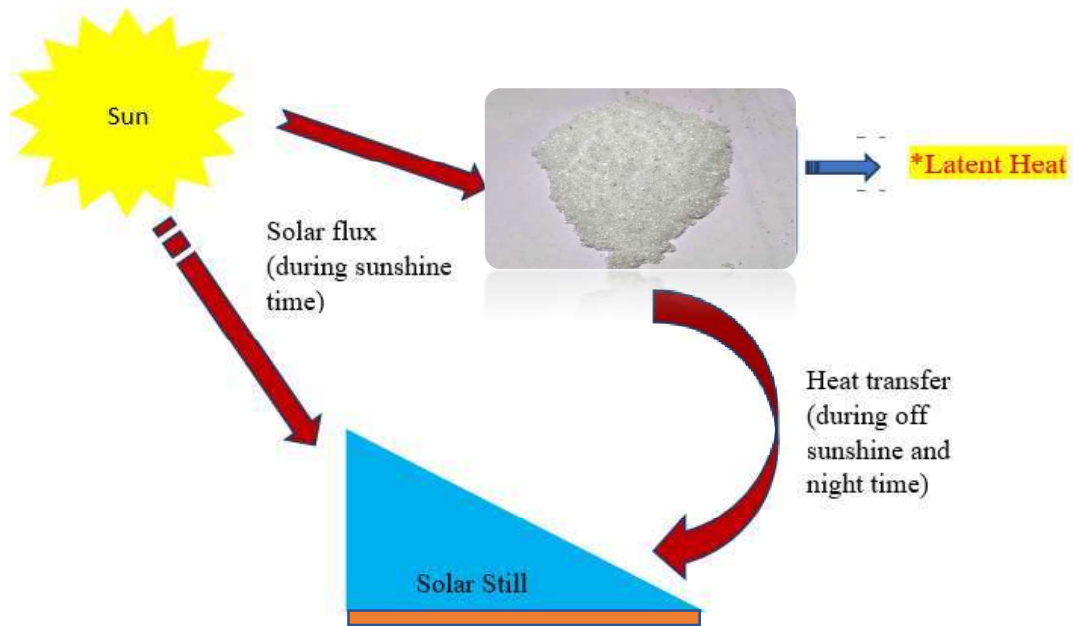


Figure 1. 9 Lauric acid as a PCM to store the heat during daylight and releases during night period

Table 1. 1 Thermophysical properties of Lauric acid

S.N.	Property		Value
1.	Latent heat of fusion		177.5-180 kJ/kg
2.	Melting point		43.9 °C
3.	Specific heat	Solid at 25°C	2.1 kJ/kg°C
		Liquid at 44°C	3 kJ/kg°C
4.	Thermal conductivity		0.16 W/m°C
5.	Density	Solid	1007 kg/m ³

		Liquid	862kg/m ³
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1.7 Quantum Dot Material

Quantum dots (QD's) materials are semi-conducting nanocrystals. These are also termed 'artificial atoms' due to their miniature size (1-10 nm) that lies below Bohr's radius of the element [13,14]. These nanocrystals are distinct from the traditional, bigger nanoparticles (1–100 nm) [15]. They have unusual optical and electrical characteristics and possess an intriguing photo-physics activity because of their size and shape. The electron-hole pairs known as 'exciton' a quasiparticle bounded by Coulomb forces whose photophysical behavior gets activated as soon as photon energy falls onto the surface of QDs. The electron gets excited and jumps to the conduction band from the valance band leaving behind holes providing incident energy equal to or greater than forbidden energy. Radiative and non-radiative decay can be observed during the absorption and emission process. As QDs can be made of various semiconducting materials, their spectroscopy property can be tuned by altering the size of the same material. It can emit a broad range of electromagnetic radiations ranging from ultraviolet to near-infrared, making it a very lucrative option for solar-based projects. Based on physical characteristics, type of nanomaterial can be selected for a project as shown in Figure 1.10.

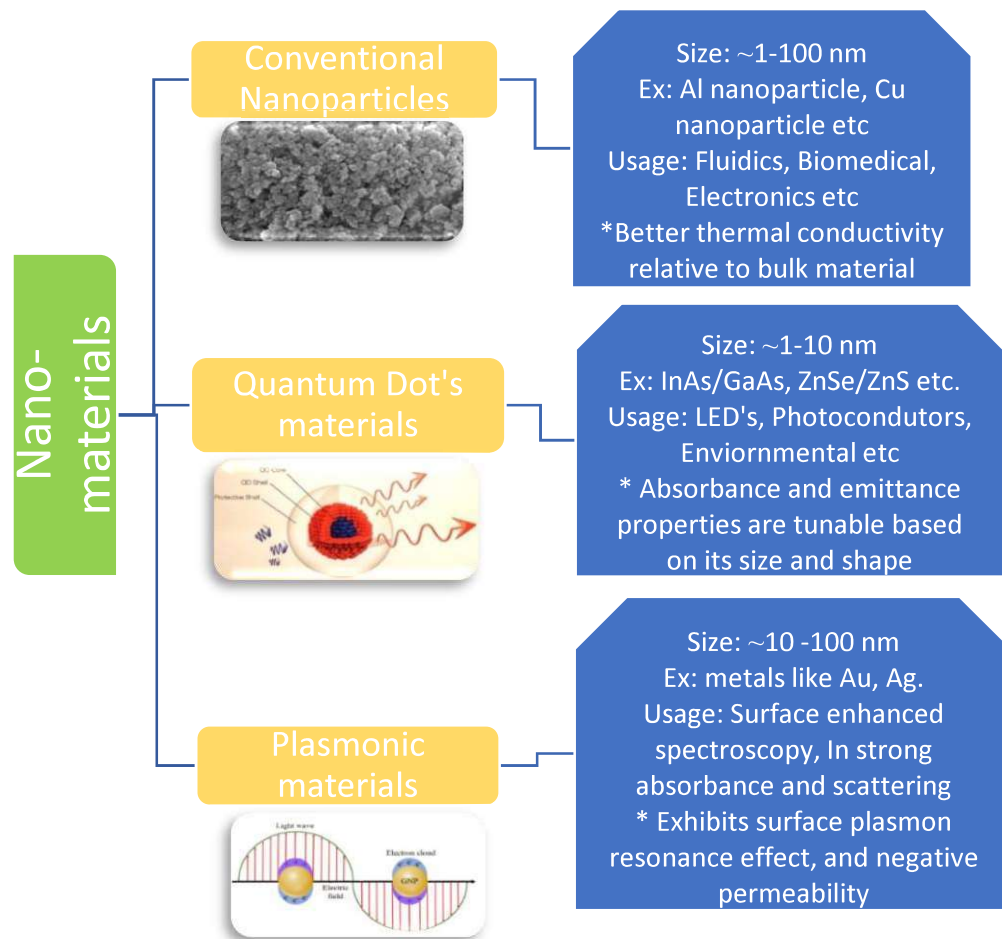


Figure 1. 10 Classification of nano-materials with their characteristics [14–16]

The average distance between electron and hole pair of excitons in quantum dot materials is called 'Bohr radii. When the size of the semiconducting material falls below Bohr's radii, the 'Quantum Confinement effect' is observed, as illustrated in Figure 1.11. Quantum confinement is the spatial confinement of the excitons in zero-D (QD's), one-D (wire type), or multi-D (well type) regions of the material. In another way confinement effect facilitates the extensive range of heat absorbance.

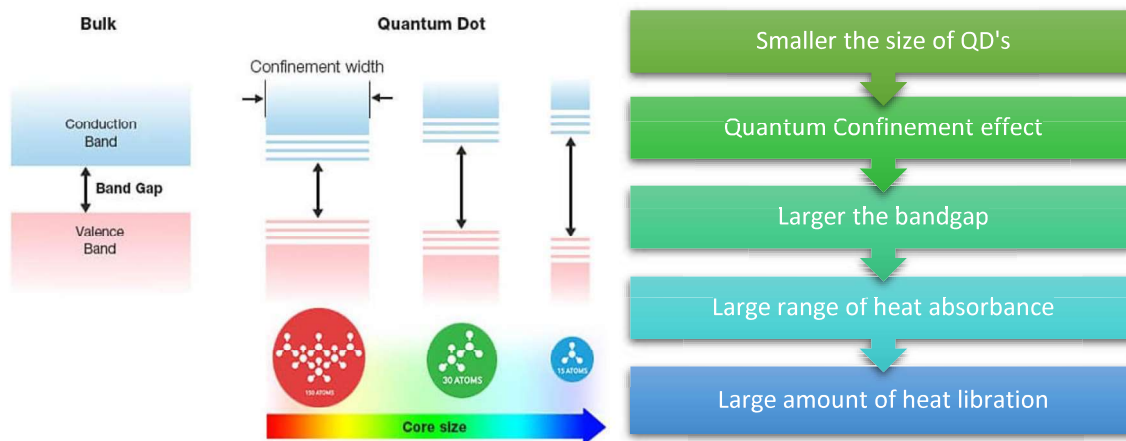


Figure 1. 11 Illustration of quantum confinement effect in QD's

Black phosphorus Q dot material is employed in this work. It is the most thermodynamically stable phosphorus allotrope in atmospheric conditions, also it is non-toxic and inflammable. Its physical properties are listed in Table 1. 2. Using magnetic stirrer, a homogeneous mixture is made by dispersing the Q dot material into black dye. Furthermore, the mixture is applied as a coating at the basin liner.

Table 1. 2 Properties of black phosphorus quantum dot material

S.N.	Property	Value
1.	Color	Light brown
2.	State	Powder
3.	Size of QD	~7 nm
4.	Size of glass	0.1-10 μm
5.	Total Amount	100g

6.	Solar absorptance	0.90-0.95
7.	Thermal conductivity of FRP	0.75 W/mK
8.	Specific heat capacity	1500 J/kgK

1.8 Organization of Thesis

The current thesis presents the parametric study of SS, material selection and preparation, and design and fabrication of modified solar still. The matter of the thesis is organized into seven chapters. **Chapter_1** briefly introduces solar desalination and the materials used in the present investigation. **Chapter_2** presents the literature review on different techniques, designs, and the use of advanced materials with SS to boost the yield. **Chapter_3** gives an overview of the experimental setup and test procedure. **Chapter_4** deals with the theoretical modelling of solar still. **Chapter_5** deals with the economic analysis of solar stills. **Chapter_6** presents the results and observations in graphical form with explanations. **Chapter_7** concludes the whole outcome that emerged from the current investigation. Some perspectives related to future studies have also been listed, and these are followed by references. Additionally, other related information and data are provided as Appendices. At the end, a list of publications has been mentioned.