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Principles and Modes of Distillation in Desalination Process

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Abstract

Distillation has been a very important separation technique used over many centuries. This technique is diverse and applicable in different fields and for different substances. Distillation is important in the desalination section. Various principles are used in desalting seawater and brackish water to fulfill the demands of freshwater. This work explains the modes and principles of distillation in desalination, their types, present improvement, challenges, and limitations as well as possible future improvements. The first and primary mode of distillation is the passive type. As times went by and the demand for freshwater kept increasing, other modes were introduced and these modes fall under the active distillation type. However, each mode has its own advantages, disadvantages, and limitations over each other. The principles and modes of distillation are as significant as understanding the energy sources needed for distillation. Hence, they are the basic knowledge needed for future innovation in the desalination industries.

Keywords: history of distillation, desalination, renewable and nonrenewable energy sources, modes of distillation, principles of distillation

1. Introduction

Over the ages, the world has been evolving in development and resources use, and this has led to enormous waste generation of different states (solid, liquid, and gas). The waste needs to be either treated or recycled, paving ways for different techniques for different wastes to be treated or recycled. One of the important resources on earth is water. It is used for everyday activities such as domestic, industrial, and commercial purposes. This has caused reduction in freshwater quantity globally and shortage in clean water supply because of pollution of the existing sources. Hence, different techniques and approaches are still being investigated that can provide adequate and sustainable freshwater. Distillation has been a promising process of separating components by heating/boiling, which causes evaporation, and cooling, which causes condensation. Distillation is a simple technique of converting liquid to vapor by heating and subsequently condensing it back to liquid after the vapor comes in contact with a cooler surface. Simple distillation may not be efficient for certain modes of treatment; therefore, some other advanced distillations were found like the fractional distillation for petroleum

refining and multi-effect distillation (MED) for desalination. Generally, distillation is meant to separate a homogenous fluid mixture using the differences in the volatility or boiling point of the mixture's components [1].

There are three definitions of distillation relevant to desalination. (a) Distillation is a process in which a liquid sample is volatilized into vapor that is later condensed into liquid with richer volatile components of the original sample. This can be achieved by heating, reducing pressure, or both. (b) Distillation is the process of separating a mixture of fluids using the differences in their boiling point or relative volatility. (c) Distillation is the application of heat to a liquid to cause its partial vaporization, and then, a separate vessel is used to collect the condensed vapor [2].

The cost for all distillation methods varies, but they have a similar process or working principle. The temperature difference allows water to evaporate even at 40°C leaving the dissolved solids behind, which require about 300°C to volatilize [3].

Distillation has various advantages such as (i) the capacity to take care of a wide range of feed flow rate range, meaning they can handle high and low flow rates contrary to some alternative techniques. For example, facultative, stabilization, oxidation, and maturation ponds all require a high flow rate of feed; (ii) it can remove various and lots of substances from feed concentrations. Numerous alternative treatments have different stages or include varied chemicals for a particular impurity removal. For example, alum is used mainly to reduce solids through coagulation and chlorine is used only for the elimination of pathogens; so, it cannot remove suspended solids or other impurities; (iii) it can produce water of very high quality (pure); this is contrary to other techniques that partially treat or only reduce the impurity level of the feed. Distillation is a very well-known technique for purification because of its robustness and versatility [1]. One of the major issues with distillation in desalination is the high energy demand for the process. **Figure 1** shows a representation of the distillation process in desalination. After feedwater is transferred to the basin, the first step is the use of energy, mostly solar energy, to heat the basin water to cause it to evaporate to produce freshwater; the byproduct remains in the basin as brine solution, which can also be extracted.

The aim of this chapter is to elaborate the principles and modes of distillation in desalination and analyze their types, improvements, features, challenges, limitation, cost, gap, and future improvements needed.

Figure 1.
Distillation process in desalination.

2. History of distillation in desalination

Despite distillation being widely used in various disciplines lately, it was first used for desalination by the people of Babylonia in Mesopotamia, which was found on the Akkadian tablet dated c. 1200 BCE. Later, Aristotle (384–322 BC) established a hypothesis that when saltwater evaporates, it forms vapor, which becomes sweet, and the condensate is salt free. Pliny the elder (AD 23–70) explained on the purification of seawater, specifically the Red Seawater *via* pearl barley leaves, the leaves absorb the salt content in the seawater. The leaves are spread around the ship so that they can absorb seawater and this makes the leaves moist; then the clean water is extracted by squeezing. Alexandria the chemist in Roman Egypt during the first century narrated on how sailors used bronze vessels covered with sponges to boil seawater and how condensates are collected by the sponges [4].

Furthermore, evidence of baked clay retorts and receivers was found at old Indian subcontinent cities; cities such as Taxila, Charsadda, and Shaikan Dheri in modern Pakistan show evidence that during early centuries distillation was practiced there. The distillers were locally called Gandhara stills and they could only produce weak liquor because they lacked efficient means for vapor collection at low heat. However, the first distinct use of distillation specifically for water (distill water) was in 200 CE by Alexander of Aphrodisia. The process continued for other liquids in the early Byzantine Egyptian during the third century under Zosimus of Panopolis [5].

In the eighth and ninth centuries, wine distillation was attributed to Arabic work by Al-Kindi and Al-Farabi, and some were found in the 28th book of Al-Zahrawi commonly known as Abulcasis. During the centuries mentioned earlier, some Medieval chemists such as Jabir ibn Hayyan known as Geber and Abu Bakr al-Razi known as Rhazes did rigorous experiments on distillation using various substances. Later in the twelfth century, a popular recipe known as aqua ardens, which means burning water, which in turn means ethanol, was produced by distilling wine with salt and by the end of the thirteenth century, it became very common in the Western European chemists [5].

In China, distillation started during Eastern Han Dynasty between the first and the second centuries, then in Southern Song between the tenth and thirteenth centuries from archeological findings, and then later in Jin between the twelfth and thirteenth centuries, although the process was predominantly related to the distillation of beverages. In the thirteenth and fourteenth centuries in Qinglong, Hebei Province of China, distillation of beverages was common during the Yuan Dynasty [4, 5].

The trend continued and up to 1500 and a German alchemist Hieronymus Braunschweig published a book called “The book of the Art of Distillation.” This was the first book on distillation and in 1512, the scope was expanded. In 1651, a book titled “Art of Distillation” was published by John French even though most of the work was from Hieronymus [5].

Alchemy later evolved into the science of chemistry, and local equipment such as alembic and retorts now became vessels or glassware in general terms. Until recently, some of the equipment like pot still made of different materials are still used for domestic production or in the manufacture of essential oils [4, 5].

In the modern or middle civilization, that is, during 1822, Anthony Perrier developed continuous still, which was later improved by Robert Stein in 1826. Aeneas Coffey further improved the still in 1830. His unit is referred to as the archetype of modern petrochemical unit. Ernest Solvay was the first to develop a distillation unit that specifically targeted ammonia removal (ammonia distillation) [5].

Currently in the twenty-first century, from the knowledge of the predecessors, various modifications were made to enhance the yield of the distillate. This led to the development of different types of desalination systems and an increase in their

usage, especially to meet the need of providing water for workers on the sea or mining regions [6].

2.1 Distillation desalination

Distillation in water desalination is a technique Or excess salts from saline water. Other minerals and impurities are from seawater or brackish water also removed during desalination and this treatment process can be extended to wastewater, industrial water, rivers, streams, lake, pond, and groundwater/wells. These salts and minerals occurred because of salts. Two products are obtained after desalina-tion—freshwater and brine, which is the waste or byproduct [7].

Desalination can alleviate the pressure on water resources and has the capacity to provide adequate clean water especially to coastal regions and is increasingly becoming an alternative for domestic and industrial freshwater supply. Desalination requires a large amount of energy; however, various energy types can be used for desalination, which makes it a good alternative. **Figure 2** shows the different energy sources that can be used for desalination. They are categorized into nonrenewable energy sources, which include nuclear, coal, petroleum, natural gas, and hydrocarbons, while the renewable energy sources include wind, geothermal, solar, and biomass. The non-renewable sources are sometimes expensive or in some cases, not environmentally friendly. On the other hand, renewable energy sources such as solar, wind, and geothermal can replace the renewable energy and are abundant and cost efficient to harness, particularly, solar energy that can be used even in rural areas [7].

Globally, there are about 21,000 desalination plants, particularly in Saudi Arabia, United Arab Emirates, and Israel [8]. In the desalination field, distillation can occur as membrane desalination and nonmembrane (thermal) desalination.

Figure 2.
Energy sources for desalination.

The membrane desalination is the type that is not a complete thermal process; that is, a membrane is needed to complete the process unlike the thermal (non-membrane) process, which does not require such medium but undergoes complete thermal process. The membrane is a porous material with a thin film, which allows water molecules to pass through, while at the same time preventing salts, larger molecule, pathogens, and metals to pass through. The most common type of distillation in desalination is the membrane distillation. Membrane distillation majorly targets seawater and brackish water [9].

The membrane desalination process includes electrodialysis (ED) and reverse osmosis (RO), which are two major desalinations used recently. They are reverse osmosis and thermal desalination systems, which account for 63.7% and 34.2% of total capacity produced, respectively. The thermal desalination includes multi-effect desalination, multi-stage flash (MSF) desalination, humidification-dehumidification, vapor compression desalination (VCD), and solar still [9].

2.2 Principles of distillation in desalination

Distillation is an ancient method of desalination. It is a phase change process where the liquid known as feedwater, which is mostly seawater or brackish water, is heated to the gaseous state known as vapor and then condensed back to liquid. The condensed water is separated leaving behind brine (byproduct) during the process of evaporation and condensation. There are different distillation types in desalination, namely, solar distillation, multi-effect distillation, multi-stage flash distillation, vapor compression distillation, and membrane distillation.

2.2.1 Solar distillation

Solar distillation imitates the natural hydrological cycle in which solar energy heats the water, causes it to evaporate, and the vapor upon encountering cool surface condenses (**Figure 3**). The condensate is mostly referred to as distillate, which is the freshwater produced, while the impurities left behind is called the brine, which is the byproduct [8]. The first solar distiller was built by Carlos Wilson in Las Salinas in Chile in the year 1872. The distillation principle in this method is that the sun heats the feedwater in the basin and the water molecule evaporates. When the evaporated water molecule (vapor) touches the still cover, which is usually cooler than the vapor, it then condenses to form droplets on the cover. The droplets keep

Figure 3.
Schematic diagram of solar distillation.

increasing in size until they reach a size that they can slide down *via* the cover and through the channel for collection. The brine remains in the basin [3]. The parts of a solar distiller are a glass cover and a basin.

The major advantage of solar distillation is the free energy sources, which is the solar energy. There are other numerous advantages of this process such as design simplicity, low cost of fabrication, and maintenance. However, the major disadvantage of this process is the limitation of the sun at night and during cloudy or rainy times. The scale can easily corrode the basin as well. Sometimes, they do not adequately treat nutrient pollutants. In addition, the distillation rate is slow, and the yield is usually small in quantity compared to the other techniques. The average volume of water produced from conventional solar still is 0.8 liters per hour of sun per meter square [10]. In 2014, globally the cost of fresh-water from solar distiller ranged between 0.019\$/m³ and 0.02\$/m³ depending on the shape of the still [11].

2.2.2 Multi-stage flash distillation

This process is like a continuous process for solar distillation. In this process, the feedwater is first pretreated; it then gets heated and evaporated in the first chamber or stage and the released energy from the condensation is used to heat the water in the second stage and continuously to the last stage after which post-treatment occurs and freshwater is obtained (**Figure 4**). This means that each flash process uses the energy from the previous vapor [8]. The process has several series of flash chambers. Unlike multi-effect distillation in multi-stage flash distillation, heating and boiling occur in the same vessel. The estimated unit cost of freshwater produced from MSF is 1.40\$/m³ as of 2018 [12].

The advantage of this system is that it minimizes the operating cost because the heat released from each stage is being reused (waste heat). The second advantage is that the strength of the feedwater does not really affect the overall freshwater quality produced because of multiple distillation process for each chamber. Finally, a large quantity of freshwater is produced. The disadvantage of this process is the scale formation during heating, although the scale remains in the brine rather than the heating surface which majorly increases the maintenance cost and frequency but do not damage the system [3]. Features of MSF include Stages (spaces), heat exchanger, distillate collector, and brine heater.

2.2.3 Multi-effect distillation

The multi-effect distillation process involves spraying the feedwater on the pipe to heat the feedwater and generate steam. The steam is utilized to heat the subsequent feedwater and evaporate it to produce freshwater and brine as

Figure 4.
Schematic diagram of multi-stage flash distillation.

Figure 5.
 Schematic diagram of MED in two stages.

byproduct (**Figure 5**). The energy is obtained through a solar collector. Flat plat collector and evacuated tube collector are energy sources for small-scale MED, while parabolic trough collector or any collector that concentrates solar energy is used for large scale. MED is a very ancient process, and only at the first stage, the first steam is independently generated. Subsequent stages use the vapor from the first and previous stage as energy source. There are about 8 to 16 effects for most MED. More number of effects means more efficiency [13]. The goal of MED is to use same heat to evaporate more feedwater. That is, the heat from the first stage helps in evaporation in the second stage and the heat from the second stage aids evaporation in the third. At the same time, each stage evaporator acts as a condenser for each previous stage. This way, large latent heat of vaporization is reused several times before dissipating to the surrounding, but it is significant that the temperature of the first effect is lower than the boiler heating steam [3]. These energy sources when tapped from the sun are converted to electrical energy to provide heat for the pump.

The advantages of MED include low consumption of energy in comparison with other thermal techniques; it works at low temperature and concentration to minimize scaling and corrosion. Pretreatment is not essential. It is very reliable and have low maintenance costs. The disadvantage of this distillation process is that there is heat and pressure losses at each stage because the process is not adiabatic and this can reduce the freshwater yield. There is corrosion and erosion at the contact surfaces between the brine and heat exchanging surface [13]. In 2003, it was found out that the average cost of freshwater worldwide that is produced from MED is 1.00\$/m³ which is lower than MSF [12]. Features of MSF include heat source, heat sink, stage and distillate collector, and a membrane (**Figure 5**).

2.2.4 Vapor compression distillation

This process requires a jet stream or mechanical compressor to compress the vapor above the liquid unlike MED and MSF that require energy sources such as crude oil, wind, natural gas, and so on. The compressed vapor supplies heat to the rest of the feedwater for evaporation. Even though the process is a complex type and is mostly used for small-scale distillation, it is far more effective than MED because one effect of VCD is almost as effective as 15 to 20 effects of MED. In **Figure 6**, the feedwater is preheated in the heat exchanger. Later, it is transferred to the tube of the evaporator where it is boiled, and the vapor goes to the mechanical compressor.

Figure 6.
Schematic diagram of VCD.

The vapor is compressed by the mechanical compressor. The hot compressed water vapor is transferred back to the evaporator, which is condensed outside the tube at the same time supplying the heating energy required for boiling feedwater. The non-condensing gases are removed with the help of a vacuum pump or ejector [3].

The advantages of this method are low operating and maintenance cost; it has a vast temperature range for operation; it is very efficient and reliable because it has good water recovery ratio and moderate energy consumption; and it is easy to use and maintain. The huge initial cost is a major disadvantage for this process. Second, it requires pretreatment to minimize fouling and scaling, and internal scaling can occur as a result of crystals accumulation in the pore [14]. Finally, quality materials are needed to prevent corrosion [15]. The average cost of freshwater produced from vapor compression distillation is 0.93\$/m³ as at 2009 findings [16].

2.2.5 Membrane distillation

This process uses differences in temperature across the membrane to evaporate the feedwater and condensed the freshwater leaving the impurities, salts, and other minerals in the form of brine solution. The concept of membrane distillation is microfiltration, which allows only water molecules to pass through porous hydrophobic membrane [17]. Membrane distillation can use different low-grade energy

Figure 7.
Schematic diagram of the direct contact membrane.

Figure 8.
Schematic diagram of the sweep gas membrane.

Figure 9.
Schematic diagram of the vacuum membrane.

sources like the sun or wind. The water molecules move from the region of high to low vapor pressure through the membrane. There are four methods by which the vapor is recovered through the membrane. The first is through the direct contact of the liquid phase with both sides of the membrane to obtain distillate and the condensation process is controlled by the thickness of the membrane (**Figure 7**). Although the heat loss in this method is higher than that in other methods because

Figure 10.
Schematic diagram of air gap membrane.

of continuous contact between the membrane, the hot feed and cold permeate. This method is called the direct contact membrane distillation. The second method is vapor withdrawal by using a vacuum on the permeate region; in this method, the process is like the first but for the introduction of the condenser and the sweep gas that differentiate them (**Figure 8**). This is also known as the sweep gas membrane distillation. The third method is having an external condensation and in this case, the vapor is removed by using an inert gas stream (**Figure 9**). This method is called vacuum membrane distillation [18]. The fourth method is the addition of air gap interposed between the condensation surface and the membrane (**Figure 10**). This process is called the air gap membrane distillation [19].

The advantages of membrane distillation include a high-rate removal of macromolecules and other substances, lower operating temperature and pressure, unadulterated interaction between the membrane and the process, and reduction in vapor spaces. The main disadvantage of membrane distillation is membrane wetting, which is caused as a result of fouling and excessive liquid entry pressure [18]. In 2004, the average cost of freshwater from membrane distillation was 0.705\$/m³ [20].

2.3 Simple desalination system

This section will focus on the first concept of distillation in desalination, improvements made on them till date, the merits, and their demerits as well as the challenges and limitations of all the mentioned distillation desalination systems experienced so far. The first developed distillation system is known as the conventional desalination system. The first step is fabrication of a basin, which is usually made of metal material. Then, the fabrication of the cover that is mainly glass material was used. The cover generally is in a triangular shape. Afterward, the glass cover is placed on the basin to form a closed system that will allow distillation/desalination. In ancient times, they did not know how to seal the bottom edges between the glass cover and the basin because of which there were high heat losses and a low yield. Later, the system was sealed with mostly silicone gel to prevent or minimize heat loss and increase the yield. This is a simple way for conventional desalination that can be replicated anywhere in the world. **Table 1** shows the different types of distillation systems, the improvisation made, current challenges, and limitations, with possible future improvements.

2.4 Modes of distillation in desalination

Distillation in desalination can occur in three different modes, although the third mode is a combination of the two independent modes. The first is the utilization of the solar irradiance directly from the sun causing heating/evaporation to the feedwater and condensation when it meets a cold surface. The second mode is the storage of the solar irradiance or any other sources of energy such as wind and geothermal to produce electricity that is used to heat and evaporate the feedwater and later condensed to obtain the distillate [18]. The third is the utilization of the solar irradiance directly and supplementing it with other energy sources that produce electricity or other forms of heating source to cause distillation.

2.4.1 Passive distillation

Passive desalination or distillation is the cheapest and most used method even in rural regions. This is because of its simplicity and because it can work on its own. It uses only energy from the sun (solar irradiance) directly to heat the water leading to

Distillation desalination types	References	Present improvements	Challenges/limits	Gap/feature improvement
Solar Distillation	[21–28]	<ul style="list-style-type: none">• Geometry improvement such as cover angle, shape, thickness. The cover angle ranges from 2 mm to 7 mm. The angle ranges from 10⁰ to 60⁰. The shapes include triangular, tubular, hemispherical, trapezoidal, and circular. These improvements are to minimize heat loss.• Use of different heat absorbers which include paraffin wax, sand, black stone, sponge, and wick to increase heat retention.• Use of nanoparticle such as Al₂O₃ nanoparticle, and SiC nanofluids to fastened evaporation.• Use of different sealants such as sawdust, glass wool, ply wool hey, and silicone gel to minimize heat loss.• Use of photovoltaic to augment solar irradiance.	<ul style="list-style-type: none">• Low yield.• The conventional system cannot be used during rain, cloud, or at night because of the absence of sunlight.• Cost of solar photovoltaic can be overwhelming and limited energy storage capacity.• Some solar distillers cannot completely remove nutrient if it is in high concentration in the feedwater.	<ul style="list-style-type: none">• More heat-retaining substances that can be used for the basin.• More heat-absorbing substance that can be used for the cover.• Advance usage of other energy sources such as biomass, wind to augment solar radiation.
Multi-stage flash (MSF)	[29–36]	<ul style="list-style-type: none">• Increasing the number of brine heater to increase the evaporation rate.• Some materials such as aluminum, brass, or titanium tubing for evaporators, combination of Cu/Ni for the evaporator wall to enhance water production.• Use of certain energy sources such as super-critical carbon dioxide Brayton cycle, solar tower power, and parabolic trough solar-based power to increase energy harnessing.• Coproduction of electricity and water from steam turbines.• Use of solar steam as heat source for brine heater.	<ul style="list-style-type: none">• Scale formation and corrosion.• Hot distillate.• High capital as cannot be used for small scale.• The need to pretreat feedwater to overcome thermal desalination problem.• System failure because of complexity.	<ul style="list-style-type: none">• Use of alternative materials or locally made materials to reduce cost.• Reduction in scale formed through filtration membrane to increase plant efficiency.

Distillation desalination types	References	Present improvements	Challenges/limits	Gap/feature improvement
Multi-effect distillation	[29, 37–42]	<ul style="list-style-type: none">• Use of air-cooled condensers.• Integrating MED and other desalination types such as membrane, adsorption cycle, and reverse osmosis to enhance freshwater recovery and reduce brine volume.• Use of sprays to reduce internal heat loss.• To reduce corrosion and increase system performance, special metal alloys, or polymers are used for the MED evaporator.• Use of equipment with high temperature.• Permeate reprocessing in different configuration.• Combination of MED with gas turbine plant.	<ul style="list-style-type: none">• More surface area may be needed for recirculation of energy.• Not suitable for small scale, because of high capital cost.• The special materials used for MED evaporator could be very costly and some have low thermal conductivity.• System complexity.	<ul style="list-style-type: none">• Improving hybrid systems (combining different system) for better performance.• Use of multiple energy sources.• Air cooled condensers specially made from nanoparticle with improved cooling effect.• Special nanoparticle materials may be used to fabricate evaporator.
Vapor compression	[43–52]	<ul style="list-style-type: none">• Use of substances such as polymer heat transfer elements to enhance freshwater production.• Use of high-temperature heat pumps to increase energy efficiency for VC as well as choosing a better working fluid like ammonia, carbon dioxide, hydrocarbons, and synthetic working fluid or their combination.• Optimizing cycle configuration into different series to give better system performance.• Making it a hybrid system like adding internal solution circuit.• Hybrid systems for multipurpose use by treating brine and recovering salts and minerals.	<ul style="list-style-type: none">• High energy demand and the need to investigate to use cheaper energy technology.• High initial/capital cost.• Contamination of the vapor water with some vapor compressions system material such as SO₂, NO and even H₂SO₄.	<ul style="list-style-type: none">• New different working fluids can be experimented to check their suitability for VC.• Investigate materials suitable for VC with little or no contamination.

Distillation desalination types	References	Present improvements	Challenges/limits	Gap/feature improvement
Membrane	[53–62]	<ul style="list-style-type: none">• Use of carbon nanotube like polydimethylsiloxane in different format to increase system efficiency.• Use of thin film nanocomposite/nanomaterials like carbon to fabricate membrane systems to improve system efficiency.• Use of interfacial polymers to enable better heat recovery.• The use of different synthetic membranes.• The use of materials with anti-wetting properties like amphiphobic polyvinylidene fluoride co-hexaflouropropylene.	<ul style="list-style-type: none">• One of the major challenges of membrane desalination is the high osmotic pressure generated because of high ionic concentrations of saline water in addition to the fouling problem.• Not reliable because of limitation of sun unless solar energy is harvested.	<ul style="list-style-type: none">• More nanomaterials like Al₂O₃ can be investigated to check their suitability in improving membrane desalination.• Hybrid or integration of other approaches with membrane desalination can be experimented to find out their efficiency.

Table 1.
Challenges, present improvements, and future prospective of distillation desalination types.

its evaporation, and the vapor condenses when it touches the cold surface. For this type of distillation to occur, an enclosed system is needed, which basically consists of a water basin and a transparent cover usually made of glass or plastic. It is then sealed to prevent vapor or heat loss [2].

The advantage of this process is that it has a cheap source of energy, as the energy comes directly from the sun. This energy is abundant in most regions and does not need conversion or storage. It is simple to fabricate, use, and maintain. It can produce very clean water for drinking and other purposes without the need for further treatment. However, the major disadvantage of this process is that it can operate only during the day when there is sunshine. At nighttime or rainy times, since there is no sun, it is not possible to carry out this process. Solar stills, solar chimneys, and humidification-dehumidification are examples of this process.

2.4.2 Active distillation

In active distillation, the same process is observed. In other words, there is heating, evaporation, and condensation of feedwater to obtain freshwater. It is just that in this case, the sources of energy are other sources such as wind, geothermal, or stored solar energy in photovoltaic cells, which are later converted to alternative current to supply the energy/heat for the distillation process.

Some of the advantages of this process include faster distillation, as the feedwater gets heated faster than it does in the passive method. The method can also be used either nighttime or daytime, especially during cloudy or rainy days when there is no solar radiation. Evident research carried out at Universiti Teknologi PETRONAS, Malaysia, shows that this method produces cleaner freshwater than passive and combined distillation. This method, however, has some challenges like more scale formation and higher and more expensive energy usage. It may require semi-skilled persons to operate some of these distillers.

Solar stills, solar chimneys, and humidification-dehumidification can also be used for this process. In addition, membrane desalination can also fall in this category, since some part of it involves phase change of the feed (distillation) with the aid of a membrane.

2.4.3 Combined

In the combined state, this is also operated during the daytime, where both solar irradiance and other energy sources such as photovoltaic, wind, and biomass are used simultaneously for distillation. This produces more freshwater than the first two mentioned methods because of the effect of combined efforts. This process increases the frequency of performing maintenance tasks, as corrosion and scale formation is high.

3. Conclusions

Historical evidence has shown that distillation has been an old technique for water purifications. Distillation in desalination has proven to be an effective technique for freshwater production. Various distillation types have a similar quality of distillate. However, they differ in distillate quantity. The mode of distillation can also have an impact on the quality of freshwater yield as evidently carried out in the laboratory where the active mode had cleaner water production. The distillation types in desalination have advantages and disadvantages over one another. Therefore, the quantity and quality of distillate needed determines the most

appropriate distillation type to choose for the desalination process. Currently, there are numerous researches that are exploring on how to enhance the distillation process in desalination. There is still the need for technological advancement to enhance yield in the case of solar distillation and reduce cost, especially in the vapor compression desalination process. The carbon nanotube membrane has been a promising solution for membrane desalination and can be exploited further. Overall, desalination has been an effective and efficient solution to augment conventional clean water supply. If given proper attention, it can be a lasting solution for clean water supply.

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Conflict of interest

The authors declare no conflict of interest.

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Appendices and nomenclature

ED	Electrodialysis
RO	Reverse osmosis
MSF	Multi-Stage flash distillation
MED	Multi-effect distillation
VCD	Vapor-compression distillation

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