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A Review on Different Design Modifications Employed in Inclined Solar Still for Enhancing the Productivity

The current challenge of human society is to meet the large demand of freshwater, which is depleting at a faster rate due to a rapid rise in human population and fast urbanization. Solar still is the economical way to obtain fresh water since it solely requires the energy from the sun alone for its operation, which is abundantly and freely available in nature. The major constraint in conventional solar still (CSS) is to maintain a large surface area of water with a minimum water depth. The best solution for the above constraint is to prefer inclined solar still (ISS) in which the surface area of water is large with a minimum water depth. In order to improvise the performance and efficiency of ISS, numerous works have been incorporated by increasing the free surface area of water. The distillate yield collected from the passive ISS was found as 1000–8100 mL/m^2 whereas active ISS produced the distillate yield of 1045–9000 mL/day. In this review, an attempt is made to analyze the present status of different designs in ISS to motivate further research in ISS technology for meeting the demand of fresh water. [DOI: 10.1115/1.4041547]

Keywords: inclined solar still, wick material, stepped solar still, passive and active mode, yield enhancement

1 Introduction

Due to the crisis in water, several desalination processes based on renewable energy methods were developed in order to meet the demand of getting fresh drinking water. Over the past few decades, the efficient and more economical solar still technologies were developed. The design and fabrication of a conventional solar still (CSS) is very simple and requires less maintenance. The basin is constructed with locally available materials and fabricated in the structure of right angle triangle and a glass is covered over it. In order to increase the absorptivity of basin material, it is coated with black paint and to prevent the loss of heat from the basin to the ambient, material such as wood and sawdust is used as thermal insulators. Inside the basin, enough spaces were provided to fill the brackish or saline water while the solar intensity is absorbed by water for quick evaporation from the top liner. Due to the partial pressure developed inside the basin, the evaporated water reaches the inner glass cover surface to get condensed by the ambient parameters. The water droplets thus formed on the collector cover gets condensed and collected in a distillate collector, which is kept at the end of the glass cover. The distillate collected in the distillate collector glides through the inclination provided and fresh water is collected in the separate calibrated flask. The main drawback of CSS is its lower yield and poor latent heat of condensation to the surrounding. To overcome the above difficulties, several design configurations were incorporated to improve the efficiency and productivity of CSS. To improve the productivity, different modifications in a solar still have done. Inclined solar still (ISS) is one such modified form of CSS.

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However, limited progress was made in the improvement of inclined still [1–4]. Inclined solar still has the following additional features incorporated to its design such as flexibility in inclination angle increased effective area, the direct projection of solar intensity toward basin, increased the length of flowing water, an increased retention time of flowing water and higher evaporation rate. All these features improve the performance of ISS as compared to CSS [5]. Researchers have taken several efforts in the modification of solar still for higher productivity and inferred that wick-type solar stills are effective [6]. Modern progression in freshwater enhancement approaches in humidification–dehumidification and solar still was summarized by Srithar and Rajaseenivasan [7]. An extensive review of pyramid solar still was recently summarized by Nayi and Modi [8]. Different approaches employed in stepped solar still (SSS) to augment the production were studied by kabeel et al. [9]. Omara et al. [10] reviewed the solar still incorporated with reflectors. Sharshir et al. [11] have done a detailed report on thermal and exergy investigation of solar still. An enhancement method of solar still efficiency was studied by Sivakumar and Sundaram [12]. Elango et al. [13] have done an extensive review of thermal models of solar still. Various design approaches used to improve the yield from multi-effect solar still were examined by Rajaseenivasan et al. [14]. A study on energy, exergy, and thermo-economic of solar still was done by Ranjan and Kaushik [15]. Different design modifications of a solar still were reviewed by Durkaieswaran and Murugavel [16], El-sebaii and El-Bialy [17], Panchal and Patel [18], Samee et al. [19], and Kumar et al. [20]. Different factors affecting the solar still yield have been summarized by Manokar et al. [21], Muftah et al. [22], and Velmurugan and Srithar [23]. Active solar still distillation system has been reviewed by Sathyamurthy et al. [24], Sampathkumar et al. [25], Chandrashekara and Yadav [26], and Manokar et al. [27,28]. This review detail explains the different design configurations of inclined solar still developed by several researchers in order to increase the performance and efficiency.

2 Classification of Inclined Solar Still

Inclined solar still is one of the best methods employed in improving the yield and in this type, various methods are employed such as tilted wick solar still, internal and external reflectors, weir type. The free flow of water by gravity method improves the yield compared with stagnant water. The flow of water is controlled by either forced or natural, and stagnant water controlled either by water mass or by its depth. Improved inclined water desalination was designed by Egelioglu et al. [29]. Egelioglu et al. [29] experimentally investigated and studied the effects of solar intensity, keeping wick on the plate and bare plate (BP) of ISS on the daily yield of fresh water. The major difficulty that they found in the system is higher glazing temperature. Higher glazing temperature enhances only the evaporation rate, and for a system balance, the glazing temperature has to be reduced. Based on the design and operating condition, ISS can be classified into the following types:

2.1 Basin Type Inclined Solar Still. The main drawback of CSS is less water production capacity because of not maintaining the minimum water depth (d_w) and large surface area of water. ISS is the best alternative method to maintain the minimum d_w and enhance the large surface area of water by placing the absorber plate of still at some angle. Due to an inclined position, ISS maintains a thin layer of water, which results in quick evaporation of water than the CSS and hence higher yield and efficiency. The main advantages of ISS over CSS are: it maintains a thin layer of water inside the solar still and produces the distillate water, and simultaneously hot water.

2.1.1 Single Basin Inclined Solar Still. El-Agouz et al. [30] theoretically examined the performance of ISS by recycling the hot water to the still basin using the water pump. The performance of the stills was analyzed by varying mass of water (M_w), water film thickness (b_w), air wind velocity (V_a), and water film (U_w) velocity. As b_w was varying from 0.25 to 3 mm, the still productivity and efficiency are higher in model-2 than those of model-1, because of large difference between the basin saline water temperature (T_w) and glass cover temperature (T_g). As U_w changes from 0.01 to 0.05 m/s, the increases in water film velocity result in a faster flow of water in the still basin; hence, it has less time to utilize the heat from the still basin. It negatively affects the still productivity and efficiency. Water film velocity is indirectly proportional to the still productivity and efficiency. As V_a varies from 0 to 10 m/s, the increases in V_a result in a higher heat transfer rate from still collector to the atmosphere, which will reduce T_g and hence result in a higher difference between T_w and T_g, which will lead to higher productivity and efficiency. As M_w varies from 10 to 50 kg, the increasing water mass in the still basin results in lower productivity and efficiency. This is because of lower return rate of water to the storage tank. Finally, it was concluded that model-2 produced 57.2% higher productivity than the CSS.

2.1.2 Double Basin Inclined Solar Still. Aybar et al. [31] have done the comparative analysis of single basin inclined solar still (SBISS) and double basin inclined solar still (DBISS). In this research work, two solar stills have the same dimensions but the number of the basin in each solar still is varied. In DBISS, lower basin was made of absorber plate and the upper basin was made of transparent glass. In SBISS, condensation takes place at one place, whereas DBISS condensation takes place at two places (upper and lower basin). Experiments were conducted under two different conditions (i) still basin with normal absorber plate (ii) still basin with a black-fleece wick.

The basin with black fleece produced higher efficiency for both SBISS and DBISS because of maintaining minimum d_w and higher evaporation surface of the water in the black-fleece wick material in the basin. In the first condition, the maximum hourly average efficiency of 10.40 and 22.16% obtained for SBISS and DBISS, respectively. In the second condition, the maximum hourly average efficiency of 29.44 and 39.07% obtained for SBISS and DBISS, respectively

2.1.3 Inclined Solar Still With Baffles. Sathyamurthy et al. [32] theoretically studied the ISS with baffle plates with varying the mass flow rate of water (m_w), the temperature of inlet feed water and basin temperature. It was observed that the water temperature is higher (65 °C) at minimum mass of water (m_w) (0.0833 kg/min) and lowest water temperature (38 °C) is obtained for a maximum m_w (0.4166 kg/min) at peak solar radiation condition. Similarly, absorber plate temperature also inversely proportional to the m_w. The higher absorber plate temperature (74 °C) is obtained at a minimum m_w (0.0833 kg/min) and lowest absorber plate temperature (35 °C) is obtained at a maximum m_w (0.4166 kg/min) at peak solar radiation condition.

The minimum m_w considerably increases the hourly productivity as well as the total productivity. The maximum hourly productivity of 0.7 kg/m^2 and minimum hourly productivity of 0.05 kg/m^2 is obtained for minimum m_w (0.0833 kg/min) and maximum m_w (0.4166 kg/min) at peak solar radiation condition. The maximum daily productivity of 3.5 kg/m^2 and minimum daily productivity of 0.5 kg/m^2 are obtained for minimum m_w (0.0833 kg/min) and maximum m_w (0.4166 kg/min) at a constant water temperature of 32 °C and wind speed of 3 m/s. The freshwater production can be increased up to 57.14% and 65% at a minimum m_w (0.0833) kg/min and maximum inlet feed water temperature of 60 °C, respectively.

Ravishankar and coworkers [33] also experimentally investigated the ISS with and without baffles. The main advantages of baffles are, they slow down the m_w and they increase the contact time between feed water and absorber plate. In this experimental work, m_w is kept as 0.0833 kg/min. The freshwater production from ISS with baffles and without baffles is 5.4 kg/m^2 and 3.4 kg/m^2, respectively. Finally, it was concluded that arranging baffles results in significant improvement in water temperature and productivity.

2.1.4 Stepped Type Inclined Solar Still. Alaudeen et al. [34] introduced the novel solar still by fixing up a stepped tray basin connected in series with inclined flat plate collector (FPC) together with a conventional basin. In this setup, three stepped tray basin has four small portions are interceding with FPC with wick materials. Water is flowing from the water storage tank to the first stepped tray basin and excess water flow over the inclined FPC and reached the second stepped tray basin and the rest. Last, preheated water is entered into the conventional basin.

Experiments were conducted by the wick, the wick with coconut coir and sponge, the wick with wood chip and pebbles, the wick with sand and wick with coal, pebbles, and sponge. Results of proposed system were compared with CSS. It was concluded that integrating FPC improved the productivity of fresh water to a maximum of about 1305 and 1745 kg/m^2 with wick and sponge, wick and rock, respectively.

The wick with wood chip and pebbles produced the higher efficiency than the other modifications. The efficiency of the CSS and propose solar still were in the range from 7 to 14% and 9 to 16%, respectively. The payback period of the CSS and the proposed solar still is 400 and 320 days, respectively.

El-Agouz [35] used a storage tank for continuous water circulation in SSS to increase the production time. The absorber plate of SSS was made by 1 m^2 area and it is divided into ten equal steps. Experiments were conducted by varying the feed water (i) sea water, (ii) salt water, and basin conditions (i) black absorber basin (ii) cotton absorber basin. In the first case of basin conditions, black absorber SSS is experimentally researched and the results were compared with CSS. It is found that the daily efficiency of black absorber SSS and CSS is 61% and 42% for seawater desalination and 55% and 37% for saltwater desalination. In the second case, the black absorber is replaced by a cotton absorber. From the experimental results, it was found that the daily efficiency of cotton absorber SSS and CSS is 61% and 40% for seawater desalination and 70% and 48% for saltwater desalination. Black absorber SSS increases the fresh water production rate up to 43% and 48% than that of CSS for seawater desalination and saltwater desalination, respectively. Cotton absorber SSS increases the freshwater production rate up to 53% and 47% than that of CSS for seawater and saltwater desalination, respectively. SSS with saltwater as inlet produced the yield of 6.3 kg/m^2/day and seawater produced 6.1 kg/m^2/day

El-Samadony and Kabeel [36] theoretically studied the comparative study of CSS and SSS with glass cover cooling techniques. They theoretically derived that best water film thickness in the range between 2.5×10^{-4} to 5.5×10^{-4} m, volumetric flow in the range between 4×10^{-5} to 8.5×10^{-5} m^3/s for the 2.8 m glass cover length. It was found that the use of cover cooling technology may increase the productivity up to 8.2% than that of CSS. It is also recommended that the cooling water can be again flowing into the still basin which will increase the productivity up to 2.87%.

El-Samadony et al. [37] theoretically studied the radiation shape factor between basin water and collector cover for SSS. At low solar radiation and higher glass cover angle, radiation shape factor mainly determined the yield from SSS. At 200 W/m^2 solar radiation and 70 deg cover inclination angle, solar still productivity is increasing up to 18.8% when considering the radiation shape factor. Higher glass cover inclination angle results in lower radiation shape factor and hence the yield from still increases. It is also reported that, to receive the maximum solar radiation, glass cover inclination should be equal to the latitude angle of the place. It is found that SSS productivity increased about 7.76 to 12.62% with incorporated the radiation shape factor.

Comparative study of CSS and SSS with reflectors attached to the perpendicular sides of the steps was done by Omara et al. [38]. The experiments were conducted at a 5 mm depth of water in the solar stills. It was found that SSS without reflectors and with reflectors increases the water temperature up to 3 and 4.5 °C, respectively than the CSS. The maximum hourly productivity of 960, 930, and 650 mL/m^2 was obtained for the SSS with reflectors, SSS without reflectors and CSS, respectively. The maximum daily yield for the SSS with reflector, without reflector and CSS, is 6350, 5840, and 3720 mL/m^2, respectively. SSS with internal reflector and without internal reflector improves the daily yield of about 75 and 57%, respectively, than that of CSS. The maximum daily efficiency for the SSS with reflector, without reflector and CSS, is 56, 53, and 34%, respectively.

Comparative study of CSS and SSS with internal mirrors and external mirrors (top and bottom) was experimentally researched by the Omara et al. [39]. Experiments were conducted by different design modifications in the SSS and results were compared with the CSS. It is found that external mirror attached on the top and bottom of the SSS produced the maximum daily yield of about 6500 and 6830 mL/m^2, respectively, which are 91 and 98% improvement in productivity than that of CSS. SSS incorporated with internal and top external mirror, internal and bottom external mirror, these two designs produced the maximum daily yield of about 7400 and 7240 mL/m^2, respectively, which are 108 and 113% improvement in productivity than that of CSS. SSS attached with both internal and external (top and bottom) mirrors produced the maximum yield of about 8100 mL/m^2, which is 125% higher than that of CSS.

Muftah et al. [40] have done a comparative analysis between the SSS and SSS with design modifications such as attaching fins on a tray, interior and exterior mirrors, and outer condenser. It was found that the maximum hourly yield of 0.914 and 1.12 kg/m^2 is obtained for before and after design modifications, respectively. The daily freshwater production of about 6.9 and 8.9 kg/m^2 is attained for before and after design modifications respectively. SSS with proposed design modifications improves the freshwater production up to 29%. SSS with fins attached to the tray improves the yield about 14%. Energy and exergy efficiency of the proposed SSS is 60.2 and 30.4%, respectively, and that of the SSS without design modifications is 52.3 and 29%, respectively.

Velmurugan et al. [41] have done the experimental investigation on SSS for sewage desalination. In this work, the effluent from textile industry was used to flow from the settling tank to the SSS. The settling tank has five portions. The top portion is for filling the raw effluent. The second portion is filled with pebbles to drain the big size solid molecule. The third portion is filled with activated charcoal to separate the bacteria. The fourth portion is filled with sand layer filters to drain the very small size solid molecule. The bottom portion is for collecting the settled effluent. The maximum water storage capacity of the SSS is 3.75 L of effluent and it consists of 50 separate trays. The experiments were conducted by modifying the SSS with fins, pebbles, and sponge in the basin of SSS. It was found that the productivity of SSS with fins, with fins and pebbles, with fins and a sponge, and with fins, pebbles and sponge were 1.27, 1.37, 1.4, and 1.65 kg/m^2, respectively. The freshwater production rate is increased about 53, 68, 65, and 98% when fins, fins and pebbles, fins and sponge, and fins, pebbles, and sponge are used in the basin of the SSS.

Abujazar et al. [42,43] researched the SSS by replacing a galvanized iron tray with copper tray. SSS is made of stainless-steel box and insulated with saw dust. The absorber plate is made of copper to increase the thermal conductivity of the system. Collector cover is made of tempered glass with an angle of 30 deg to the horizontal. This SSS enhances the evaporation area of about 55.6% than the normal CSS. It was found that copper inclined SSS produced the daily maximum freshwater production of about 4383 kg/m^2 and maximum hourly efficiency of 58% at 5 P.M.

2.1.5 Weir Type Inclined Solar Still. Sadineni et al. [44] have done the theoretical and experimental studies on weir-type ISS. It consists of a weir-shaped absorber plate, collector cover, and water circulating pump. The entire setup is made of 1 mm thickness galvanized steel. The height of weir-shaped absorber plate is 1.6 mm to maintain the minimum d_w in the still basin. Water is flowing over the weir-shaped absorber plate covered with 0.25 mm thickness nylon wick material and collected in the bottom basin. Vinyl window meshes (wick material) uniformly distribute the water and increase the contact time on the absorber plate. In this research, single and double layer tempered glass covers are used. The entire experimental setup is insulated by 15.2 mm thickness glass fiber insulator. The unevaporated water from the weir type absorber again returns to the water storage tank by using a water pump capacity of 0.7 L/min at 1 m elevation. Experiments were done by comparing the performance of weir type solar still with single and double layer glass cover. It was submitted that weir-type solar still with a single layer glass cover and double layer glass cover produced the daily distillate yield of 5.5 and 2.2 L/m^2. Double layer glass cover reduces the yield up to 60%. The maximum distillate yield produced from the weir-type solar still was 20% higher than that of CSS.

2.1.6 Weir Type Cascade Solar Still. Tabrizi et al. [45] designed a weir-type cascade solar still (WCSS) and conducted experiments by varying the m_w. The schematic diagram of the cascade solar still is made of aluminum sheets to prevent the corrosion. Absorber plate was made of 15 steps and each step is a horizontal and vertical area with the length of 50 and 30 mm, respectively. Due to stepped absorber surface, the flowing water increases the residence time of water in the still. Weir surface maintains the water thickness as shallow as possible, which improves the evaporation rate. Experiments were conducted by different m_w (0.065, 0.1, 0.15, and 0.2 kg/min) in four consecutive days. It was submitted that the maximum water temperature is obtained at the minimum flow of water. The maximum daily yield produced from the WCSS is 7.4 and 4.3 kg/m^2 for tiny and most m_w, respectively. The overall efficiency for WCSS is 63.3 and 36.6% for tiny and most m_w, respectively.

Zoori et al. [46] have done the energy and exergy efficiency of the WCSS [45]. Effects of m_w, water film thickness, solar intensity, atmospheric temperature, and inlet brine temperature on the energy and exergy efficiency were investigated. It was found that minimum m_w produced the maximum hourly productivity. Tiny water flows over the absorber plate results in quicker increases in water temperature and hence improvement in productivity. Increasing the water layer thickness and inlet atmosphere temperature negatively affect the WCSS performance and increasing the solar intensity and inlet brine temperature positively affect the WCSS performance. The maximum energy efficiency of 83.3 and 44.1% and exergy efficiency of 10.5 and 3.14% is obtained for WCSS with tiny and most m_w, respectively.

Dashtban and Tabrizi [47] enhanced the yield of WCSS by using latent heat thermal energy storage system (LHTESS). The experimental setup is same as described by Tabrizi et al. [45] except that the phase change material (PCM) (paraffin wax) is incorporated under the absorber plate. The theoretical and experimental analysis was done for WCSS with and without LHTESS. Experiments were conducted by four different d_w inside the basin (0.02, 0.04, 0.07, and 0.1 m). From the experimental results, it is observed that minimum d_w produced the higher productivity at morning and increasing the d_w produced the higher productivity at afternoon due to water storage capacity. The WCSS operated at 2 and 10 cm d_w produced the yield of about 6.75 and 4.12 kg/m^2 day, respectively. It was concluded that WCSS without LHTESS produced higher yield than WCSS with LHTESS during the high solar intensity because of absorber plate spent on some heat energy to increase the PCM temperature, which results in the decrease in water temperature and hence decrease in the yield. PCM discharges the stored heat energy when there is less solar intensity, so still with PCM increases the evening and nighttime productivity. It is found that WCSS with and without PCM produced the maximum productivity of 6.7 and 5.2 kg/m^2 day and efficiency of 64 and 47%, respectively. Still with LHTESS increases the productivity up to 31% than still without LHTESS.

Tabrizi et al. [48] have done the comparative study of WCSS with and without LHTESS on bright and partially dark days. Also, WCSS was investigated by five different m_w (0.055, 0.07, 0.085, 0.1, and 0.115 kg/min). It is submitted that WCSS with LHTESS produced the maximum yield of 4.85 and 3.4 kg/m^2 day for bright and partially dark days, respectively. Similarly, WCSS without LHTESS produced the maximum yield of 5.14 and 2.1 kg/m^2 day for bright and partially dark days, respectively. It was found that for bright days, WCSS without LHTESS produced the maximum productivity and for partially dark days WCSS with LHTESS produced the maximum productivity.

Sarhaddi et al. [49] have done the energy and exergy analysis for WCSS with and without LHTESS (PCM). From the experimental investigation, it is found that PCM temperature increased with increasing of solar intensity and reached its melting point (56 °C) at 2 to 4 P.M. After that, PCM discharges the temperature gradually until it has become solid. WCSS with PCM produced the maximum yield of 6.63 and 4.94 kg/m^2 on sunny and cloudy days. WCSS without PCM produced the maximum yield of 7.05 and 3.84 kg/m^2 on sunny and cloudy days. The thermal efficiency of WSCC with and without PCM is 74.35 and 76.69% during cloudy and sunny days, respectively. Similarly, exergy efficiency with and without PCM is 8.59 and 6.53% during cloudy and sunny days, respectively.

2.2 Wick-Type Inclined Solar Still. One of the important design modifications of solar still is ISS. It consists of an inclined absorber plate to maintain the minimum thickness of the water layer to increase the water temperature and evaporation rate; hence, the productivity increases. The main disadvantage of bare plate absorber is unevenly flowing of water due to deformation of the bare plate. To overcome this issue, wick-type materials are incorporated in an ISS. Wick-type materials increase the contact time between the flowing saline water and inclined absorber plate, which would result in higher productivity than that of bare plate ISS.

2.2.1 Single Slope Wick-Inclined Solar Still. Sharon et al. [50] have done the experimental research on the ISS with partitioned basin and wick basin. It is made of a 1.5 mm thick stainless steel sheet. The collector cover of the still is kept at 13 deg inclination. Experiments were conducted on ISS for the two different modifications (i) ISS with splitting the basin for reducing the volume of basin water. (ii) ISS with a black blended woolen wick. It was found that ISS with partitioned basin and wick basin produced the maximum daily freshwater production of about 4.475 and 4.620 L, respectively. The maximum thermal and exergy efficiency of 42.71, 39.54%, and 3.35, 3.65% is obtained for the ISS with basin and wick, respectively.

Aybar et al. [51] experimentally researched the performance of ISS by three different conditions such as a bare plate, black-cloth, and black-fleece wick. A schematic representation of the ISS consists of an absorber plate made of galvanized iron and covered with a collector cover made of glass. When the saline water flows over the absorber plate, it does not uniformly distribute the water over the lengths of the plate. For uniform distribution of saline water, wicks are placed over the absorber plate. Experiments were conducted by varying the m_w. Results show that ISS with a bare plate, black wick, and black fleece produced the maximum freshwater production of about 1290, 1705, and 2995 mL, respectively. ISS with wicks material enhances the yield of fresh water about 2 to 3 times than that of ISS with bare plate.

Aybar [52] mathematically derived the ISS performance by varying the m_w. ISS is simulated with the constant solar irradiance of 500 W/m^2 and atmospheric temperature, initial water temperature, and absorber plate of 28 °C and varying the three different m_w (3.6, 5.4, and 7.2 kg/m^2). It was found that distillate rate is directly proportional to the solar intensity and inversely proportional to the m_w. It is estimated that ISS produced the daily distillate water of about 3.5 to 5.4 kg for a 1 m^2 area of inclined absorber plate.

Deniz [53] reported that ISS performance can be increased by providing uniform water film layer and reducing the glass cover temperature. Deniz has done the experimental investigation on ISS by using black-cloth wick (BCW) material on the absorber plate and shaded plate over the collector cover. Experiments were conducted for four different types namely, (i) ISS with a BP, (ii) ISS with a bare and shaded plate (BSP), (iii) ISS with a BCW, (iv) ISS with a black-cloth wick and shaded plate (BCWS). The daily productivity from BP, BSP, BCW, and BCWS was 2020, 2144, 2718 and 2798 mL/m^2, respectively. It is found that freshwater and efficiency from BCWS are 19 and 5% higher than the BP. To achieve higher energy efficiency, ISS is incorporated with black-cloth wick and shaded plate is advisable.

Hansen et al. [54] studied the ISS with innovative wick materials and wire mesh in the basin. ISS was made of mild steel with a cover inclination of 30 deg. In this experiment, three different absorber plates are used: (i) flat absorber plate, (ii) rectangular stepped absorber plate, and (iii) weir absorber. The wick materials such as polystyrene sponge, wood pulp paper, and water coral fleece are tested at three different absorber plates and results were compared. It was found that flat absorber ISS with polystyrene sponge, wood pulp paper, and water coral fleece were produced the distillate yield of 3140, 2500, and 3635 mL, respectively. Stepped type ISS with polystyrene sponge, wood pulp paper, and water coral fleece were used to increase distillate yield up to 3550, 2875, and 3930 mL, respectively. Weir mesh absorber ISS with polystyrene sponge, wood pulp paper, and water coral fleece was produced the distillate yield of 3950, 3230, and 4280 mL, respectively. The freshwater production is increased about 71% in the case of weir mesh absorber with water coral fleece than that of flat absorber.

Effect of water flowing over a collector cover of floating cum inclined wick solar still (IWSS) was investigated by Janarthanan et al. [55]. In this work, blackened jute wick is used in the inclined portion and corrugated shape wick is floated inside the water reservoir with a polystyrene sheet. Based on the theoretical results, it was concluded that collector cover cooling technique reduces the glass cover temperature significantly, solar still productivity is higher during the peak sunny hours, and 1.5 m/s water flow rate is optimum for the glass cover cooling.

Mahdi et al. [56] experimentally researched the performance of an ISS with a charcoal cloth as a wick material. In this research work, water is first flowing into the constant head device to maintain the d_w inside the ISS. From the bottom of the ISS, water is again sent back to the constant head device by using the peristaltic pump. It was found that increasing the m_w and salinity of water results in decreases in ISS efficiency. The maximum daily thermal efficiency and productivity of 53% is obtained at the m_w at 2.5 kg/m^2 h.

2.2.2 Wick-Type Double Effect Solar Still. Yeh and Ma [57] mathematically derived the energy balance equation for the upward type double-effect solar still. It uses energy more than the single effect solar still. The uppermost part of the still is covered of glass material; the middle part of the still is made of glass plate, which separates the basin into two regions. The bottom part of the still is designed with absorber plate, which is made by a steel plate. During the operation, water is flowing into both lower part (the first effect) and an upper part (the second effect) simultaneously. It was concluded that upward type system is more effective than a downward type system.

Yeh and Chen [58,59] have done the experimental studies and energy balances on wick-type double effect solar still by enhanced condensation rate with flowing air to the second effect unit. The basins of solar still were placed on a blackened wet jute cloth, and one heat source (150 W, 110 V) was used to maintain the basin temperature as higher than the normal solar still and a fan is used to reject the heat from glass cover to the atmosphere to enhance the condensation rate. The main advantages of using the heater and the fan are maintaining higher difference between the T_w and T_g. It was concluded that flowing air at the optimal rate results in considerable improvement in still efficiency.

2.2.3 Multiwick Inclined Solar Still. Tiwari and Yadav [60,61] introduced the fiber-reinforced plastic double slope multiwick solar still. In order to receive the maximum solar intensity during the summer months, the system is placed toward the east and west directions. The inlet water goes upward through the inlet I and due to capillary action in the multiwick (jute and black polythene), water rolls down on the tilted surface due to gravity and forms a thin layer of water. The evaporation and condensation process occurs quickly in the IWSS compared to the CSS. It was found that solar still manufactured by fiber-reinforced plastic results in two time's higher efficiency than the still manufactured by galvanized iron sheets. The distillate yield from double slope still is higher than the single slope still during the summer conditions.

Singh and Tiwari [62] numerically derived the performance of the double-slope double-effect multiwick solar still by allowing constant water flowing over the upper and lower basins of the still. In this experimental setup, two basins (upper and lower) are arranged and water is flowing in both basins. Due to water flowing in the upper basin, the condensation rate of lower basin gets increased. Double-basin wick solar still operates at low flow velocity producing the maximum yield, increasing the flow velocity, and reducing the overall thermal efficiency.

Singh and Tiwari [63] have done a simple thermal analysis of double-slope triple basin multiwick solar still. In this experimental setup, three basins are arranged and water is continuously flowing to all the basins. The water flowing in the upper basin of the still utilizes the latent heat of condensation from the middle basin of the still and so on. In this experiment, multiwick material is placed in the lower basin, whereas glass is provided in the middle and upper basins of the solar still. It was reported that optimum flow rate is 10^{-3} kg/s for the triple effect multiwick solar still. A further theoretical analysis was made on multi-effect solar still by increasing the number of basin to six. It was submitted that multi-effect solar still produced the maximum yield at an optimum m_w at 10^{-5} kg/s. But it is very difficult to achieve 10^{-5} kg/s m_w in experimental work.

Dhiman and Tiwari [64] have done the analytical model of a multiwick (blackened jute cloth, foam and polythene sheet) solar still water flowing over the collector cover. In this study, explicit expressions for glass, water, flowing water temperature, and distillate yield have been derived. Jute cloths are separated by polythene sheets to maintain the wick materials wet at all times due to capillary action of the wick material. Experiments were analyzed in multiwick solar still with and without water flowing over the collector cover. It is found that water flowing over the collector cover increases the output by 10%. It is also concluded that still productivity increases with increasing heat transfer coefficient from the collector cover to the water flowing over it. Sodha et al. [65] have done the experimental analysis for multiwick solar still. Experimental output shows that the maximum yield of 2.5 L/m^2 is obtained with an efficiency of 34%.

2.2.4 Inclined Wick Still With Vertical Flat Plate External Reflector. Tanaka and Nakatake [66] introduced the novel vertical flat plate reflector (VFPR) attached with IWSS and numerically derived its performance. In this system, the wick-type absorber received the direct, diffuse, and reflected solar intensity. It was found that IWSS with VFPR and without VFPR produces the daily maximum yield of about 6.5 and 5.7 kg/m^2, respectively. IWSS with VFPR increases the fresh water production of about 9% than the IWSS without VFPR. It is also predicted that VFPR increases the yield by 26% for the entire year. IWSS attached with VFPR is less effective than CSS attached with VFPR.

2.2.5 Inclined Solar Still With Bottom Reflector. Tanaka [67,68] also numerically studied the performance of bottom flat plate reflector (BFPR) attached with IWSS. The schematic diagram of BFPR is attached with IWSS. In this experimental setup, mirror finish metal plate is attached to the bottom of the IWSS. Bottom reflector reflected the solar intensity to the collector cover and wick-type absorber to enhance the productivity of the IWSS. It was found that IWSS with BFPR and without BFPR produces the daily maximum yield of about 7.5 and 6.01 kg/m^2, respectively. IWSS with BFPR increases the fresh water production of about 13% than that of the IWSS without BFPR. The optimum BFPR inclination for summer and winter are 50 and 20°, respectively. It was concluded that the optimum still inclination is higher and optimum reflector inclination is lower for the winter session and optimum still inclination is lower, and optimum reflector inclination is higher for the summer session.

2.2.6 Azimuth Tracking Tilted-Wick Solar Still With Vertical Flat Plate Reflector. Tanaka and Nakatake [69] numerically derived the performance of a one-step azimuth tracking IWSS with VFPR. In this experimental setup, cover angle and direction of the still are adjusted manually just once daily at southing of the sun. The direction of the still during the morning and afternoon is southeast and southwest, respectively. The still locate −45 deg during the morning and +45 deg during the afternoon session. It was found that azimuth tracking IWSS at orientation equal to 45 deg with reflector and without reflector produces the increased in yield of about 25, 22%, respectively, comparing with the fixed solar still. Similarly, the azimuth tracking IWSS at orientation equal to 90 deg with reflector and without reflector produces the increase in yield of about 57, 36%, respectively, greater than that of the fixed solar still. It is also submitted that the optimum orientation of tracking IWSS with reflector and without reflector during the summer is 80 deg and during the winter, it is 30 deg. The daily yield produced by one-step azimuth tracking IWSS is 57% and 27% higher than that of the CSS in the summer and the winter, respectively.

2.3 Semicircular Trough-Absorber Inclined Solar Still With Baffles. Sathyamurthy et al. [70] introduced a novel semicircular trough-absorber solar still with baffles. It consists of trough, absorber, baffles, and collector cover. Experiments were conducted by m_w at 8 kg/h and 10 number of baffles arranged in an absorber plate and the results were compared with CSS. It was concluded that still with baffles and CSS produced the maximum yield of 3.2 and 2.6 kg/m^2 and maximum efficiency of 38.48 and 32.4%, respectively. It is concluded that the yield is 16.66% higher than that of the CSS.

2.4 Basin and Wick Inclined Solar Still Integrated With Other Type of Solar Still. Minasian and Al-Karaghouli [71] experimentally studied the performance of WISS integrated with CSS. In this research, two types of solar stills were constructed and integrated as one single unit. Water was made to flow from the storage tank to the WISS at the m_w of 25 to 50 mL/min depending on the season. The hot water from WISS is directly fed into the CSS and distilled water from WISS and CSS is collected by using collecting channel. From the experimental results, it is found that the maximum yield from the basin, wick, and wick-basin solar still were 5103, 5970, and 8477 mL/m^2, respectively, in June. Similarly, minimum productivity of 552, 1002, and 1603 mL/m^2 is obtained from the basin, wick, and wick-basin solar still, respectively, in December. It was concluded that wick-basin solar still produced 85% and 43% higher annual productivity than the basin and wick type solar still.

Eltawil and Zhengming [72] manufactured a hybrid solar still for enhancing the productivity. In this novel method, single basin solar still is constructed by using galvanized sheets with a basin area of 3600 cm^2. At the center of main solar still (MSS), horizontal rotating hollow shaft with four impellers is placed. Turbine is made of lightweight semistainless steel hollow balls with three cups arrangement. The area of the ISS is 1600 cm^2.

From the experimental results, it is found that MSS at minimum d_w produced the maximum yield. The maximum daily productivity from MSS at south facing and tracking the sun is 1235 and 1410 mL, respectively, at 0.01 m d_w. Similarly, the maximum productivity from ISS at south facing and tracking the sun is 709 and 826 mL, respectively, at m_w at 25 mL/min. Tracking mechanism increases the daily productivity from MSS and ISS about 12.4 and 14.16%, respectively. It is found that MSS produced higher productivity than ISS because of a smaller area of ISS than the MSS. The maximum daily yield from MSS and ISS is 3.43 and 4.43 L/m^2 for the due south and 3.92 and 5.16 L/m^2 for tracking the sun, respectively. The average daily efficiency from MSS at the due south and tracking the sun is about 69.59 and 69.01%, respectively. The average daily efficiency from ISS at the due south and tracking the sun is about 62.01 and 62.38%, respectively.

Naveen Kumar et al. [73] theoretically studied the performance of triangular pyramid solar still (TPSS) integrated to an ISS with baffles. Theoretical analysis has been made by varying the water mass in the TPSS (20 to 100 kg). It was submitted that TPSS and TPSS integrated with ISS produced the maximum hourly productivity of 0.6 and 1.3 kg/m^2, respectively, at 20 kg water mass. The maximum daily productivity from TPSS and TPSS integrated with ISS is 3.2 and 7.2 kg/m^2, respectively, at minimum d_w. It is submitted that increasing the water mass from 20 to 100 kg the yield from the still decreases about 6–46% at morning and increases about 46–86% at evening.

Experimental study of TPSS integrated with an ISS with baffles has been done by Naveen Kumar et al. [74]. In this research, three solar stills (TPSS, ISS, and TPSS integrated with ISS) were tested. All three stills were made of mild steel material with an area of 0.5 m^2. Water is flowing from the saline water storage tank to the ISS and then hot water is fed into the TPSS. Condensed water is collected from both stills. Experiments were conducted by ISS at a flow rate of 8.33 kg/h and TPSS at d_w of 0.02, 0.04, and 0.06 m, respectively. The maximum daily yield produced from the TPSS, ISS, and TPSS integrated with ISS is 4.2, 5.04, and 7.52 kg/m^2, respectively.

Economic and exergy analysis of TPSS (standalone) and TPSS integrated with ISS with baffles (integration) has been done by Panchal et al. [75] From the exergy analysis, it was found that exergy efficiency during the off shine period is higher for 0.05 m d_w. The maximum exergy efficiency of 14 and 35% is obtained for the standalone and integration still at higher d_w.

Hansen and Murugavel [76] used a different new absorber to augment the performance of integrated solar still. The area of ISS, CSS, and hot water storage tank is 1, 0.3, and 0.12 m^2, respectively. All the subsystem was manufactured by a mild steel of 0.15 m thickness. Experiments were conducted by three different design modifications of the absorber plate in ISS, ISS integrated with CSS, and ISS integrated with CSS and hot water storage tank.

It was found that the maximum freshwater yield of 2990, 3410, and 3760 mL/day is obtained for ISS with FA, GA, and FSA, respectively. The maximum productivity of 1045, 1310, and 1450 mL/day is obtained for ISS integrated with CSS, on FA, GA, and FSA configuration, respectively. The maximum productivity from ISS integrated with CSS and hot water storage tank, on FA, GA, and FSA configuration, is 4035, 4720, and 5210 mL/day, respectively. It is also submitted that the overall efficiency of 30.5, 34.7, and 38.3% is obtained for ISS with FA, GA, and FSA

Table 1 Daily productivity and efficiency of various design modifications made in inclined solar still by various researchers

S. no	Author name	Experimental work done	Productivity (L/m^2 day or mL/m^2/day)	Efficiency (%)
1	Aybar et al. [31]	SB-ISS with normal absorber plate	0.85 kg/m^2 d	9.976
		SB-ISS with black-fleece wick	2.245 kg/m^2 d	27.518
		DB-ISS with normal absorber plate	1.808 kg/m^2 d	21.248
		DB-ISS with black-fleece wick	3.086 kg/m^2 d	37.784
2	Ravishankar et al. [32]	ISS with baffle plates (*theoretical study*)	3.5 kg/m^2	—
3	Ravishankar et al. [32]	ISS with baffles	5.4 kg/m^2	—
		ISS without baffles	3.4 kg/m^2	—
4	Alaudeen et al. [34]	FPC with wick and sponge	1.305 kg/m^2	—
		FPC with wick and rock, sponge	1.745 kg/m^2	—
5	El-Agouz [35]	SSS with salt water as inlet	6.3 L/m^2/day	—
		SSS with sea water as inlet	6.1 L/m^2/day	—
6	Omara et al. [38]	SSS with reflector	6350 mL/m^2	56
		SSS without reflector	5840 mL/m^2	53
7	Omara et al. [39]	SSS with external mirror attached on the top	6500 mL/m^2	—
		SSS with external mirror attached on the bottom	6830 mL/m^2	—
		SSS incorporated with internal and top external mirror	7400 mL/m^2	—
		SSS incorporated with internal and bottom external mirror	7240 mL/m^2	—
		SSS attached with both internal and external (top and bottom) mirrors	8100 mL/m^2	—
8	Muftah et al. [40]	SSS with attaching fins on tray, interior and exterior mirrors and outer condenser	8.9 kg/m^2	60.2
9	Velmurugan et al. [41]	SSS with fins	1.27 L/m^2	—
		SSS with fins and pebbles	1.37 L/m^2	—
		SSS with fins and sponge	1.4 L/m^2	—
		SSS with fins and pebbles and sponge	1.65 L/m^2	—
10	Shadi et al. [42]	Copper absorber inclined SSS	4383 mL/m^2	—
11	Sharon et al. [50]	ISS with partitioned basin	4.475 L/m^2	—
		ISS with wick basin	4.620 L/m^2	—
12	Aybar et al. [51]	ISS with bare plate	1290 mL/m^2	—
		ISS with black-wick	1705 mL/m^2	—
		ISS with black-fleece	2995 mL/m^2	—
13	Aybar [52]	ISS performance by varying the m_w (*theoretical study*)	5.4 kg/m^2	—
14	Deniz [53]	ISS with bare plate	2020 mL/m^2	—
		ISS with bare and shaded plate	2144 mL/m^2	—
		ISS with black-cloth wick	2718 mL/m^2	—
		ISS with black-cloth wick and shaded plate	2798 mL/m^2	—
15	Hansen et al. [54]	ISS with polystyrene sponge	3140 mL/m^2	—
		ISS with wood pulp paper	2500 mL/m^2	—
		ISS with water coral fleece	3635 mL/m^2	—
		Stepped type ISS with polystyrene sponge	3550 mL/m^2	—
		Stepped type ISS with wood pulp paper	2875 mL/m^2	—
		Stepped type ISS with water coral fleece	3930 mL/m^2	—
		Weir mesh absorber ISS with polystyrene sponge	3950 mL/m^2	—
		Weir mesh absorber ISS with wood pulp paper	3230 mL/m^2	—
		Weir mesh absorber ISS with water coral fleece	4280 mL/m^2	—
16	Sodha et al. [65]	multiwick ISS	2.5 L/m^2	34%
17	Tanaka et al. [66]	IWSS with VFPR	6.5 kg/m^2	—
		IWSS without VFPR	5.7 kg/m^2	—
18	Tanaka et al. [68]	IWSS with BFPR	7.5 kg/m^2	—
		IWSS without BFPR	6.01 kg/m^2	—
19	Sadineni et al. [44]	Weir type solar still with a single layer glass cover	5.5 L/m^2	—
		Weir type solar still with a double layer glass cover	2.2 L/m^2	—
20	Tabrizi et al. [45]	WCSS at minimum m_w	7.4 kg/m^2	—
		WCSS at maximum m_w	4.3 kg/m^2	—
21	Dashtban et al. [47]	WCSS with PCM	6.7 kg/m^2	64%
		WCSS without PCM	5.2 kg/m^2	47%
22	Tabrizi et al. [48]	WCSS with LHTESS	3.4 kg/m^2	—
		WCSS without LHTESS	2.1 kg/m^2	—
23	Sarhaddi et al. [49]	WCSS with PCM	4.94 kg/m^2	—
		WCSS without PCM	3.84 kg/m^2	—
24	Ravishankar et al. [70]	Semicircular trough-absorber solar still with baffles	3.2 kg/m^2	38.48%

Table 1 (continued)

S. no	Author name	Experimental work done	Productivity (L/m^2 day or mL/m^2/day)	Efficiency (%)
25	Minasian et al. [71]	Basin solar still	5103 mL/m^2	—
		Wick solar still	5970 mL/m^2	—
		Wick-basin solar still	8477 mL/m^2	—
26	Naveen Kumar et al. [73]	TPSS	3.2 kg/m^2	—
		TPSS integrated with ISS	7.2 kg/m^2	—
27	Naveen Kumar et al. [74]	TPSS	4.2 kg/m^2	—
		ISS	5.04 kg/m^2	—
		TPSS integrated with ISS	7.52 kg/m^2	—
28	Hansen et al. [76]	ISS with FA	2990 mL/m^2 day	30.5
		ISS with GA	3410 mL/m^2 day	34.7
		ISS with FSA	3760 mL/m^2 day	38.3%
		ISS integrated with CSS, on FA	1045 mL/m^2 day	31.6
		ISS integrated with CSS, on GA	1310 mL/m^2 day	37
		ISS integrated with CSS, on FSA	1450 mL/m^2 day	40.9%
		ISS integrated with CSS and hot water storage tank, on FA	4035 mL/m^2 day	44.9
		ISS integrated with CSS and hot water storage tank, on GA	4720 mL/m^2 day	46
		ISS integrated with CSS and hot water storage tank, on FSA	5210 mL/m^2 day	46.9%
29	Kabeel et al. [78]	Active SSS	6080 mL/m^2 day	—
30	Morad et al. [79]	ISS integrated with external condenser (ground water)	10.94 L/m^2 day	—
		ISS integrated with external condenser (Mediterranean Sea water)	10.16 L/m^2 day	—
		ISS integrated with external condenser (Red Sea water)	9.04 L/m^2 day	—

respectively. The overall efficiency of 31.6, 37, and 40.9% is obtained for ISS integrated with CSS, on FA, GA, and FSA, respectively. The maximum overall efficiency from ISS integrated with CSS and hot water storage tank, on FA, GA, and FSA configuration, is 44.9, 46, and 46.9%, respectively.

It is concluded that the maximum productivity of 5210 mL/day and efficiency of 46.9% are obtained in the case of FSA-type ISS integrated with CSS and hot water storage tank. It enhanced the daily distillate productivity and efficiency up to 74.25 and 34.1% than CSS.

2.5 Active Inclined Solar Still. Abdullah [77] has done the design modifications of the SSS such as the use of aluminum filling in the absorber plate as a thermal storage medium, integrating solar air heater (active mode) and glass cover cooling technology. He compared the productivity of this modified SSS with CSS. Both solar stills were designed with the same basin area of 0.5 m^2 for comparative study purpose. Basin of SSS is made of five equal parts. It was observed that both stills produced same productivity at the time of morning and evening because of lower solar intensity. SSS produced up to 8 °C higher basin temperature than the CSS. The daily productivity of 3350 mL/m^2 and 4350 mL/m^2 is obtained for CSS and SSS without any modifications, respectively. SSS produced 30% higher productivity than CSS. It is seen that SSS integrated with air heater increase the water temperature up to 18 °C than that of the CSS. The average daily production of 3400 mL/m^2 and 6300 mL/m^2 is obtained for CSS and SSS integrated with the solar air heater, respectively. This modification increases the daily productivity of SSS up to 85% higher than CSS. The average daily production of 3500 mL/m^2 and 5400 mL/m^2 is obtained for CSS and SSS integrated with the sensible heat storage material. This modification increases the daily productivity of SSS up to 53% higher than CSS.

Kabeel et al. [78] have done the theoretical and experimental studies on SSS with the effect of varying the width of trays, depth of water, attaching wick material on the vertical side of trays, and integrating vacuum tube solar collector (active mode). Experiments were conducted on both the stills and results were compared. It is found that SSS with wick material at 100 and 110 mm tray width produced the maximum distillate yield of 4685 and 5190 mL/m^2 day, respectively. In the final experimentation, an active SSS is investigated at the optimum d_w and the tray width. The maximum distillate yield of 6080 mL/m^2 is obtained. Active SSS increases the fresh water production rate up to 66.6% than the CSS.

2.6 Inclined Solar Still Integrated With External Condenser. Morad et al. [79] enhance the ISS performance by integrating external condenser and vacuum pump. In this research, experiments were conducted in two different ISS, namely ISS without and with external condenser, and experiments were conducted by three different salinity of water (4.5, 35.5, and 44.5 ds/m), and mass flow rate (0.4, 0.6, and 0.8 L/m^2 h). It is submitted that the temperature of water and vapor is higher at the conditions of 0.4 L/m^2 h. The daily yield of 5.54, 5.07, and 4.45 L/m^2 d and 10.94, 10.16, and 9.04 L/m^2 d was obtained for groundwater, Mediterranean Sea water and Red Sea water, respectively, for ISS without and with condenser.

2.7 Photovoltaic/Thermal Integrated Inclined Solar Still. Manokar et al. [80,81] introduced a photovoltaic/thermal (PV/T) integrated ISS. In their work, PV panel is integrated with an ISS to produce electrical power and freshwater. It consists of PV panel as an absorber plate, glass collector cover and water storage tank. Water is uniformly distributed through the PV pipe which is attached at the top of the experimental setup. Constantly water is flowing over the PV panel, which absorbs the heat energy from the panel and produces simultaneously hot water and freshwater. Increasing the m_w, positively affect the panel performance and negatively affect the still performance. It is submitted that increases in basin temperature results in higher distillate yield and lower power production. The maximum yield of 7.3 kg and efficiency of 71.2% is obtained when the system is fully insulated condition.

3 Conclusion

A review of various papers dealing with the different design modifications in inclined solar still such as basin-type, wick-type, stepped-type, weir-type, semicircular trough-absorber inclined solar still with baffles, inclined solar still integrated with other solar still, active inclined solar still and inclined solar still integrated with external condenser and its daily fresh water production and efficiency is carried out to have knowledge of the feasibility of a inclined solar still. The daily yield and thermal efficiency of inclined solar still studied by various researchers with their proposed design modifications are compared and shown in Table 1. This review will allow the researchers to decide appropriate inclined solar still technology for promoting development.

3.1 Suggestion for the Scope of Future Research Work in Inclined Solar Still

- For future investigations, evaporation rate of inclined solar still can be improved by using nanocoating in the still basin.
- The condensation rate of inclined solar still can be increased by using peltier cooling technology.
- Theoretical study and inclined solar still dimensions can be optimized.
- Investigating the system performance using different heating methodologies processes.
- New research may be carried out in an active inclined solar still with external condensers.
- The sun tracking system is more efficient so it can be integrated with inclined solar still.
- It is concluded that new research is looked for on inclined solar still/hybrid systems particularly waste heat recovery from other resources for water and power cogeneration because both are important in isolated areas.

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