**Utilization of** **LSTM neural network for water production forecasting of a stepped solar still with a corrugated absorber plate**

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**Highlights:**

* The thermal performance of a stepped solar still was compared with a conventional one.
* A corrugated absorber plate was provided in the stepped solar still.
* The water yield of the stepped solar still was enhanced by 128% compared with the conventional one.
* LSTM model was used to forecast the water yield of the solar stills.
* Statistical measures have been used to assess the forecasting model.

# Abstract

This study introduces a long short-term memory (LSTM) neural network model to forecast the freshwater yield of a stepped solar still and a conventional one. The stepped solar still was equiped by a copper corrugated absorber plate. The thermal performance of the stepped solar still is compared with that of conventional single slope solar still. The heat transfer coefficients of convection, evaporation, and radiation process have been evaluated. The exergy and energy efficiencies of both solar stills have been also evaluated. The yield of the stepped solar still is enhanced by about 128% compared with that of conventional solar still. Then, the proposed LSTM neural network method is utilized to forecast the hourly yield of the investigated solar stills. Field experimental data was used to train and test the developed model. The freshwater yield was used in a time series form to train the proposed model. The forecasting accuracy of the proposed model was compared with those obtained by conventional autoregressive integrated moving average (ARIMA) and was evaluated using different statistical assessment measures. The coefficient of determination of the forecasted results has a high value of 0.97 and 0.99 for the conventional and the stepped solar still, respectively.

**Keywords:** Stepped solar still; Corrugated absorber plate; Forecasting; LSTM neural network.

# Introduction

The availability of freshwater is a critical issue for human survival ([Faramarzi et al., 2013](#_ENREF_32)). Conventional desalination systems such as reverse osmosis, multi-effect desalination, multi-stage flash, ion exchange, solvent extraction, phase change, and electrodialysis are energy intensive and expensive, sometimes not affordable everywhere ([Cheng et al., 2011](#_ENREF_13)). In this case, solar desalination and distillation processes are attractive alternatives. Currently, numerous researches investigated different solar desalination technologies to overcome the lack of freshwater resources and energy crisis ([Ahmadi et al., 2021](#_ENREF_6)). Solar stills are one of the common efficient solar desalination technologies that utilize solar energy without any harmful environmental impacts ([Katekar and Deshmukh, 2020b](#_ENREF_44)). However, they suffer from their low freshwater yield. Therefore, many design modifications were applied to increase the freshwater yield of conventional solar stills as is briefly discussed further below where an overview is given of the state of the art. The freshwater yield of different types of solar still can be enhanced by using nanomaterials, phase change materials, and/or thermal devices. All of these enhancement methods require additional operating and maintenance costs. Therefore, the need for a simple desalination system with the reasonable cost is highly desirable. Moreover, forecasting the freshwater yield of that system is also a critical issue to evaluate the feasibility of the application of that system in a certain application.

Given the wide variety of solar still designs and modifications, accurate prediction and forecasting of the freshwater yield is in fact a crucial issue to evaluate and compare the capability of these designs to supply freshwater to a certain application without involving in carrying out more costly and time-consuming field experiments. Here, we investigate the application of a recurrent artificial neural network in the forecasting of solar still performance. Artificial intelligence-based models have been evolving rapidly over recent decades and have a wide range of engineering applications ([Babikir et al., 2019](#_ENREF_9); [Chen et al., 2019](#_ENREF_12); [Elaziz et al., 2019](#_ENREF_20); [Elsheikh et al., 2020](#_ENREF_26); [Essa et al., 2020b](#_ENREF_28); [Shehabeldeen et al., 2020](#_ENREF_73)). The daily distillate production of single slope solar still was modeled using a traditional artificial neural network model trained by daily weather observations ([Santos et al., 2012](#_ENREF_66)). The productivity of inclined stepped solar still was modeled using a cascaded forward neural network ([Abujazar et al., 2018](#_ENREF_5)). The proposed artificial intelligence model had a better prediction accuracy compared with that of traditional regression models ([Anwar and Deshmukh, 2019](#_ENREF_8)). The thermal performance of an inclined passive solar still was also modeled using an artificial neural network model ([Mashaly and Alazba, 2017](#_ENREF_50)), where the proposed model had better accuracy compared with the multiple linear regression model. A hybrid artificial intelligence model composed of a multilayer perceptron neural network and Harris Hawks optimizer has been developed to predict the freshwater yield of active solar still coupled with an external condenser ([Essa et al., 2020a](#_ENREF_27)). The proposed optimizer has been used to obtain the optimal structure and the optimal values of the network parameters that maximize the prediction accuracy of the neural network.

In this study, a stepped solar still with a corrugated copper absorber plate is investigated. The performance of the stepped solar still is compared with a conventional solar still in terms of energy efficiency, exergy efficiency, and freshwater yield. Moreover, a long short-term memory (LSTM) neural network model is employed to forecast the yield of the investigated solar stills. The forecasting accuracy of the proposed model is evaluated using different statistical measures.

# Literature survey

## Basic design

Different basic solar still designs include single-slope ([Essa et al., 2020c](#_ENREF_29)), double-slope ([Essa et al., 2020d](#_ENREF_30)), pyramid ([Modi and Nayi, 2020](#_ENREF_53)), single basin ([Jani and Modi, 2019](#_ENREF_37)), multiple basins ([Joe Patrick Gnanaraj et al., 2017](#_ENREF_39)), inclined ([Kaviti et al., 2016](#_ENREF_45)), stepped ([El-Agouz, 2014](#_ENREF_19)), spherical ([Modi et al., 2020](#_ENREF_54)), and tubular ([Sharshir et al., 2019](#_ENREF_69)) solar stills. Moreover, integrations between different solar still types and different thermal devices such as evacuated solar collector ([Shehata et al., 2020](#_ENREF_75)), heat pipe solar collector ([Fallahzadeh et al., 2020](#_ENREF_31)), flat plate solar collector ([Alwan et al., 2020](#_ENREF_7)), parabolic trough solar collector ([Hassan et al., 2020a](#_ENREF_33)), reflectors ([Bataineh and Abbas, 2020](#_ENREF_11)), photovoltaic modules ([Elbar et al., 2019](#_ENREF_21)), and Fresnel lens ([Mu et al., 2019](#_ENREF_56)) have been reported.

## Use of nanoparticles and nanofluids

Nanoparticles have been utilized in many of these different types of solar stills to augment the absorption of the sunlight and heat transfer process inside the basin ([Elsheikh et al., 2018](#_ENREF_25); [Jilte et al., 2019](#_ENREF_38)). Graphite and copper oxide nanoparticles have been added into the basin of a conventional solar still to augment the thermophysical properties of the brackish water ([Sharshir et al., 2018](#_ENREF_68)). The total yield of the solar still was increased by about 41.18% and 32.35% compared with the conventional one when graphite and copper oxide were used, respectively. Adding copper oxide nanoparticles into the basin of modified solar still incorporated with thermoelectric cooling channel resulted in increasing the total freshwater yield by about 81% ([Nazari et al., 2019](#_ENREF_57)). The higher increase in the total yield of the modified solar still compared with that of ([Sharshir et al., 2018](#_ENREF_68)) is attributed to the vital role of the thermoelectric module in reducing the temperature of the glass cover and, consequently, the circulation of the humid air inside the solar still trough as well as the condensation process is enhanced. The hourly freshwater yield of stepped solar still was enhanced by about 22% when aluminum oxide is added to the saline water ([Rashidi et al., 2018](#_ENREF_63)).

The use of nanofluids in the thermal devices integrated with solar stills to supply the latter with heated brackish water has been also investigated. Silicon dioxide and copper nanoparticles have been utilized to improve the thermal performance of a solar collector which used to heat up the saline water in the solar still basin via an immersed heat exchanger ([Mahian et al., 2017](#_ENREF_48)). At low inlet temperatures of the solar collector, copper-based nanofluid was more effective than silicon dioxide-based nanofluid for enhancing the solar still yield. The use of copper-based nanofluid inside the solar collector enhanced the total yield by about 9.86% compared with that of nanoparticle-free solar collectors. The use of three different nanoparticles, aluminum oxide, titanium dioxide, and copper oxide, to enhance the thermophysical properties of the working fluid of a hybrid photovoltaic thermal/ flat plate solar collector system incorporated with double slope solar still have been experimentally investigated ([Sahota and Tiwari, 2017](#_ENREF_65)). Copper oxide nanoparticles have been reported as the optimal one among the others to enhance the total yield of the solar still ([Katekar and Deshmukh, 2020a](#_ENREF_43)). The thin film devices have been also proposed to enhance the productivity of solar stills via heat localization action ([Elsheikh et al., 2019b](#_ENREF_24)).

## Use of phase change materials

Phase change materials have also been used in various types of solar stills exploiting their superior properties to store energy in the form of sensible or latent heat during the sunrise period and then release it during the sunset period ([Deshmukh, 2011](#_ENREF_17); [Kumar et al., 2020](#_ENREF_46)). Copper tubes were filled with candle wax submerged under the saline water of conventional single slope solar still ([Mousa et al., 2019](#_ENREF_55)). However, the production period is extended to nighttime hours; the total freshwater yield is decreased by using the candle wax. This claim was also reported by ([Yousef and Hassan, 2019](#_ENREF_76)), as the use of phase change had a negative effect on the solar still yield. Paraffin wax was used to extend the production period of a double-slope solar still incorporated with photovoltaic/thermal module ([Hedayati-Mehdiabadi et al., 2020](#_ENREF_35)). The daily freshwater yield of the solar sill reached a high value of 6.5 kg/m2.h. The use of glass as a basin material that contains different heat storage materials such as ethylene glycol, wax, sand, and zinc nitrate in a single-slope solar still has been investigated ([A et al., 2015](#_ENREF_1)). The use of a sponge and aluminum cubes as well as a corrugated sheet on the basin has also been investigated. The highest daily yield (2.64 kg/m2) was obtained using a basin with a corrugated sheet. The feasibility of using plastic solar still has also been investigated and a maximal daily yield of 2.1 kg/m2 was obtained ([Phadatare and Verma, 2007](#_ENREF_62)).

Nanocomposite phase change materials have been also used to improve the performance of various types of solar stills. Nanocomposite phase change material consists of nanoparticles added to phase change materials to enhance the heat transfer process ([Zayed et al., 2019](#_ENREF_77)). Tubular solar still with nanocomposite phase change materials (graphene oxide nanoparticles in paraffin wax) has been experimentally studied ([Kabeel et al., 2020](#_ENREF_41)). The freshwater yield of the solar still with the nanocomposite material is improved by 53.91% compared with that of the conventional tubular solar still. An attempt to enhance the thermal properties of paraffin wax by adding different nanoparticles, titanium dioxide, graphene oxide, and copper oxide, has been carried out and verified on a conventional solar still ([Dsilva Winfred Rufuss et al., 2018](#_ENREF_18)). Copper oxide with paraffin gave the highest daily freshwater yield (5.28 l/m2) among other investigated nanoparticles.

## Wick materials

Wick materials have been utilized to augment the solar still yield via enhancing the evaporation process from the basin which caused by the high surface area of the wick and the localized heating on it. Different wick materials such as waste cotton pieces, light cotton cloth, coir mate, and sponge sheet have been applied on a finned basin of double slope solar still. A maximal daily yield of 3.8 kg/m2 was obtained when the finned basin is covered with cotton cloth ([Kalidasa Murugavel and Srithar, 2011](#_ENREF_42)). The inclusion of a wick pile on the basin of double-cover solar still enhances the daily yield by 23.71% ([Modi and Modi, 2020](#_ENREF_52)). Hanging cotton wick inside the trough of double slope solar still enhances the daily yield top reach a high value of 4.05 kg/m2 ([Pal et al., 2018](#_ENREF_61)). The use of a wick belt which is continuously moved inside the solar still has been proposed to improve the evaporation rate and freshwater yield ([Abdullah et al., 2019](#_ENREF_3)). A maximal daily yield of 8 kg/m2 was obtained when the belt motion is well controlled (the belt is turned off for 30 min and is turned on for 5 min).

The integration between single basin solar still that contains double layers wick and evacuated tube solar heater has been investigated and the daily yield was increased by about 114% compared with conventional standalone solar still ([Omara et al., 2013](#_ENREF_60)). The basin of inclined wick solar still was padded by a wick-metal chips sandwich ([Sharshir et al., 2020b](#_ENREF_72)). The daily yield was increased by about 65.3% when copper chips are inserted between the wick layers. Exfoliated graphite flakes and carbon foam were incorporated with wick and act as heat localization devices to augment the heating process inside the trough of single basin solar still and consequently, the evaporation rate, as well as the total yield, is increased ([Sharshir et al., 2020a](#_ENREF_70)). The total yield was increased by about 51.8% compared with that of conventional solar still.

## Integration with hybrid thermal devices

The incorporation between solar stills and different thermal devices has been widely investigated ([Aboelmaaref et al., 2020](#_ENREF_4)). A hybrid desalination system composed of a conventional solar still, a parabolic trough solar collector, and a condenser with forced water cooling has been experimentally investigated under hot operating conditions ([Hassan et al., 2020b](#_ENREF_34)). The use of a parabolic trough solar collector with the solar still produced a high daily freshwater yield of 7.74 kg/m2; while the use of condenser with forced water cooling with the previous system enhanced the daily freshwater productivity to reach 9.45 kg/m2. The integration between single slope solar still and a parabolic trough collector, as well as a flat plate collector, has been experimentally investigated ([Madiouli et al., 2020](#_ENREF_47)). The freshwater yield of the proposed hybrid desalination system was enhanced by 203% and 172% in summer and winter solstices, respectively, compared with the standalone solar still. A new design of a solar still has been developed and coupled with a parabolic trough concentrator and the whole system was equipped with a solar tracking device to follow-up of the sun in both azimuth and elevation ([Maliani et al., 2020](#_ENREF_49)). The daily yield was significantly improved by about 683%. A tubular solar collector was coupled with a double slope solar still ([Bait, 2019](#_ENREF_10)). The annual freshwater yield of the modified solar still reached a high value of 549.77 kg/m2.

## Use of corrugated absorber plate

The use of corrugated absorber plate has been proposed to augment the thermal performance of different thermal devices such as solar collectors and solar stills ([Kabeel et al., 2017](#_ENREF_40); [Zheng et al., 2016](#_ENREF_78); [Zheng et al., 2017](#_ENREF_79)). The main advantage of the corrugated plate over flat plate absorber is the increased surface area which enhances the absorption of solar radiation as well as the heat transfer process. The thermal performance of corrugated wick type solar still was compared with that of conventional solar still ([Matrawy et al., 2015](#_ENREF_51)). Productivity of corrugated solar still was higher than that of conventional type by about 34%. An experimental investigation was carried out to explore the effect of corrugated absorber plate instead of a flat plate on the thermal performance of a single basin solar still ([Shalaby et al., 2016](#_ENREF_67)). The cost per liter obtained by the investigated solar still was 0.07182 $/l, which was competitive with those reported for solar stills with complicated designs. The performance of a tubular solar still with two different water absorber plates; flat plate and semi-circular corrugated was investigated by ([Elshamy and El-Said, 2018](#_ENREF_22)). The water productivity was enhanced by about 26.27% using semi-circular corrugated surface.

# Experimental methodology

In our current study, two solar stills (conventional and stepped) were designed and fabricated. Figure 1 illustrates a scheme of the experimental setup. A flat plate and a corrugated plate were used as absorber plates for the conventional and stepped solar stills, respectively. The experiments were carried out at Nagpur city, India (Latitude 21.14° N, and longitude 79.08° E) during February and March 2020.

The solar still body was made from 8 mm thick plywood with water-resistant properties. A highly reflective aluminum sheet was used to cover the inner sides of the still. The absorber plate is made of a 1 mm thick copper sheet due to its superior anticorrosion and thermophysical properties. The anticorrosion properties of copper sheets increase its lifetime in an aggressive environment, saline water, and high temperature, compared with conventional absorber plates made of steel. Moreover, its enhanced thermophysical properties enhance the heat transfer process in the basin and save a reasonable amount of the heat that is consumed to heat-up the absorber plate. To increase its capability of harvesting solar energy, the absorber plate was painted with a thin (<1 m) layer of dull black paint. The absorber plate was flat in the case of conventional solar still and it was v-corrugated in the case of the modified one. The v-corrugated absorber plate has five identical steps. The depth of V-cavity is 2 cm with an angle of 45 degree. The solar still trough is covered by a 4 mm thick glass cover which acts as a condenser plate. The glass cover was inclined by 22⁰ with the horizontal which is the same as the latitude of Nagpur city. The basin area was 0.27 m2 (520 mm x 520 mm). The stepped solar still has five identical steps. Each step is 10 cm width and 2 cm depth. The corrugated plate has a v-inclination of 45⁰.

The condensate water is collected using a side trough which connected to a flask by a flexible plastic pipe. All solar still surfaces are insulated using fiberglass insulation to minimize the heat losses to the surroundings. K-type thermocouples were used to measure the temperatures at various locations such as saline water, absorber plate, glass surface, and bottom surface. The solar intensity and the wind speed were measured using a pyranometer and an anemometer, respectively. A graded flask was used to measure the distillate amount. Moreover, other measuring apparatus are used to measure the quality of the produced water such as TDS meter to measure salts, minerals, and metals dissolved in the water and pH meter to measure the acidity and alkalinity of the water. The main characteristics of the measuring apparatuses are tabulated in Table 1.

Table The characteristics of the measuring apparatus.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Device** | **Dimension** | **Unit** | **Accuracy** | **Range** | **Uncertainty** |
| Pyranometer | Solar intensity | W/m2 | ± 1 W/m² | 0 – 5000 W/m2 | 0.577 W/m2 |
| K-type thermocouple | Temperature | °C | ± 0.01°C | -20 – 130°C | 1.73°C |
| Anemometer | Ambient speed | m/s | ± 0.1 m/s | 0.4 – 30 m/s | 0.0577 m/s |
| Graded flask | Distillate | L | ± 5 mL | 0 – 5 l | 2.886 mL |
| pH meter | pH | pH | ±0.1 pH | 0-990 ppm | 0.577 ppm |
| TDS meter | TDS | ppm | 2% | 0-9999 ppm | 1.154% |

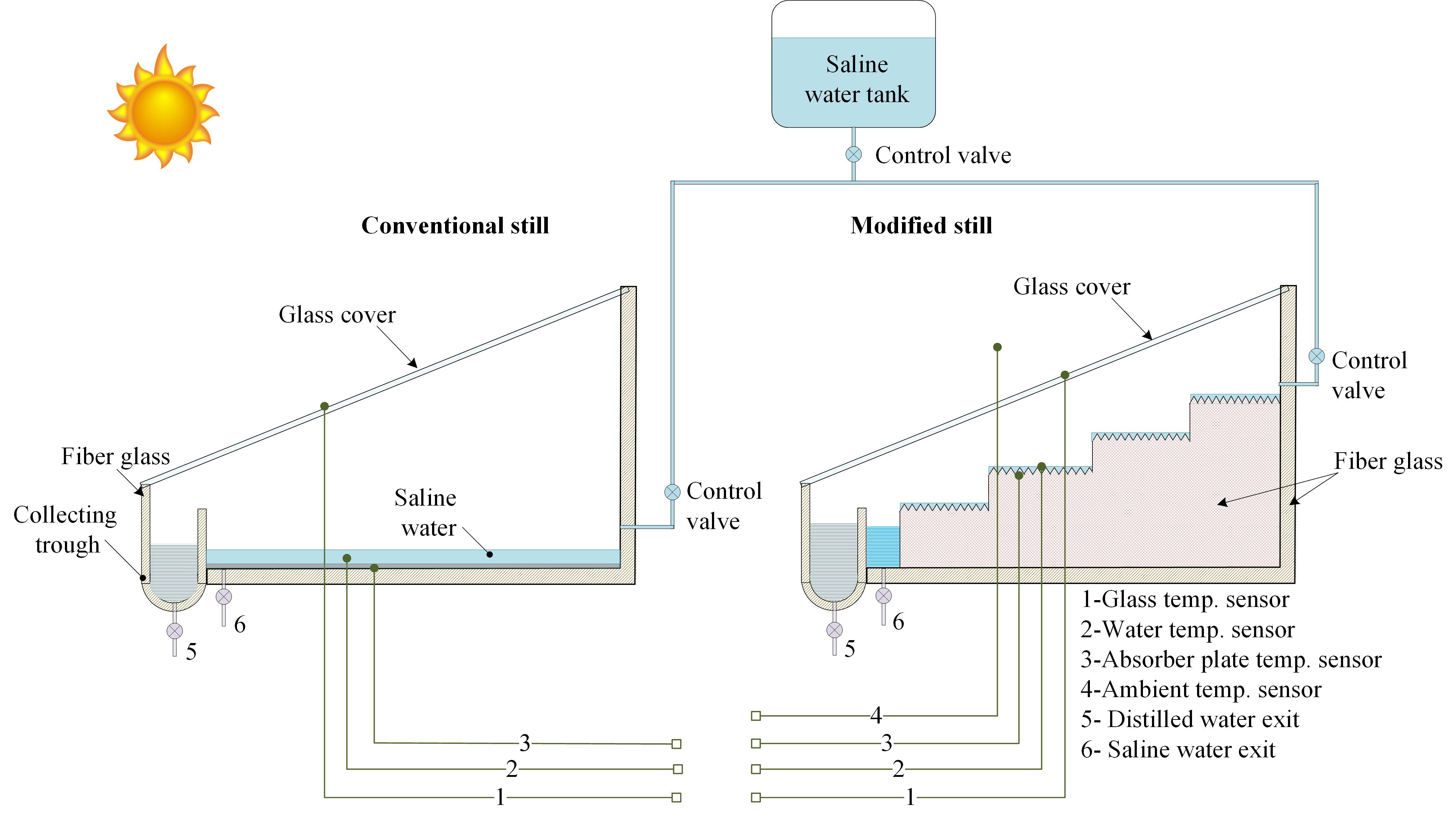


Fig. 1. Scheme of the experimental setup.

# Thermal analysis

Energy and exergy efficiencies have been employed to evaluate the performance of different types of solar stills ([Sharshir et al., 2017](#_ENREF_71)). These efficiencies are dependent on the freshwater yield of the solar still as well as on the heat transfer process in a solar still. There are two main mechanisms of heat transfer process: internal or external. Internal heat transfer occurs inside the solar still between the water, the glass cover, and the basin and governs the evaporation of water. The external heat transfer occurs between the glass cover and the ambient air and regulates the condensation of vapor. These two mechanisms and the related heat transfer coefficients (HTCs) will be discussed in this section.

Following the conventional theoretical analysis of the solar still, the convection HTC between the saline water and the glass cover, hCW, is calculated by ([Sharshir et al., 2017](#_ENREF_71)) :

............ ............................................... (1)

Where *T­w* and *Tgi* are the temperatures (in °C) and *Pw* and *Pgi* are the partial pressures of the vapor on water and the inner surface of the glass cover. *Pw* and *Pgi* are given by:

....................................................................................................................... (2)

...................................................................................................................... (3)

The radiation HTC between the saline water and the glass cover, hTW, is calculated by:

........................................................... (4)

The effective remittance between the glass cover and the saline water, eff, is calculated by:

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Here w and g, are the remittances for the glass cover and the saline water. The evaporation HTC between the saline water and the glass cover, hew, is calculated by:

........................................................................................ (6)

Here hcw denotes the convective HTC from water to the inner surface of the glass cover. The total internal HTC between the saline water and the glass cover is the sum of the individual HTCs and is given by the equation:

................................................................................................................ (7)

The convection HTC () between the glass cover and the ambient is calculated by:

.................................................................................................................. (8)

Here *v* is the wind speed.

The radiation HTC between the glass cover and the ambient (*hra*) is calculated by:............................................................................... ..(9)

where

 ......................................................................................................................... (10)

Here *Ta* is the ambient temperature.*Tgo* is the temperatures (in °C) of the outer surface of the glass cover.

The energy efficiency, , is calculated as a function of the hourly yield  , the evaporation latent heat , solar radiation , and the surface area of the glass cover :

……………………………………………………………………..(11)

The exergy efficiency of, , is defined as the ratio between the exergy output of the distillate water and the exergy input of solar radiation. It can be determined from:

** ………**(12)

The temperatures in the previous equation are measured in Kelvin and the sun temperature is assumed to be 6000 K ([Sharshir et al., 2017](#_ENREF_71)).

# LSTM for forecasting

Artificial neural networks have been promising applications in different engineering fields ([Abd Elaziz et al., 2020](#_ENREF_2); [Deng et al., 2020a](#_ENREF_14); [Saba and Elsheikh, 2020](#_ENREF_64); [Shehabeldeen et al., 2019](#_ENREF_74)). Long short-term memory (LSTM) is a Recurrent Artificial Neural Network (RANN) which has been widely used in the deep learning field. The main advantage of the LSTM over conventional feed-forward neural networks is its capability to remember patterns over a long time because of its advanced structure which depends on feedback connections. It also can alleviate the problem of vanishing gradient which is a critical issue in other RANN models. LSTM networks have the general capability to deal with sequence prediction and forecasting problems. The architecture of the LSTM network, shown in Fig. 2, is an improved version of a RANN architecture which is trained using the back-propagation technique ([Hochreiter and Schmidhuber, 1997](#_ENREF_36)). LSTM uses multiple gates that act as memory cells to manage the flow of the inputs and outputs inside the network instead of a conventional hidden layer architecture with non-linear activation functions. Thus, LSTM has a complex hidden layer that contains many parameters compared with conventional RANN. The network is working as follows:

At time , the current input element  as well as the hidden state result from the previous time step  produce the input of the current hidden state. Thus, the network can map a sequence of input into a sequence of output, with each depending on all the previous according to the following recurrent relationship

….……………………………………..……..………... (13)

….……………………………………………..……..………... (14)

where  is an activation function; and are the applied bias; ,, and are the layer weights.

The main difference between the LSTM network and other RANN networks is that the LSTM uses gates instead of recurrent hidden neurons. These gates have a self-connection at the next time step and have a decision-making unit that controls the memory clearing. The gates control the flow of the information within the network. There are many types of gates; forget, input, and output. The forget gate obtains the usefulness of the information and makes a decision on removing the useless information from the cell state. The decision has two main forms: zero for clearing the former cell state and one for keeping the former cell state.

….……………………………………………..……..………... (15)

After that, a decision is made to store the information in the cell state. This kind of decision is performed through two gates: the first is the input gate in which the useful information is determined to be used in updating the cell state; while the second one is an activation gate that applies tanh activation function on the information to update the state.

….……………………………………………..……..………... (16)

….……………………………………………..……..………... (17)

….…………………………………………………..……..………... (18)

The output gate is responsible for controlling the information flow through the following hidden state.

….……………………………………………..……..………... (19)

The final step is the computing of the new hidden state.

….……………………………………………..……………..……..…... (20)

Where ,, ,,, and are the outputs of the forget gate, input gate, potential cell state, cell state, output gate, and hidden state, respectively;  is a sigmoid activation function,  is the hyperbolic tangent activation function;  are the weight/bias set at each gate.

Fig. 2. The structure of a typical LSTM network ([Ni et al., 2020](#_ENREF_58)).

# Model assessment criteria

In order to evaluate the forecasting accuracy of the proposed LSTM model, five statistical criteria were used, namely, coefficient of determination (R2), root mean square error (RMSE), mean absolute error (MAE), efﬁciency coefﬁcient (EC), and overall index (OI) ([Elsheikh et al., 2019a](#_ENREF_23)).

RMSE is used to compute the error between the forecasted and measured data and is calculated by:

….…………………………………………..……..………... (21)

Where, *ns*, *d,* and *s* denote to the number of data, measured value, and the forecasted value, respectively. Moreover*, dmax, dmin,* andused further below denote the maximum, minimum, and average values of the measured data, while  is the average value of the forecasted data.

R2 is used to compute the correlation between forecasted and measured data. The approach of its value to unity indicates a high correlation between the forecasted and measured data. R2 is calculated by:

….…………………….…………..……..………... (22)

MAE is used to evaluate the model accuracy, and it is calculated by:

….……………………..…………..………….……….…..……... (23)

EC assesses the model accuracy. The approach of its value to unity indicates the high accuracy of the model. It is calculated by:

….……………………..………...……………..……..………... (24)

OI is dependent on RMSE and EC. It is calculated by:

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# Results and discussions

## Experimental evaluation

The solar stills were investigated experimentally to compare their performances. The variations of solar radiation and ambient temperatures for eleven testing days are shown in Fig. 3. The solar radiation had a similar behavior for all testing days; it increases through the morning hours and reaches its peak value at noon. Then, it begins to decrease to its minimum in the evening. The ambient temperature had the same trend as the solar irradiance with a little deviation due to the existence of clouds and the wind.

The variations in the temperature of saline water, basin, and glass cover are shown in Fig. 4. The saline water, basin, and glass temperatures had the same behavior as the solar radiation plotted in Fig. 3. The temperatures start to increase as the solar irradiance increases in the morning and begin to decline with decreasing the solar intensity in the afternoon. The measured temperatures of the three components in case of the stepped solar still are much higher than that of conventional solar still; which indicates the role of the corrugated absorber plate and the stepped design to enhance the harvesting of solar energy and converting it into heat. This issue is also observed in Fig. 5; as all HTCs related to stepped solar still is much higher than that of conventional solar still. The higher values HTCs indicate the enhanced heat transfer process in the solar still and guarantee adequate water evaporation and vapor circulation inside the solar still trough. Finally, the outperformance of the stepped solar still over the conventional one could be observed from Fig. 6. The energy efficiency, exergy efficiency, and hourly freshwater yield of the stepped solar still are much higher than that of the conventional solar still. This claim is also confirmed by Fig. 7, in which the normalized average values of the energy efficiency, exergy efficiency, and freshwater yield are plotted. The values of the three plotted quantities for the stepped solar still are three times higher than that of the conventional solar still. The enhanced thermal performance and freshwater yield of the stepped solar still over the conventional solar still are attributed to the role of the corrugated copper plate to harvest the solar energy and convert it into heat to heat-up the saline water and the low space inside the solar still trough which enhance the circulation process of the vapor. The solar radiation harvesting and the heat transfer process are enhanced due to the enlarged surface area of the corrugated absorber plate.



Fig. 3. Variations of solar irradiance and ambient temperatures.



Fig. 4. Variations of the saline water, basin, and glass cover temperatures.



Fig. 5. Variations of heat transfer coefficients.



Fig. 6. Variations of: a) exergy and energy efficiencies; b) hourly freshwater yield.



Fig. 7. Normalized average values of exergy efficiency, energy efficiency, and hourly freshwater yield.

## Forecasting of the solar still performance using LSTM

The freshwater yield of both the conventional and modified solar stills was forecasted using the proposed LSTM model. The actual productivity of the solar stills for nine days was considered as a time series input of the LSTM model. First, the proposed model is trained using the measured data of nine days for both solar stills. Then, the trained network is used to forecast the freshwater yield of the subsequent two days. The forecasted yield is compared with the measured yield for these two days. Moreover, the forecasted results by LSTM network were compared with those obtained by conventional Autoregressive Integrated Moving Average (ARIMA) method. Five statistical criteria have been used to evaluate the forecasting accuracy of the proposed network. Once the network succeeds to forecast the yield of these two days with a reasonable accuracy based on different statistical measures, it may be used to forecast the freshwater yield.

For the two investigated solar still, the LSTM model is trained using 72 datasets (nine days) and tested using 16 datasets (two days). To guarantee the convergence of during the learning process as shown in Fig. 8, 400 epochs were applied with a learning rate of 0.00004. The convergence of the conventional solar still model is is a little bit faster than convergence of the modified solar still model. The error loss approaches zero as the training epochs reach 400. The proposed model shows a reasonable accuracy for both solar stills as shown in Fig. 9 in the red region. The red region represents the testing of the network, we hide the water yield of two days from the network during training process and LSTM is used to forecast them and then the forecasted results are compared with the measured ones; while blue region represents the forecasted results for two days after the measured data. The forecasted results are in good agreement with the measured results. During the test process, the RMSE was 0.006 and 0.002 l for the conventional and the modified solar stills, respectively. The obtained RMSE values are adequate for both solar stills, however; it has a lower value for the stepped solar still compared with the conventional one. Other statistical measures also indicate a better forecasting accuracy for the stepped solar still compared with the conventional one as shown in Fig. 10 and Table 2. From Table 2, it is also observed that the proposed LSTM network outperform ARIMA method; as ARIMA failed to forecast the periodic nature of the experimental data. In case of LSTM network, the R2, RMSE, MAE, EC, and OI values are 0.9752, 0.0066, 0.0044, 0.9172, and 0.9131 for the conventional solar still; and 0.9976, 0.0021, 0.0018, 0.9973, and 0.9897 for the stepped solar still. In case of ARIMA method, all computed statistical measures indicate the very bad performance of that method to forecast the yield of both solar stills. The high values of R2, low values of RMSE and MAE, and approaching the values of EC and OI to the unity indicate the excellent forecasting accuracy of the proposed model. Therefore, the proposed LSTM model is recommended to forecast the freshwater yield of the investigated solar stills and may also be applied to other types of solar stills. It is recommended to use metaheuristic optimization approaches to obtain the optimal structure and parameters of the LSTM which will be our future work ([Deng et al., 2020b](#_ENREF_15); [Deng et al., 2019](#_ENREF_16); [Oliva et al., 2019](#_ENREF_59)).



Fig. 8. Learning curve of LSTM network: a) RMSE; b) Loss.



Fig. 9. The measured and forecasted hourly freshwater yield for the investigated solar stills: a) hourly yield of the conventional solar still; b) hourly yield of the stepped solar still; c) forecasted yield of the conventional solar still; d) forecasted yield of the stepped solar still; e) forecasting error of the conventional solar still; f) forecasting error of the stepped solar still.

Table Model assessment measures.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | R2 | RMSE | MAE | EC | OI |
| Conventional solar still | LSTM | 0.9752 | 0.0067 | 0.0045 | 0.9172 | 0.9132 |
| ARIMA | 0.0001 | 0.0482 | 0.0409 | -2.8891 | -1.2728 |
| Stepped solar still | LSTM | 0.9976 | 0.0021 | 0.0018 | 0.9973 | 0.9897 |
| ARIMA | 0.0017 | 0.0801 | 0.0683 | -3.1854 | -1.4335 |



Fig. 10. Spider plot of different statistical measures for LSTM results.

# Conclusion

In this study, an LSTM neural network model was employed to forecast the yield of single slope solar still and stepped solar still. The stepped solar still had a copper corrugated absorber plate. Both solar stills were operated under the same metrological conditions of Nagpur city, India. The freshwater yield of the stepped solar still was enhanced by 128% compared with that of conventional solar still. The enhanced freshwater yield of the stepped solar still over the conventional solar still is attributed to 1) the role of the corrugated copper plate to harvest the solar energy and convert it into heat to heat-up the saline water; 2) the low space inside the solar still trough which enhances the heat transfer process and circulation process of the vapor. The LSTM neural network has superior advantages over other feed-forward neural network models in forecasting time series behavior due to its capability to remember patterns for a long time. This is attributed to its advanced structure which depends on feedback connections. The forecasting accuracy of the proposed model was evaluated using different statistical measures. The R2, RMSE, MAE, EC, and OI values are 0.9752, 0.0066, 0.0044, 0.9172, and 0.9131 for the conventional solar still; and 0.9976, 0.0021, 0.0018, 0.9973, and 0.9897 for the stepped solar still.

The performance of stepped-corrugated solar still can further be enhanced by incorporating latent heat storage materials (Nano-PCM) to diminish heat losses from the bottom and sidewalls and mixing nanoparticles in the absorber paint for higher absorption of solar energy. Thus, stepped-corrugated still can be developed at a commercial scale for ordinary households living in rural as well as remote locations.

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