Augmenting the clean water generation rate of solar desalination unit through novel absorber under Indian climatic conditions: Thermal performance, energy and carbon credit analysis

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ABSTRACT

This work aimed to explore a novel method for augmenting the fresh water production rate of solar stills (SSs) through utilizing nanoparticles of reduced graphene oxide (rGO) and copper oxide (CuO) mixed black paint coating on absorber to increase the solar absorption and evaporation rate. The three types of SS with absorber plate only coated with black paint (CSS), absorber coated with rGO doped in black paint and absorber coated with CuO doped in black paint (SS-CuO) were fabricated, and investigated under Indian climatic conditions. The obtained results showed that the daily water productivity was enhanced by 11.8 % and 6.3 % for SS-rGO and SS-CuO, respectively in comparison to that of CSS. Moreover, the efficiency of the SS reached about 39.9 % for SS-rGO; while, it reached about 38.1 % and 35.7 % for the SS-CuO and CSS. Moreover, it is perceived that the proposed SS with rGO coated absorber has reduced 13.19 tons of CO_2 emissions for 0.01 m water depth during its life cycle. In addition, quality of water samples achieved from experimental investigation is suitable for drinking purposes and also meets the requirements of the Indian Council of Medical Research.

Keywords: *Clean water, Solar Desalination, Energy storage material, Environment-economic, Water quality*

INTRODUCTION

Globally, mankind is facing enormous challenges in meeting increasing demands of fresh water as the clean water resources are shrinking due to the growing population, industrialization and severe environmental changes. Increasing population and rapid industrial growth is creating severe concern on the objective of achieving SDG-6 (Sustainable Development Goal, Clean Water and Sanitation). Moreover, the water scarcity can be handled very proficiently if it is sensibly conserved, properly managed and very carefully distributed with the potential knowledge concerning the import of water. The polluted water contains injurious bacteria and viruses; chemical and physical toxin suspended and undisclosed matters which are injurious to health. Therefore, it is compulsory to explore the process of converting brackish water, contaminated freshwater, industrial wastewater, and sea water into clean water. Different techniques such as reserve osmosis, cleaning by UV, flash distillation, membrane distillation, and ion exchange are widely used for converting the brackish water into clean water. However, most of these technique uses high end energy and expensive. Water purification through utilization of solar energy i.e. solar distillation is the most viable and economic option for producing clean water especially in the rural areas (Thakur et al. 2020 c; Thakur et al. 2018 b; Kumar Thakur and Kumar Pathak 2017). This method is widely adopted for achieving the objective of SDG-7 (Affordable and Clean Energy) in most proficient way. In tropical countries like India, the average daily solar radiation varies between 4 – 7 kWh/m^2 with an average 250 - 300 sunny days in a year and therefore, the country receives about 5000 trillion kilowatt-hours of solar energy a year. With the abundant availability of solar radiation, solar still (SS) is considered to be the most effective technique for solar desalination process due to its wide-ranging advantages such simple construction using local low-cost material, lower maintenance cost and ease of operations. However, the main limitation of SS is low productivity of distilled water as compared to other distillation methods. Different type of SS such as passive, active, concentrated type, flat plate type, multi-stage and the hybrid designed still are developed and invested for augmenting the water productivity of the device. Higher water yield of the SS can be achieved by enhancing the heat transfer process through suitable working fluid with enhanced thermal transport properties and it can be further improved by the dispersion of the nanoparticles with base fluid in the basin of the SS. Generally, nanoparticles possesses unique physical-chemical properties such as higher thermal conductivity and excellent solar intensity absorption characteristics. Kabeel et al. (2014) experimentally evaluated the performance of the solar still using CuO and Al_2O_3 nanoparticle and reported significant increment in fresh water production. Thakur et al. (2018 a) developed a novel Al_2O_3 nanoparticle coated SS and achieved the improved water yield of 17.5 % compared to the conventional SS. With the dispersion of Al_2O_3 nanoparticle in the coated basin, the yield further augmented by 24. 3 %. Sharshir et al. (2018) fabricated a modified solar stills (MSSs) and studied its yield using graphite and copper oxide (CuO). Results showed that the daily water yield of MSSs was increased by increased by 32.3 % (CuO) and 41.2 % (graphite) compared to the conventional SS. Thakur et al. (2020 b) explored the role of various energy storage material such as black granite, metal scrap and Al_2O_3 nanoparticle on performance of single basin SS. Authors reported that highest water yield was exhibited by Al_2O_3 (33.5 % compared to conventional SS) nanoparticle amongst all the storage medium. In addition, daily efficiency was found to be maximum of 33.6 % using Al_2O_3 in basin.

It has been inferred from the above literature that nanoparticle dispersion improves the yield and efficiency of solar stills. However, the major issue is stability of the nanoparticle with the base fluid along with its high cost. In addition, majority of the literature examined the stability of nanofluid just for the period of their experimentation. In this view, an alternative cost effective methods should be developed to overcome the aforementioned limitation of SS. Hence, the present work aims to explore the role of carbonaceous and metallic nanoparticles coating on the absorber of SS and evaluate the water yield and energy efficiency of the SS under the climatic conditions of Jaipur, India (26.9124˚ N latitude, 75.7873˚E longitude). In addition, the carbon credit earn and the quality of distilled water will be evaluated.

METHOD

Experimental setup and observations

Three different solar still were fabricated: SS with only black paint coated absorber, SS with reduced graphene oxide (rGO) nanosheets (2 wt. %) mixed in black paint coated absorber and the SS with copper oxide nanoparticle (2 wt. %) mixed in black paint coated absorber. Figure 1 shows the photographic view of experimental scheme and Figure 2 shows the dimensions of solar still. The inside surface of solar still was made from 1.2 mm thick mild steel sheet and the basin area of the solar still was 1 m^2. The vertical height of solar still was 0.65 m and 0.235 m and the length of the solar still was 1 m. The absorber plate of solar still was made by mild steel sheet of 1.2 mm thickness and all the side walls and the basin of the solar still are insulated by thermocol of thickness 3 cm and bounded by wooden box 2 cm thick plywood to shield the side's heat loss to surrounding. Inclination angle of glass surface is the most important factor affecting the received solar intensity and thus, very important in determination of fresh water yield. Inclination angle of 26° towards the south, which is the similar to the experimental site latitude has been given to the glass cover in order to make sure that solar still captures maximum average radiations during the year. The experimental analysis was performed in Jaipur, Rajasthan, India (26.9124˚ N latitude, 75.7873˚E longitude) from 8.00 am - 5.00 pm.

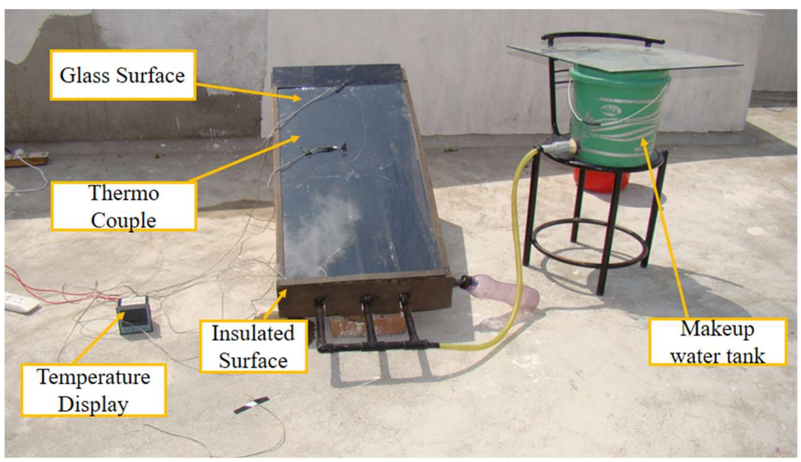


Figure 1: Photographic view of experimental setup

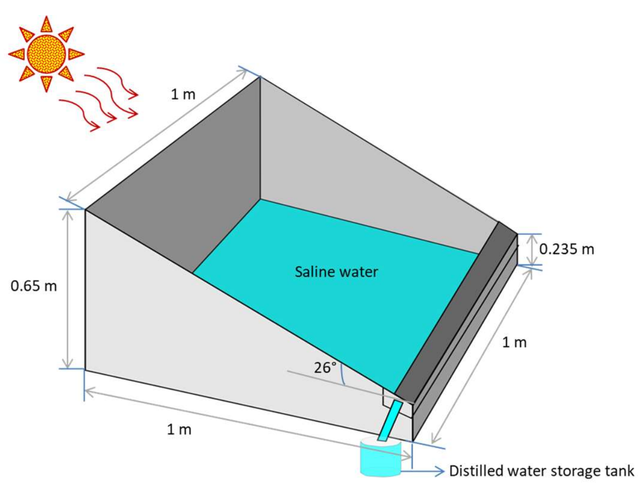


Figure 2: Dimension of the solar still

To compare the yield production and thermal performance of conventional solar still and modified solar still with nanoparticles coating; ambient temperature, glass temperature and water temperature and distilled water productivity are measured for each one hour. The temperatures are measured by using K- type thermocouple and multi point data recorder (Thermocouples reader). A pyrometer is used to measure the solar radiation. The comparative performance of both the conventional solar stills and modified solar still is analysed at the water depths of 0.01 m for different nanoparticles-based absorber plate.

UNCERTAINTY AND ERROR ANALYSIS

In this study, based on the range, precision and inaccuracy of the devices have been illustrated in Table 1, and the uncertainty in the present study (u_{et}) is calculated in Eq. (1) (Thakur et al. 2020 a) as follow:

$$u_{et} = \left[\left(\frac{\partial et}{\partial x_1} . u_1 \right)^2 + \left(\frac{\partial et}{\partial x_2} . u_2 \right)^2 + \left(\frac{\partial et}{\partial x_3} . u_3 \right)^2 + \ldots\ldots\ldots + \left(\frac{\partial et}{\partial x_n} . u_n \right)^2 \right] \quad (1)$$

where, n is the numeral of variables, and u is the measuring apparatus standard uncertainty.

Apparatus	Precision	Range	Inaccuracy
Digital thermometer	± 1 °C	0 - 100 °C	0.03
Pyrometer	± 25 W/m^2	0 - 1500 W/m^2	0.01
Thermocouple	± 0.1 °C	−100°C - 150 °C	0.003
Measuring pot	± 1 ml	0 - 1000 ml	0.05

Table 1: Description of measurement instruments

THERMAL MODELLING OF SOLAR STILL

Radiative heat transfer

The rate of radiative heat transfer from water surface to glass cover can be given as

$$q_{r,bw} = h_{r,bw} \left(T_{bw} - T_g \right) \quad (2)$$

Rate of heat transfer coefficient through radiation is given by

$$h_{r,bw} = \epsilon_{eff} \ .\sigma \left[\left(T_{bw} + 273 \right)^2 + \left(T_g + 273 \right)^2 \right] \left[T_{bw} + T_g + 546 \right] \quad (3)$$

Where, Stefan-Boltzmann σ = 5.6 × 10^{-8} W/ m^2 K^4 and the water surface and glass cover are regard as to be parallel surfaces, so the effectual emissivity (ε_{eff}) is considered to be 1.

Convective heat transfer

Heat exchange inside the single basin still occurred due to free convection. This is a direct result of buoyancy force and thus convective current has been generated and it circulates from water basin to the glass surface. Subsequently, the convective heat transfer from basin water to glass cover is given by

$$h_{c,bw} = 0.884\left[\frac{\left(T_{bw}-T_g\right)+(P_{bw}-P_g)\left(T_{bw}+273.15\right)}{268900-P_{bw}}\right]^2 \tag{4}$$

Evaporative heat transfer

The rate of heat transfer from the basin water to the glass cover can be given as

$$q_{e,bw} = h_{e,bw}\left(T_{bw}-T_g\right) \tag{5}$$

The evaporative heat coefficient is given by

$$h_{e,bw} = 16.273\times10^{-3}h_{c,bw}\left[\frac{P_{bw}-P_g}{T_{bw}-T_g}\right] \tag{6}$$

The total inner heat transfer coefficient from the water surface to the condensing cover is given by

$$h_{1bw} = h_{c,bw}+h_{r,bw}+h_{e,bw}$$

Efficiency of solar still is given as

$$\eta_d = \frac{M_d \times L_w}{A_p\left(\sum I\right)\Delta t} \tag{7}$$

RESULTS AND DISCUSSIONS

The SS receives solar energy, which is used to heat the water inside the basin, that inturns increases the evaporation rate. The evaporated vapor is condensed on the inner glass surface, drips down due to gravity and collected in a beaker. Figure 3 shows the recorded ambient temperature and solar radiation during the experimentation. The maximum solar radiation of 970 W/m^2 was observed at 1.00 pm and the average solar radiation throughout the day was 672 W/m^2. In addition, the peak ambient temperature of 37.1 °C was seen at 1.00 pm.

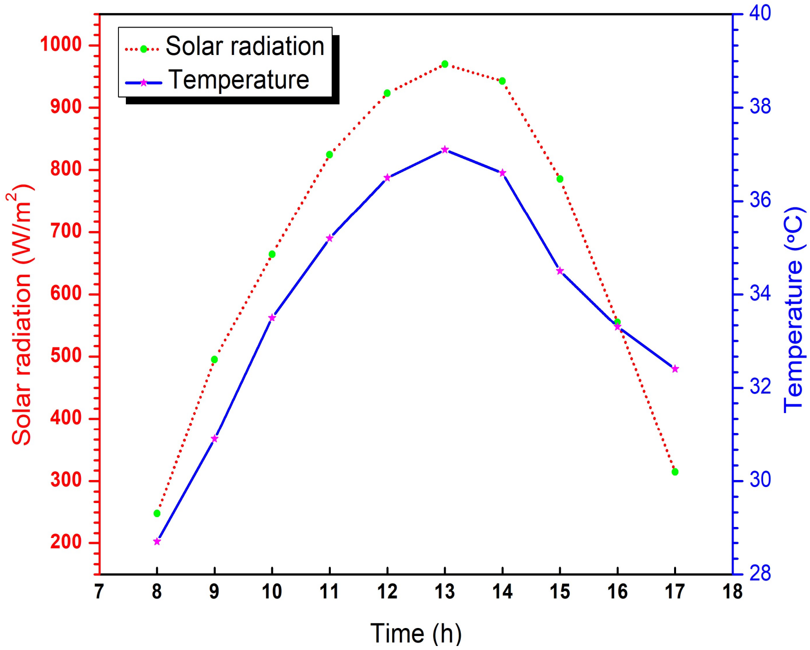
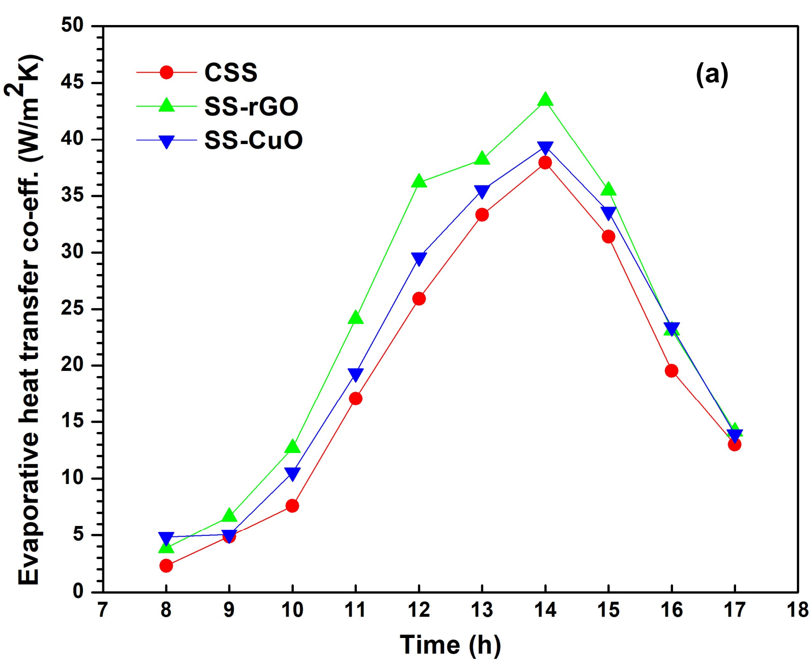
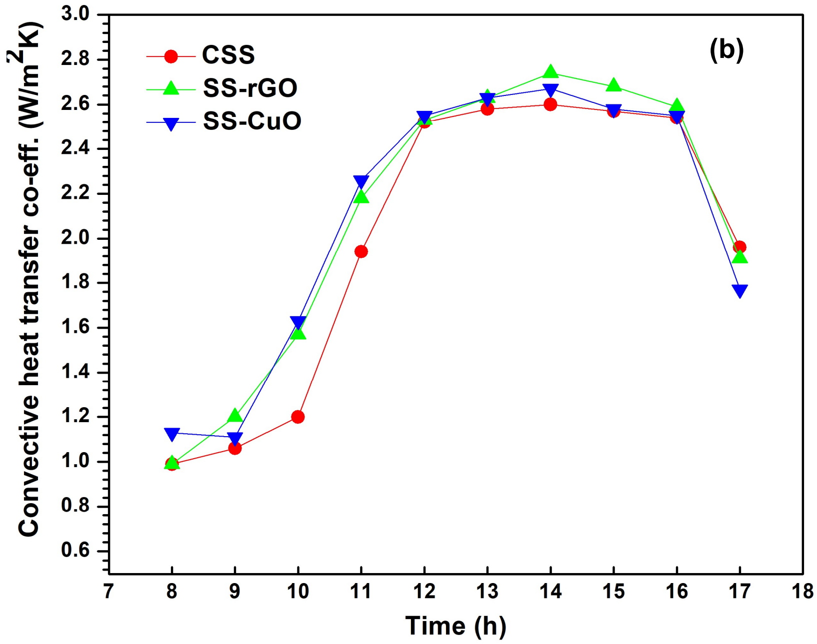


Figure 3: Solar radiation and ambient temperature

Heat transfer analysis of SS

The hourly evaporative, convective and radiative heat transfer coefficients for conventional solar still with only black paint coated absorber (CSS), solar still with rGO coated absorber (SS-rGO) and solar still with CuO coated absorber (SS-CuO) are shown in Figure 4 (a-c). As seen in Figure 4 (a), the evaporative heat transfer coefficient of a conventional SS ranged from 2.23 to 37.93 W/m^2 K, whereas it was 4.42 - 39.37 W/m^2 K and 3.86 - 43.44 W/m^2 K for SS-rGO and SS-CuO, respectively. The augmented heat transfer is achieved mainly due to the higher temperature of the coated absorber plate as compared to a conventional absorber plate.





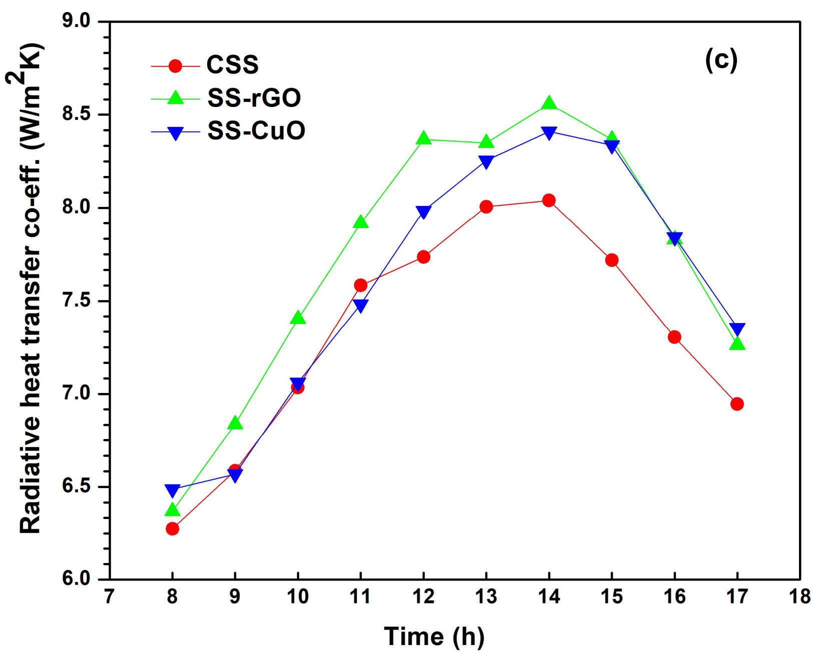


Figure 4: Heat transfer coefficients (a) evaporation, (b) convection, and (c) radiative

Moreover, the radiative and conductive heat transfer coefficients values of nanoparticles coated absorber plate showed significantly improved values compared to the conventional SS, owing to significantly higher absorptivity of solar radiation by black paint mixed metallic particles coated on the absorber plate. Figure 4 (b-c) showed the convective and radiative heat transfer coefficient for three SSs. The higher absorbed solar radiation helps to increase the absorber plate temperature, which leads to a higher heat transfer rate from the basin to the glass surface. It was also seen from the results that higher thermal conductivity of rGO, compared to CuO leads to higher heat transfer and all the heat transfer coefficient values of rGO are higher as compared to the other cases.

Temperature, freshwater production and energy analysis of SS

The diurnal variations in the inner glass cover and basin water temperature of the SS with and without the coating of different nanoparticles are plotted in Figure 5 (a-b). As seen from the figure, the basin water temperature increases along with the inner glass cover temperature until maximum ambient temperature (usually occurred between 12 noon to 2 PM) and thereafter temperature starts reducing. The maximum glass and water temperature of CSS was found to be 54.9 °C and 62 °C, respectively. Furthermore, the SS with rGO coated absorber showed higher temperatures compared to conventional SS, owing to the excellent solar absorption properties of rGO along with the higher thermal conductivity, which promotes the high temperature inside the basin. The highest glass and water temperature of 59.9 °C and 66.2 °C was noticed for SS-rGO, whereas it was found to be 55.4 °C and 64.2 °C for SS-CuO. This can be attributed to the fact that, CuO possesses lower than conductivity and solar absorption behaviour than that of rGO and the peak temperature across SS was shown by rGO. High absorption the rGO absorber leads to higher heat transfer rate from the absorber plate to the basin water, which helps to increase the evaporation rate of water and therefore, the higher temperature was noticed at the glass cover for SS-rGO.

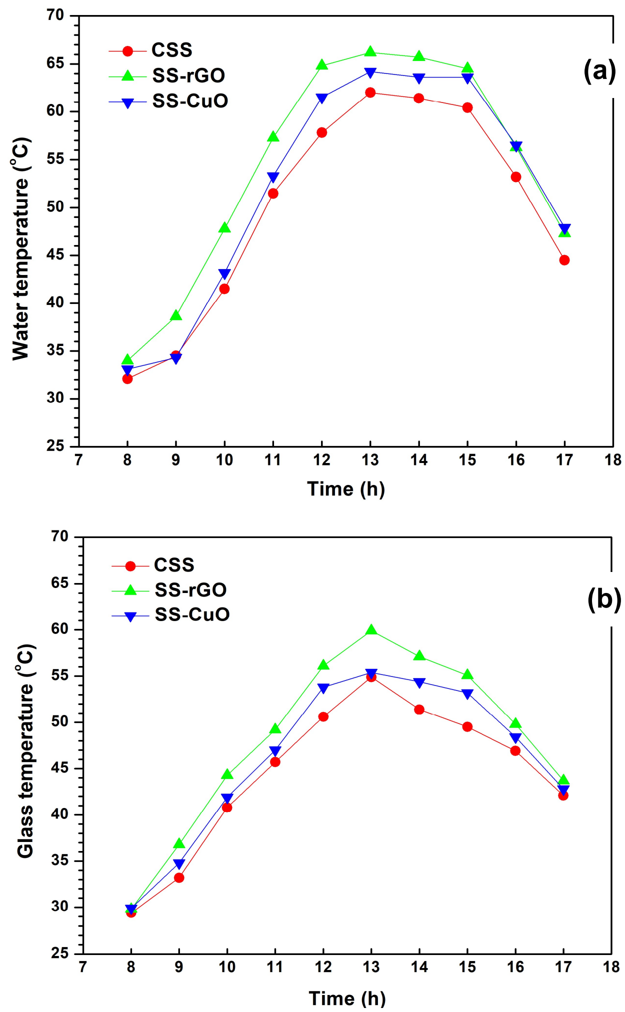


Figure 5: Diurnal variations in the temperature of (a) water and (b) glass cover of SSs

Figure 6 shows the fresh water yield of the SS with and without nanoparticles coating and the CSS yield was found to be 3.97 L/m^2/day. With the coating of rGO and CuO on absorber, fresh water yield augmented by 11.8 % and 6.8 %, respectively. The nanoparticle coated absorber plate absorber higher solar radiation due to the lager area to volume ratio along with the inherent higher thermal conductivity of carbonaceous particles, which augment the rate of heat transfer of SS. This higher heat transfer leads to increase in evaporation rate and thus, augmented fresh water output was achieved. Figure 7 shows the full day efficiency of the SSs and it was found to 35.7 %, 39.9 %, and 38.1 % for CSS, SS-rGO and SS-CuO, respectively. It was concluded from above results that the rGO coating on the absorber plate plays a significant role in augmenting the temperature, which will leads to improved fresh water yield and full day efficiency.

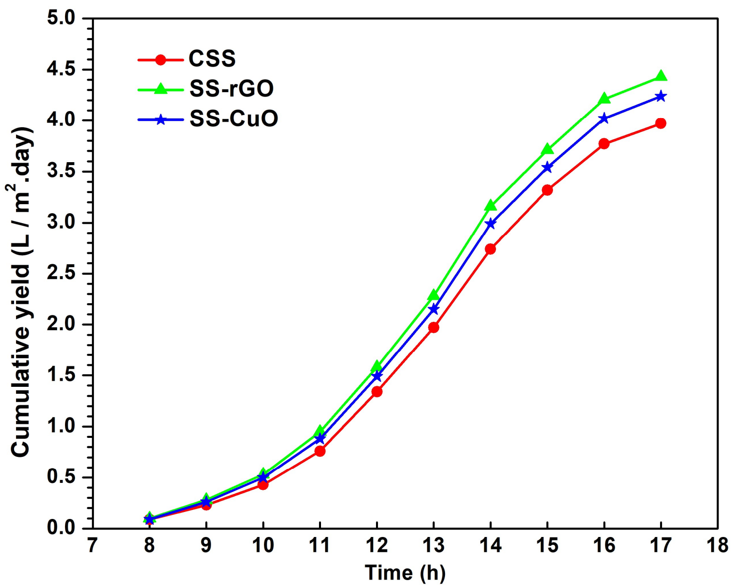


Figure 6: Cumulative water yield of SSs

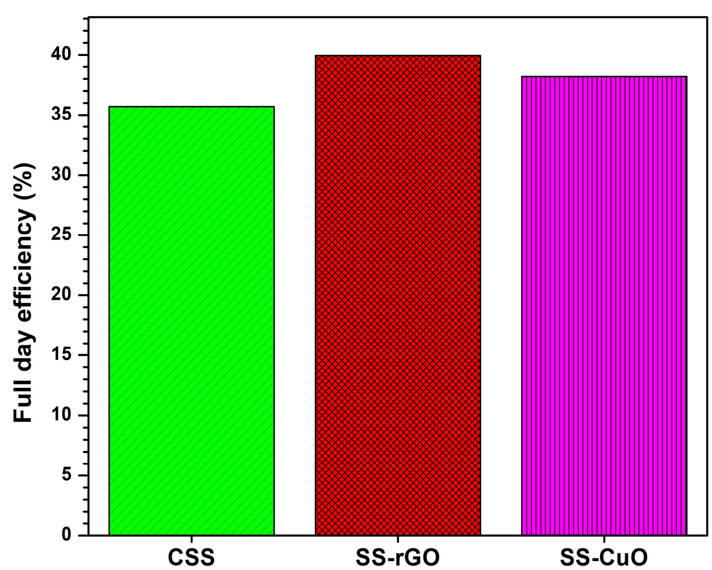


Figure 7: Full day efficiency of SSs

Environmental and economic analysis

CO_2 mitigation and earned carbon credit have been calculated using environment-economic analysis. 1.58 kg/KWh of CO_2 was produced from fossil fuels in a typical coal power plant (Sharshir et al., 2020). The enviro-economic analysis has been determined using following equations:

Emission of CO_2 emission throughout the lifespan of SS (kg) = $\epsilon_{emb} \times 1.58$ (8)

here, ϵ_{emb} is the embodiment energy

CO_2 mitigation throughout the lifespan of SS (kg) = $\epsilon_{out} \times 1.58 \times LS$ (9)

here, LS is the lifespan of SS (10 years) and the yearly energy output (ϵ_{out}) is determined using following equation :

$$\epsilon_{out} = \frac{m_{ss} \times H_{fg}}{3600} \tag{10}$$

The net CO_2 mitigation in tons throughout the lifespan of the SS is calculated using the following equation:

$$N_{M,CO_2} = \frac{1.58 \times (\epsilon_{out} \times LS - \epsilon_{emb})}{1000} \tag{11}$$

The carbon credit produced (CCP) by the entire system is determined using following eq:

$$CCP = N_{M,CO_2} \times R_{CO_2} \tag{12}$$

The consequences of the environment-economic analysis for all SSs are tabulated in Table 2 and Table 3. The total embodied energy of different SS components and various materials used in the present experimental studies is depicted in Table 2. The total embodied energy of conventional SS was estimated at about 241.4 kWh and in the case of all coated SSs, it was found to be 324. 7 kWh. The variations of mitigated CO_2 and carbon credit produced for the entire lifespan of SSs i.e., 10 years is depicted in Table 3. It was seen from table that net mitigation of CO_2 in the case of CSS, SS-rGO and SS-Cu were 10.96 tons, 13.19 tons, 12.08 tons. It is interesting to note that the produced nanoparticles have significantly contributed towards the CO_2 mitigation and the lowest value was exhibited by conventional SS without any modification. The maximum carbon credits produced were 134.86 USD for SS-rGO. It was reduced to 128.67 USD and 114.38 USD, respectively in the case of SS-CuO and CSS.

SS components	Materials	Embodied energy (ϵ_{emb}) (kWh)	
		CSS	**Coated SSs**
Basin plate	Iron	55.5	55.5
Body frame	Iron	138.8	138.8
Glass surface	Glass	25	25
Insulation	Thermocol	2.7	2.7
Basin absorber plate coating	Black paint (CSS)	12.5	12.5
	Nanoparticles	-	83.3
Seal and control valve	Rubber	6.9	6.9
Total embodied energy	-	241.4 kWh	324.7 kWh

Table 2: The embodied energy of several components of SSs

SS type	CSS	SS-rGO	SS-CuO
Annual yield, kg	1191	1329	1272
ϵ_{emb}, kWh	241.4	324.7	324.7
ϵ_{out}, kWh	654.55	867.68	797.03
CO_2 emissions, kg	381.41	513.02	513.0
Net CO_2 mitigation, tons	10.96	13.19	12.08
CCP, USD	114.38	134.86	128.67

Table 3: Environment - economic analysis of SSs

Water quality analysis

The quality of water samples before and after the distillation was compared as per the standard of Indian Council of Medical Research (ICMR) and presented in Table 4. All the parameters of the generated fresh water from the experiment was fairly suitable for drinking purpose by addition of some required minerals and also full-fills the ICMR standards.

Parameters	ICMR Standard	Brackish water	Distilled water
Total dissolved Solids (mg/L)	500	610	50
pH	7.0-8.5	7.31	7.2
Total hardness (mg/L)	300	540	20
Total alkalinity (mg/L)	200	140	10
Calcium hardness (mg/L)	75	120	30
Magnesium hardness (mg/L)	50	170	20
Nitrate (mg/L)	20	44	2
Fluoride (mg/L)	1	1.7	0.1

Table 4: Water quality comparison with ICMR data

APPLICATIONS OF DEVELOPED TECHNOLOGY DURING COVID-19 PANDEMIC

During this COVID-19 pandemic, as there was complete lockdown in most parts of the world and it is advised to do regular and through hand wash for preventing the COVID-19. As a result, the access to clean water for different application including house hold and drinking has become very critical. The developed method can distilled the brackish water and it can full-fills the need of a small family with the utilization of complete renewable energy. As the majority of population in India still lives in village and with the abundant solar energy, this method of generating clean water will be very helpful for in-house generation of fresh water. In addition, with the extreme stress on water supplying agencies during this period, the developed technology will make the people self-reliable.

CONCLUSIONS

Single basin solar still with nanoparticle coated absorber plate was designed and investigated under the climatic conditions of Jaipur, India and the heat transfer coefficients, energy efficiency, environment-economic analysis were evaluated. The following experimental outcomes can be concluded:

- Nanoparticles coated absorber plate showed significant enhancement in all the three heat transfer coefficients, compared to the CSS and among the SSs, rGO coated showed the highest gain in heat transfer coefficients.
- Maximum enhancement in glass and water temperature of 9.1 % and 6.7 % was showed by rGO coated SS, as compared to the CSS.
- The full day yield/m^2 of in the case of CSS, SS-rGO and SS-CuO were 3.96 L, 4.43 L, and 4.24 L, respectively, while the energy efficiencies were 35.7 %, 39.9 %, and 38.1 %.
- The proposed SS with 0.01 m water depth in the basin has reduced 13.19 tons CO_2 during its 10 years of lifetime.
- The quality of water samples attained from experimental investigation is suitable for drinking purposes and also meets the requirements of the ICMR standards.
- During the COVID-19 pandemic, there is extreme stress on water supplying agencies to full-fill the water need of large population under lockdown and the developed technology will make the population self-reliable through purification and generation of fresh water in most sustainable and cost- effective manner.

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