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Combined effects of composite thermal energy storage and magnetic field to enhance productivity in solar desalination

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Abstract

The conventional solar still is limited to a daily yield of approximately 2 – 3.5 kg/m^2/day. To increase the yield, this study investigates experimentally the combined effects of latent and sensible energy storage together with magnetization. Paraffin and novel high-thermal conductivity nanomaterial (graphite plate) were used as latent and sensible heat storage materials, respectively. There was an overall increase of 62% and 235% in the daytime and night-time yield, respectively, giving a total yield of 5.5 kg/m^2/day compared to 3.4 kg/m^2/day for a conventional still. Enviro-economic parameters like emissions, CO_2 mitigation and carbon credit (CC) earned were also investigated. Energy matrices analysis and water quality checks were performed to estimate the energy-payback time, life cycle conversion efficiency (LCCE) and purity of desalinated water. The cost per liter of freshwater was found to be 3.7% cheaper than for a conventional still and 69% cheaper than bottled water in India. Over a 30 year period, 40.3 Tonnes of CO_2 will be mitigated contributing a CC and LCCE of $402 and 0.52, respectively. The proposed modified still is recommended as a substitute for conventional stills and stills with simple energy storage.

Keywords: composite thermal energy storage; graphite plate-paraffin; modified still; ferrite magnets; techno-enviro-economical; productivity.

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Nomenclature	
AC	annual cost ($)
AMC	annual maintenance and operational cost($)
ASV	annual salvage value ($)
BIS	bureau of Indian standards
CC	carbon credit earned ($)
CNT	carbon nanotube
CO_2	carbon dioxide
CPL	cost per liter ($)
CRF	capital recovery factor
CuO	copper oxide
DO	dissolved oxygen (%)
DSC	Differential scanning calorimeter
FAC	fixed annual cost ($)
GDP	Gross Domestic Product
GO	graphene oxide
LCCE	life cycle conversion efficiency
M	annual productivity (kg/m^2)
N	number of days
NO	nitric oxide
P	present capital cost ($)
PCM	phase change material
pH	parts of hydrogen
Ppm	parts per million
PVC	Polyvinyl chloride
R&D	research and development
S	salvage value ($)
SAS	School of Advanced Sciences
SFF	sinking fund factor
SO_2	sulphur dioxide
Ta	ambient temperature (℃)
TDS	total dissolved solids (mg/L)
TES	thermal energy storage
Tgraphite	temperature of graphite plate (℃)
Tg	temperature of glass (℃)
TiO_2	titanium dioxide
Tpcm	temperature of phase change material (℃)
Tw	water temperature (℃)
USD	United States dollar ($)
VIT	Vellore Institute of Technology
Y	Total years of operation

1. Introduction

Freshwater is one of the basic requirements of all living creatures on the earth. Even though 73% of the earth is covered with water, only 3% is freshwater. The total freshwater available for usage is estimated to be 0.36% [1,2]. Roughly one million people die each year due to lack of access to good quality water [3]. Desalination technologies help to remedy this water crisis. The various desalination techniques include membrane desalination technologies (electrodialysis, reverse osmosis, forward osmosis) and thermal desalination technologies (vapour compression evaporation, adsorption desalination, solar stills, multi-stage flash and distillation) [4,5,14,6–13]. In general, membrane technologies and most of the thermal desalination technologies are expensive, energy-intensive processes, as such not very feasible in rural areas [15]. Among the various options, the solar still is a thermal desalination technology that operates at zero fuel cost (as it is driven by solar energy) and as such one the more economic technologies available [16–18].

The conventional solar still is limited to a low daily yield of approximately 2–3.5 kg/m^2/day, which is insufficient for an average family [19]. Enhancing this yield is an important research and development (R & D) area, wherein researchers are trying to incorporate advanced techniques like solar collectors, solar photovoltaic, thermal energy storage and solar pond. [20–23]. Among these, thermal energy storage is used to improve the daily yield by providing freshwater even during the night [24–26].

Generally, thermal energy can be stored by sensible heat (without phase change) and latent heat (with phase change) energy storage materials [27]. Many sensible heat energy storage materials (Fig. 1) were used by researchers from the year 1981 to 2020, including jute cloth [28], black rubber mat [29], black gravel [30], aluminium plates [31,32], charcoal granules [33], packed glass ball [34], granite [35], sponges [36,37], fins [38], sand [39], black rocks [40], dried sand [41], vertical jute cloth [42], dry cow dung [43], thermic fluid [44,45], bamboo cotton [46], marble pieces [47] and fins [48]. In recent years (i.e. 2018 and 2019), research was carried using novel materials and combining more than one materials [49], [50], [51], [52], [53], [54], [55], [56] to enhance the productivity. A detailed comparison of productivity enhancement using these various materials is shown in Table. 1. It is evident that the sensible heat energy storage materials gave a significant productivity improvement. However, emerging high-thermal conductivity energy storage materials such as CNT and graphite plates (in the bulk volume) have not yet been incorporated and investigated in the solar still.

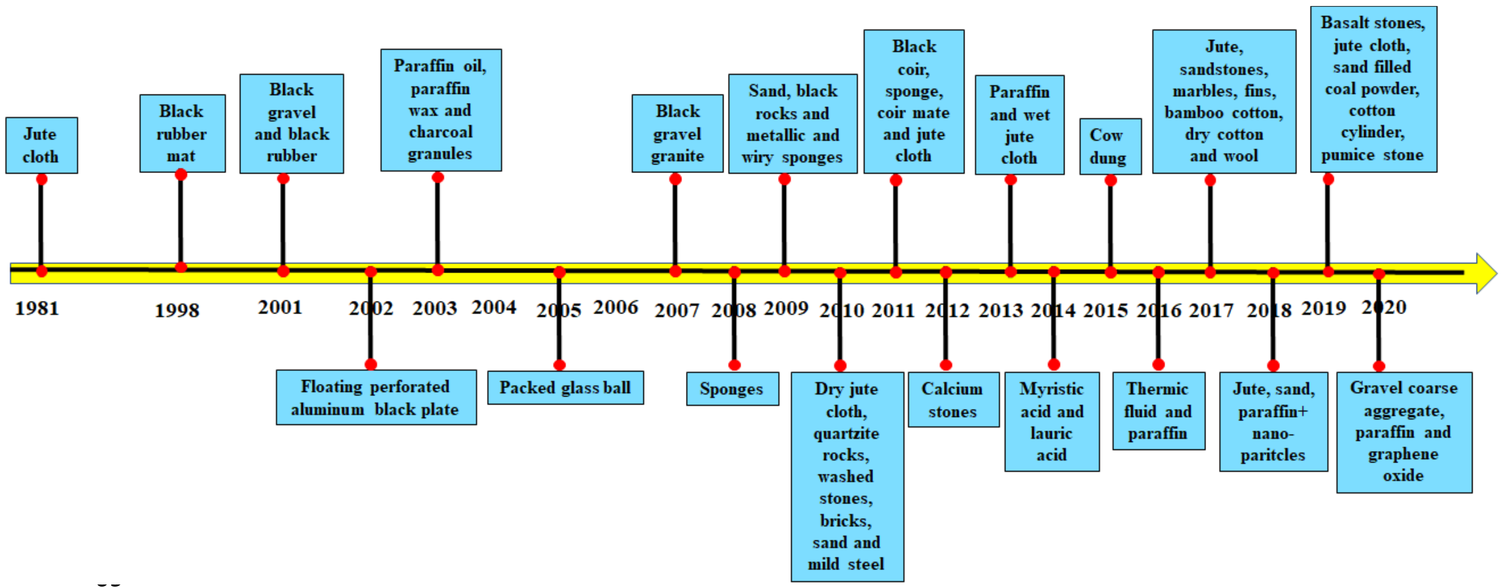

Fig. 1. Historical evolution of thermal energy storage materials in solar desalination

Unlike sensible heat energy storage, latent heat energy storage in solar still gained interest relatively recently in 2003 [57], and slowly gained momentum since then [58–62]. There are many reviews available about the integration of latent heat energy storage material in the solar still [63,64], covering various types of latent heat energy storage materials such as paraffin, lauric acid, glauber's salt and stearic acid [24,27]. Among these, paraffin is most widely used owing to its low cost and favourable thermo-physical and chemical properties [26,63,65,66]. Up till now, studies only looked at materials used individually. Composite thermal energy storage is a new concept that combines both sensible and latent heat energy storage in the solar still. This technique was initiated in 2016 [67] and only a few studies have been reported so far.

Shalaby et al. (2016) used wick and paraffin for composite thermal energy storage and achieved a 41% improvement in yield over a conventional still [67]. Kabeel et al. (2019) used black gravel (as sensible heat energy storage material) and paraffin wax (as latent heat energy storage material) to obtain an improvement of 37% [68]. These experiments show it to be a promising technique that merits further investigation. Moreover, none of the studies investigated the integration of recently evolved high thermal conductivity sensible heat energy storage materials (like CNT and graphite) along with the latent heat energy storage materials in a solar still.

Recently (in 2019) Indian researchers found that magnetizing (through ferrite magnets) the feed water enhances the distillate yield [69]. Usually, in conventional stills, the presence of Van der Waals force between the soluble salts and water molecules increases the boiling point elevation and leads to the low vapor pressure [70–75]. Whereas the still integrated with ferrite magnets induce a magnetic field which tends to break the Van der Waals force between the water molecules and soluble salts [70–75]. This phenomenon increases the diffusion coefficient of salt ions and mobility of water molecules, which in turn increase the vapor pressure and enhances the evaporation process [70–75]. The integration of magnets increases the partial pressure difference between the water and glass cover, which in turn increases the evaporative heat transfer coefficient and enhances productivity by 49% [69]. However, the combined effects of heat storage and magnetisation have yet to be investigated.

To summarise these findings, the following areas have not yet been investigated in solar stills: (i) new (graphite plates and CNT) sensible heat energy storage materials; (ii) combination of such materials with latent heat energy storage; (iii) magnetisation together with such composite energy storage. The current study aims to address these research gaps. Thus, the specific objectives are to: (i) analyse the productivity enhancement through composite thermal energy storage technique along with the magnetizing effect together in solar still (modified still); (ii) investigate the technical and economic feasibility of the proposed modified still, (iii) conduct an enviro-economic analysis of it; (iv) perform energy matrices analysis associated with the modified still, and (v) test the quality of water from the modified still to reassure that the desalinated water quality is within the permissible limits of the Bureau of Indian Standards (BIS).

Table 1. Summary of existing literature in solar still integrated with sensible and latent heat energy storage materials (where data are provided)

Sl. No	Reference	Year	Types of energy storage	Materials used	Findings
1.	[28]	1981	Sensible heat energy storage	Jute cloth	Productivity augmented by 34%
2.	[29]	1998	Sensible heat energy storage	Black rubber mat	38% increase in the productivity
3.	[30]	2001	Sensible heat energy storage	Black gravel and black rubber	20% improvement in the cumulative yield
4.	[31,32]	2002	Sensible heat energy storage	Floating perforated aluminium black plate	Yield was enhanced by 40%
5.	[33]	2003	Sensible heat energy storage	Charcoal granules	Yield was enhanced by 15%
6.	[57]	2003	Latent heat	Paraffin oil and paraffin wax	The efficiency was enhanced to 36.2%

7.	[34]	2005	Sensible heat energy storage	Packed glass ball	Productivity improved by 7.5%
8.	[35]	2007	Sensible heat energy storage	Black gravel granite	Productivity improved by 20% Productivity enhanced to 3.9 kg/m^2
9.	[36–38]	2008	Sensible heat energy storage	Sponges	Productivity is 2.26 kg/m^2. 15.3% higher productivity compared to the conventional still
10.	[39]	2009	Sensible heat energy storage	Sand	23% enhancement in the productivity
11.	[40]	2009	Sensible heat energy storage	Black rocks and metallic wiry sponges	Black rocks gave better productivity as compared to wiry sponges
12.	[41]	2010	Sensible heat energy storage	Sand	75% enhancement in the productivity
13.	[42]	2010	Sensible heat energy storage	Dry jute cloth	20% increase in the cumulative yield. Daily yield enhanced to 4 kg/m^2
14.	[25]	2010	Sensible heat energy storage	Quartzite rocks, washed stones, bricks and mild steel	Quartzite rock gave the maximum yield comparing other materials.
15.	[58]	2014	Latent heat energy storage	Myristic acid, lauric acid	Lauric acid gave better yield as compared to myristic acid
16.	[43]	2015	Sensible heat energy storage	dry cow dung	35% increase in the daily yield
17.	[44,45]	2016	Sensible heat energy storage	Salt encapsulated spherical plastic container and thermic fluid	The daily yield was enhanced by 66%
18.	[59]	2016	Latent heat energy storage	Paraffin	31% increase in the productivity
19.	[60]	2016	Latent heat energy storage	Paraffin	67.18% increase in the productivity
20.	[61]	2016	Latent heat energy storage	Paraffin	109% increase in the daily yield
21.	[62]	2016	Latent heat energy storage	Paraffin	Productivity increases by 49%. The daily yield was 2.1 kg/m^2.
22.	[67]	2016	Sensible heat and latent heat energy storage	Paraffin	Daily yield increased to 3.7 kg/m^2.
23.	[46]	2017	Sensible heat energy storage	Jute, bamboo cotton, dry cotton and wool	Bamboo cotton yielded better results with 51.9% higher yield

24.	[47]	2017	Sensible hear energy storage	Sandstones, marble pieces	Sandstones gave higher productivity as compared to marbles
25.	[48]	2017	Sensible heat energy storage	Fins along with condensers	41.9% improvement in the daily yield
26.	[49]	2018	Sensible heat energy storage	Jute cloth and sand heat storage	15% improvement in the yield
27.	[50]	2018	Sensible heat energy storage	Absorber tube coated with graphite	80% improvement on the cumulative yield
28.	[27]	2018	Latent heat energy storage	Paraffin+CuO, Parffin+TiO_2, Paraffin+GO	Paraffin with titanium oxide gave better productivity of 5.28 kg/m^2 compared to the GO and CuO
29.	[51]	2019	Sensible heat energy storage	Sand-filled coal powder and cotton cylinder	Yield improved by 30.9%
30.	[52,53]	2019	Sensible heat energy storage	Basalt stones Jute cloth	Yield improved by 33.37% Productivity enhanced by 18%
31.	[54]	2019	Sensible heat energy storage	Copper oxide nanoparticles coated absorber plate and sponges	41% improvement in the daily yield
32.	[55]	2019	Sensible heat energy storage	Pumice stones	Cumulative yield enhances by 28%
33.	[68]	2019	Latent heat and sensible heat energy storage	Paraffin and Black gravel	Achieved daily yield of 3.27 kg/m^2
34.	[56]	2020	Sensible heat energy storage	Gravel coarse aggregate	Productivity enhanced to 4.21 kg/m^2

2. System description

Two solar stills (conventional and modified), each of 1m^2 area, were fabricated using aluminium sheets and covered with a transparent glass cover of thickness 4 mm. The inclination of the cover was at 12° (equal to the latitude of the Vellore, Tamil Nadu, India, where the still was located). To reduce the heat loss from the system to the surroundings, a foam strap with epoxy glue was used to fix the glass on the top of both solar stills. The inner walls of the solar stills were coated with aluminium enamel and the base was coated with black synthetic enamel paint to enhance the absorptivity and reflectivity of solar radiation onto the system. The modified still included ferrite magnets, graphite plates and paraffin arranged as follow (Fig. 2).

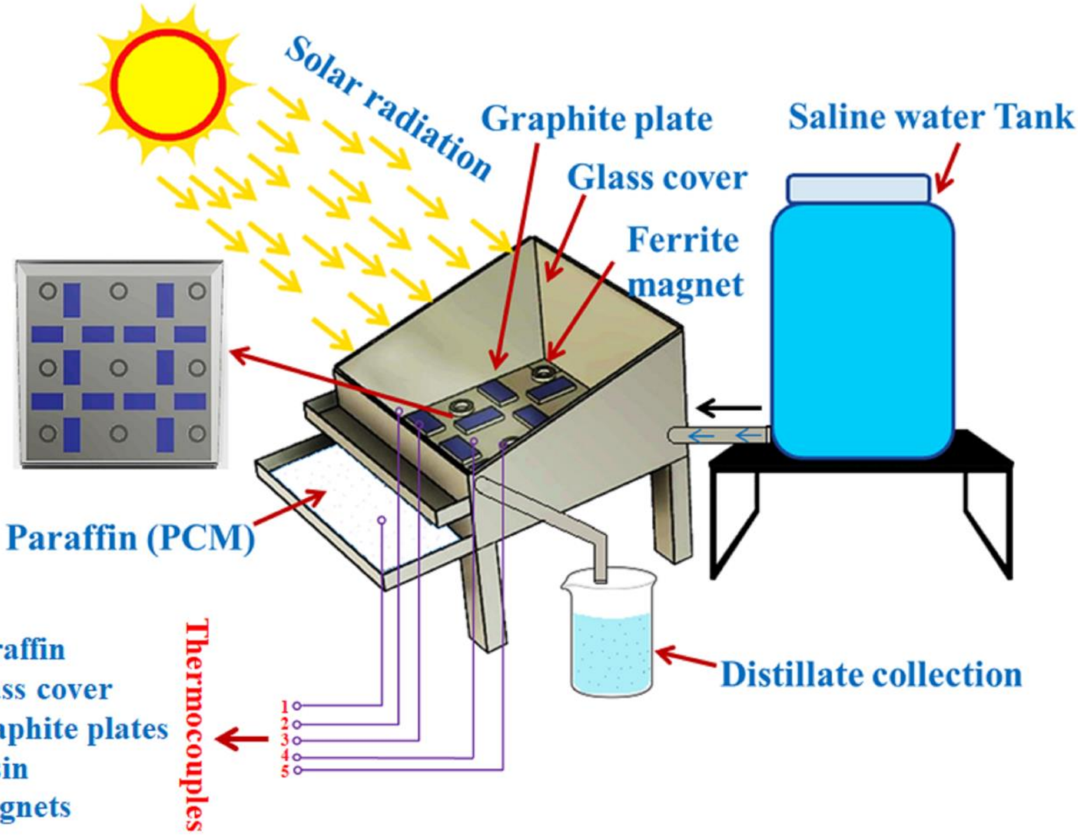

Fig. 2. Schematic setup of modified solar still with composite energy storage and ferrite magnets

Fourteen graphite plates (each of 150 mm × 70 mm × 25 mm), which are insoluble in water, were purchased from Triton Graphite, Gujarat, India and placed on the basin of the solar still following the pattern suggested by Dumaka et al. (2019) [69] (Fig. 3). The specifications of graphite plates are tabulated in Table 2. Ring-shaped hollow ferrite magnets of grade N42 (09 numbers) each of 6 cm outer diameter and 3.2 cm inner diameter with a magnetic field strength of 90 mT were purchased from Magna Tronix, Chennai, India. The magnets were arranged geometrically as suggested in the literature to provide a uniform distribution of magnetic field strength across the basin [69,76,77]. The detailed specifications of the ferrite magnet are given in Table 3. A small reservoir of 2.5 cm height was fabricated below the basin to hold 10 kg latent heat energy storage material (paraffin). The melting and solidification characteristics of the paraffin were tested using Nano DSC differential scanning calorimeter from TA instruments in the School of Advanced Sciences (SAS), VIT University, Vellore, India. As per the recommendations given in the literature [27,78,79] suggesting that the amount of brine water should be less than the total volume of paraffin, 9 kg of saline water (tap water) was fed inside the solar still. The specifications of the paraffin used in the study are tabulated in Table 4. Experimental observations were carried out during March 2020 at the roof-top of

Renewable Energy Sources Laboratory-GDN block, VIT University (12.91° N, 79.13° E), Tamil Nadu, India.

Table 2. Specification of graphite plates used in the present study

Parameters	Specifications
Grade and color	1st grade and black color
Length x bredth x thickness (mm)	150 x 70 x 25
Thermal conductivity (W/mK)	390
Temperature	up to 2000°C
Thermal expansion (µm/m-K)	4.9
Young's Modulus (GPa)	21
Ultimate tensile strength (MPa)	18
Heat of vaporization	128 k-Cal/gm atom at 4612°C

Table 3. Thermal properties of ferrite magnet used in the modified still

Properties	Specifications
Density (g/cm^3)	4.9 to 5.1
Thermal conductivity (W/mK)	4186.92
Electrical resistivity (ohm-cm)	106
Tensile strength (psi)	5000
Flexural strength (psi)	9000
Hardness (Mohs)	7
Curie temperature (°C)	450
Remanence (Br)	0.41-0.42
Intrinsic coercive force (Hcj)	250-260
Max. energy (kJ/m^3)	32.0-33.0

Table 4. Properties of the phase change material (paraffin)

Sl. No	Properties	Corresponding value
1	Melting temperature range	57-59°C
2	Density (solid/liquid)	820/770 kg/m^3
3	Specific heat (solid/liquid)	2.9/2.51 kJ/kg
4	Latent heat of fusion	285 kJ/kg
5	Thermal conductivity	0.28 W/mK

K-type (KC-PVC-K-24-180) thermocouples have been used to detect the temperatures of magnets, graphite, paraffin, inner glass, ambient and water in the solar still. The tap water with pH: 7.7, TDS: 330 ppm, hardness: 254 mg/L, dissolved oxygen: 78%, fluoride: 1.9 mg/L, chloride: 31.4 mg/L, electrical conductivity: 637 μs/m, calcium ions: 29.7 mg/L, magnesium ions: 33 mg/L, sodium ions: 372 mg/L, potassium ions: 95 mg/L and sulphate ions: 37 mg/L was used as the feed water. The temperatures of the various components of the solar still were observed on an hourly basis from 9:00 h to 21:00 h. A plastic graduated cylinder was used to measure the distillate output. The whole system was insulated with glass wool of 30 mm thickness to lessen the heat loss further. The solarimeter and anemometer were used in the experiment to measure the solar intensity and wind velocity, respectively.

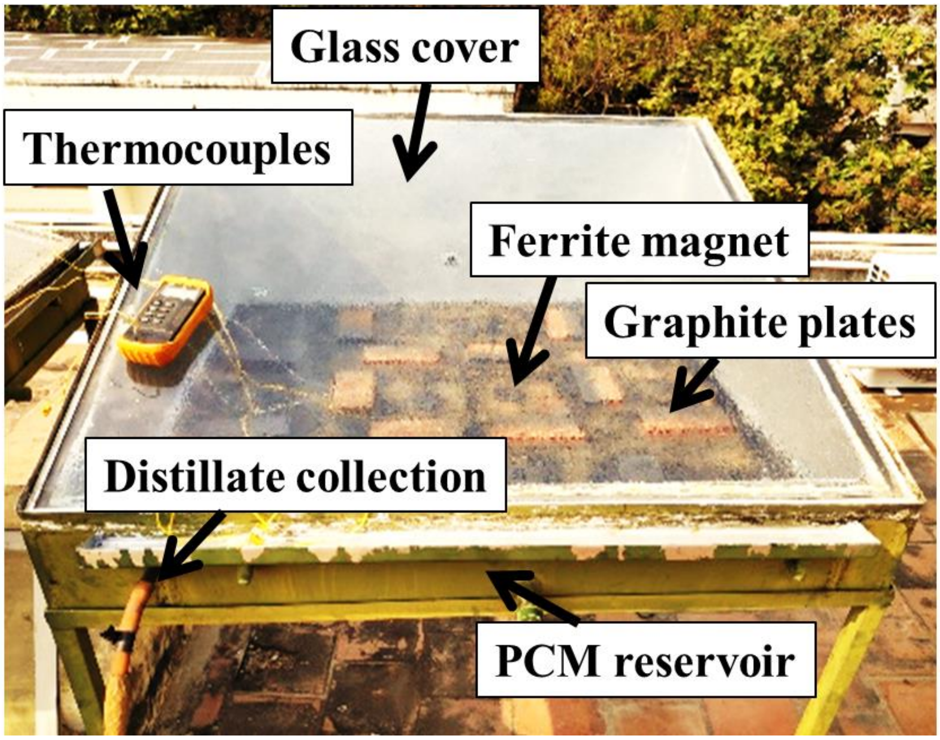

Fig. 3. Experimental picture of the modified solar still showing graphite plates, ferrite magnets and paraffin

The technical details of the various measuring instruments including their range and accuracy are tabulated in Table 5. To estimate the impacts of errors associated with the experiments on the results and conclusions, an uncertainty analysis was carried out for the experimental observation parameters such as various temperature components, hourly yield and cumulative productivity, as per the procedure suggested in the literature [27,36,64,80]. The internal uncertainty and the average of averages in the observations were found to be 0.0024 and 0.19 respectively, corresponding to an uncertainty percentage of 1.2%. The uncertainty percentage of the experiment was thus found to be very low and consistent with that achieved by the other researchers e.g. Kabeel et al. [68] with 6.8%, Arunkumar et al. [54] with 1.88%

and Rufuss et al. [27] with 2.06%. After the experiments, the desalinated water was taken for quality testing in the Environmental and Water Resource Laboratory, VIT University, Vellore, India.

Table 5. Accuracy and range measurement instruments used for the experiment

Sl. No	Instrument	Accuracy	Range
1	Solarimeter	± 2 W/m^2	0 – 2000 W/m^2
2	Thermocouple	± 0.1 °C	0 – 1300°C
3	Graduated cylinder	± 1 ml	1000 ml
4	Gaussmeter	0.1 mG / 0.01 µT	0-2000 µT
5	Anemometer	±0.1 m/s	0.4-35 m/s
6	Differential scanning calorimetry (DSC)	Baseline stability ±0.028 µWatts	10 °C to 160 °C with the scan rate 0.05 °C to 2°C/minute

3. Working principle

Fig. 4 shows the working principle of the modified still which has PCM, graphite plates and ferrite magnets.

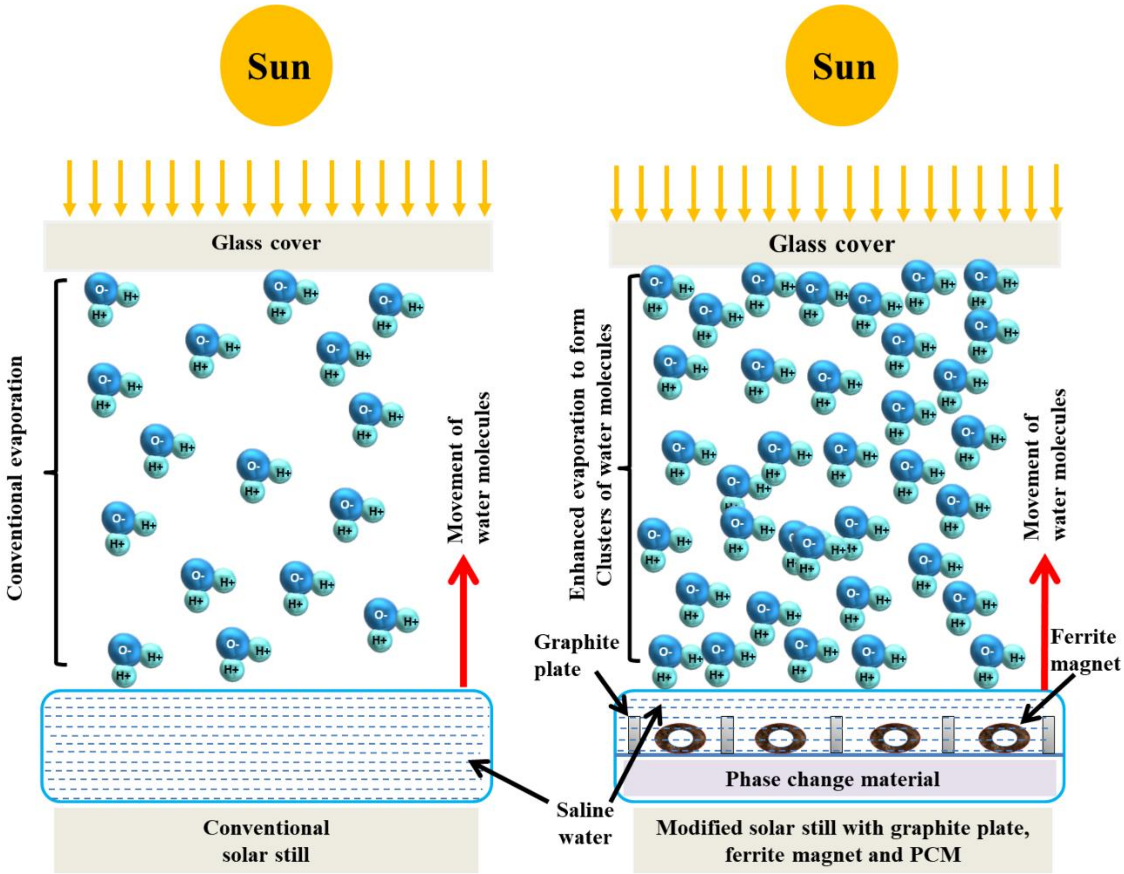

Fig. 4. Working principle of modified still showing a productivity enhancement with graphite plates, paraffin (PCM) and ferrite magnets

The addition of graphite plates increases the evaporation of water molecules from the brine to the inner surface of the glass cover. The magnetization of water molecules also plays an important role in the evaporation of water molecules. Generally, in saline water, the water molecules adhere to the salt ions through weak Van der Waals bonding. It is important to weaken the bonding between the salt ions and water molecules to increase the mobility of salt ions (from salinized water to the basin) and water molecules (from the basin to the inner surface of the glass cover). This can be achieved through the electric field or magnetic field [69,81]. In this study, the magnetic field is preferred based on previous studies in solar desalination [69,82,83]. The magnetic field is also responsible for increasing the partial pressure difference between water and glass cover, which should improve the evaporation process.

In addition, sensible heat storage materials in solar still absorb the heat energy from the sun and store them in the form of sensible heat and release the heat during the nocturnal hours without changing phase. Whereas the latent heat storage material works on the same mechanism as the sensible heat storage materials, except for the fact that they change their state of matter from solid to molten state while they absorb the heat and vice-versa when they release the heat. These materials absorb and release the heat as the latent heat when they are in the melting and solidifying temperature range (usually ±3℃ from the melting and solidification point) and as the sensible heat during the rest of time [27]. Thus, the composite energy storage materials helped to maintain the water temperature higher even during the late evening and nocturnal hours to get maximum productivity.

4. Results and Discussion

The results related to the investigations (i.e. technical, economic, enviro-economic, energy matrices analysis and water quality test) carried out in this study are discussed under the following sections.

4.1. Technical investigations

The effects of climatic parameters during experimentation and temperature of the various components (glass, water, energy storage materials) associated with the conventional and modified still are discussed in the following sub-sections. Furthermore, the melting and solidification characteristics of the phase change material along with the hourly and daily yield of the conventional and modified still are discussed in detail. Also, to aid comparison, the productivity of the present study is compared against the existing literature at the end of this section.

4.1.1. Effect of climatic parameters

The hourly variation of the solar intensity and wind velocity is depicted in Fig. 5. It was observed that the intensity gradually increased from 9:00 h and reached its maximum intensity (1056 W/m²) at 13:00 h and then seamlessly dips down to zero during the late evening hours. The peak intensities were observed during 13:00 h, 12:00 h, and 14:00 h corresponding to 1056 W/m^2, 997 W/m^2 and 967 W/m^2, respectively. A parabolic trend was observed in the intensity profile of the solar radiation during the entire span of the experiment.

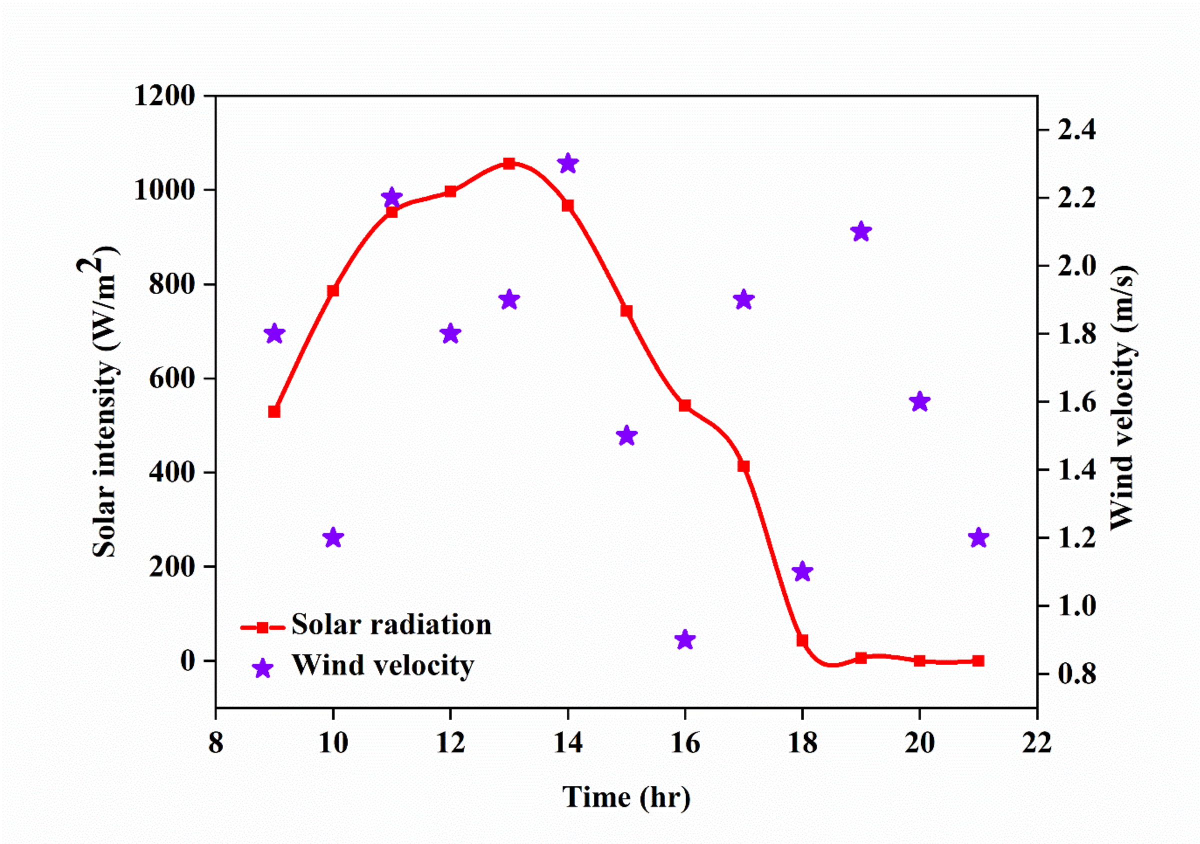

Fig. 5. Hourly variations of solar intensity and wind velocity during the experiment

The maximum, minimum and average wind velocity observed was 2.4 m/s, 0.9 m/s and 1.6 m/s, respectively. These velocities are sufficiently small not to affect the experimental observations [17,84].

4.1.2. Effects of the glass and water temperatures

The glass and water temperatures of the modified still were greater than the corresponding temperatures of the conventional still after 12:00 h (Fig. 6). This increase was due to the addition of ferrite magnets, graphite plates and phase change material (PCM) in the modified still. The better thermal conductivity of sensible heat energy storage material (which was in direct contact with water) along with the presence of PCM have considerably decreased the water temperature in the modified still during the initial stage of the experiment (i.e. till 12:00 h) as compared to the conventional still. During 9:00-12:00 h, the heat energy from the water was absorbed by the graphite plates, ferrite magnets and phase change material (i.e. during charging of PCM). After 12:00 h, the absorbed heat was gradually released to the water which in turn further increased the temperature of the water (discharging of PCM) [27,85]. Also, this mechanism helped the water to maintain its temperature at a higher level even during nocturnal hours.

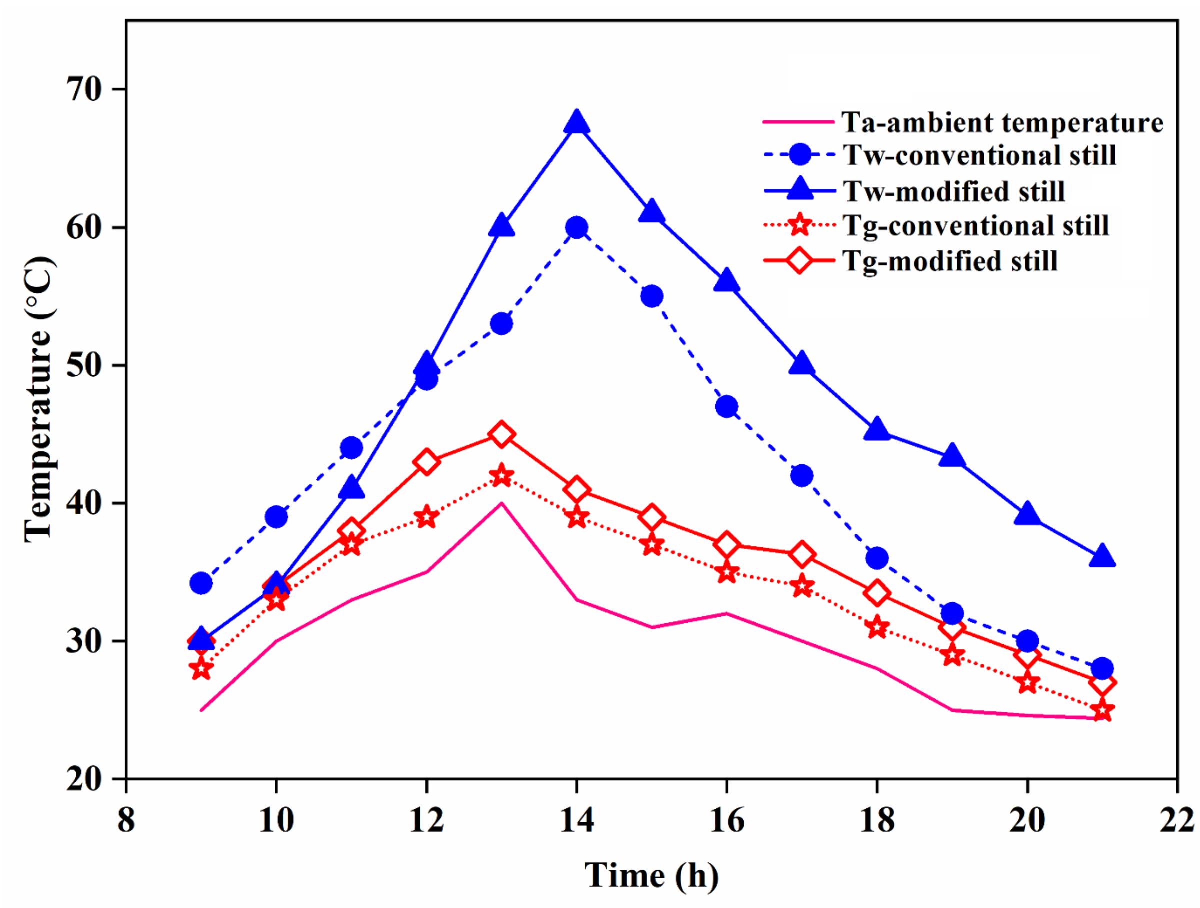

Fig. 6. Hourly variations of glass, water and ambient temperatures for conventional and modified still

A peak trend was observed from 15:00 h to 19:00 h showing the maximum variation in the water temperature of the modified still as compared to the conventional still. During this time, PCM was in the range of its peak solidification temperature wherein it released its latent heat completely [27,85]. In addition to this, the graphite plates also released its heat to the water, which accounted for a substantial increase in the water temperature. Due to these reasons, the water temperature was significantly higher for the modified still than the conventional still. In summary, the integration of composite thermal energy storage along with ferrite magnets have augmented the water temperature of the modified still.

4.1.3. *Effects of integrated energy storage materials*

The temperature variations of the various storage materials in the modified still are presented in Fig. 7. The temperature of the phase change material was considerably low as compared to the magnet temperature during the first four hours of the experiment. This was because the melting characteristics (melting time) of the PCM was higher as compared to the magnet. Moreover, the magnet was in direct contact with the water which enabled the magnet to increase its temperature till 12:00 h.

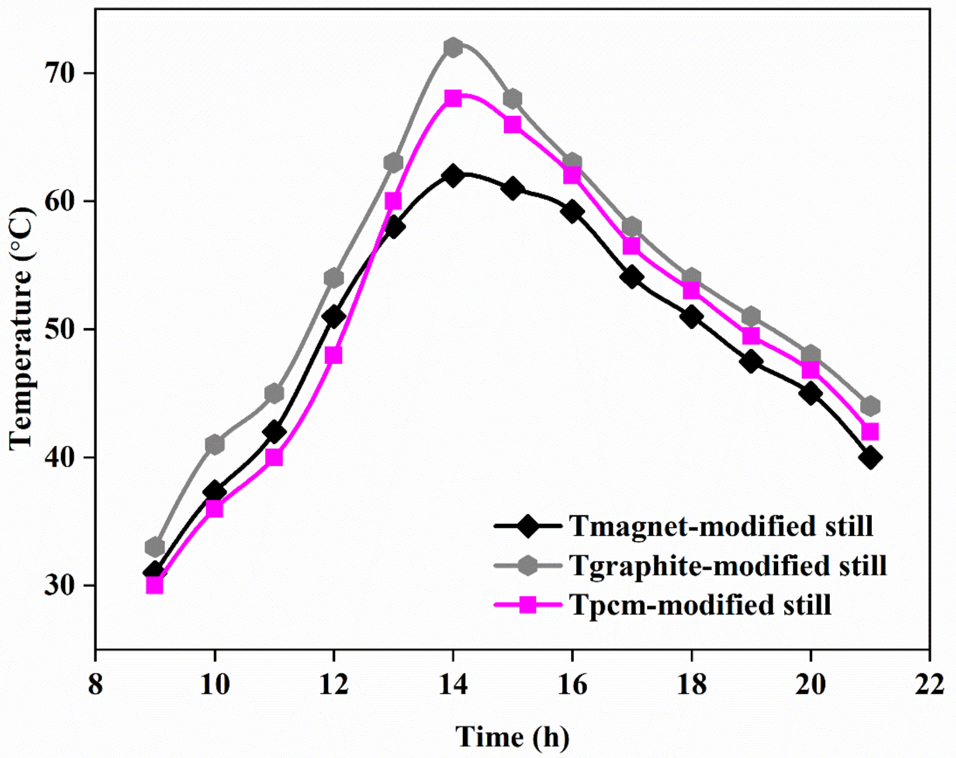

Fig. 7. Temperature variations of composite thermal energy storage materials and ferrite magnets in the modified still.

Furthermore, it also acted as an additional heat source allowing the water to maintain a higher temperature during the cloudy hours. The maximum temperature of magnet, graphite and PCM was observed to be 62°C, 72°C and 68°C, respectively at 14:00 h. A 16% and 6% increase in the temperature was accounted for graphite plate comparing the magnet and PCM temperatures (at 14:00 h), respectively. During the late evening hours (17:00 h to 21:00 h), graphite plate and PCM temperatures dominated the temperature of the magnet. There was a 2-4% increase in the temperatures of the PCM and graphite plate as compared to the magnet's temperature.

The graphite plates consistently extend their supremacy over the other two materials throughout the experiment due to the high thermal conductivity. In summary, the melting and solidification characteristic of PCM (which is discussed below) moderated the temperature variation across the storage unit beneath the basin. Furthermore, the energy storage units temperature played a vital role in governing the water temperature to increase the temperature difference with that of glass temperature and in turn, increased the productivity.

4.1.4. Effects of melting and solidification characteristics of PCM

The melting and solidification characteristics of the latent heat energy storage material (i.e. paraffin) are depicted in Fig. 8. The melting commenced at 52°C and gradually reached its peak melting temperature of 64°C. There was a 20% difference in the temperature between the start and peak melting temperature of the paraffin. Thus, there was considerable latent heat absorbed by paraffin between 52°C and 64°C. The peak melting and solidification temperatures of the paraffin were found to be 64°C and 58°C, respectively.

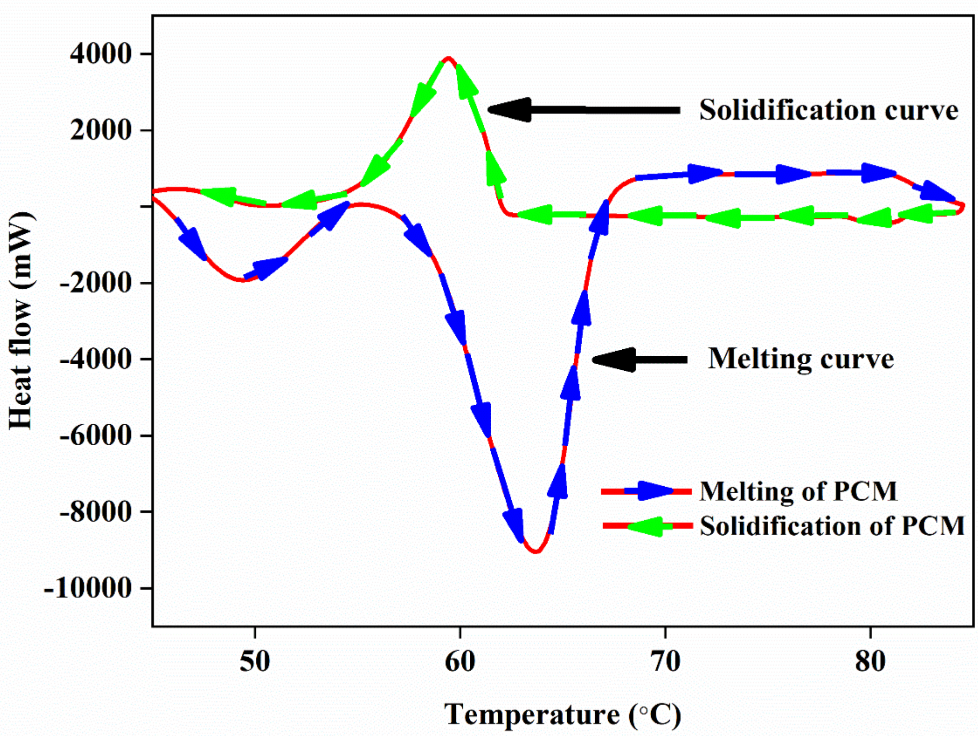

Fig. 8. Melting and solidification characteristics of PCM

The solidification starts at 61°C and lasts till 53.5°C contributing a 7.5°C temperature difference with a 14.5% increase in the amount of latent heat released during solidification. The PCM has released its latent heat till 53.5°C during solidification, inducing a greater temperature difference between water and glass cover increasing the daily yield. Thus, the addition of latent heat energy storage material has acted as an additional heat source to increase the water temperature in the modified still as compared to the conventional still. The prolonged melting and solidification behavior of the paraffin made a significant contribution in melting and solidifying characteristics by absorbing and releasing considerably a higher amount of the latent heat during the charging and discharging process, respectively.

4.1.5. Effect of the temperature difference between water and glass cover

The temperature difference plays an important role in augmenting the hourly and cumulative yield of the solar still [27,35,42]. Fig. 9 depicts the difference in temperatures of water and glass cover for conventional and modified still. The maximum temperature difference of 26.5°C (at 14:00 h) was observed in the modified still whereas the maximum temperature difference observed in the conventional still was only 21°C (at 14:00 h). A 26% increase was observed in the peak temperature differences between the water and glass cover.

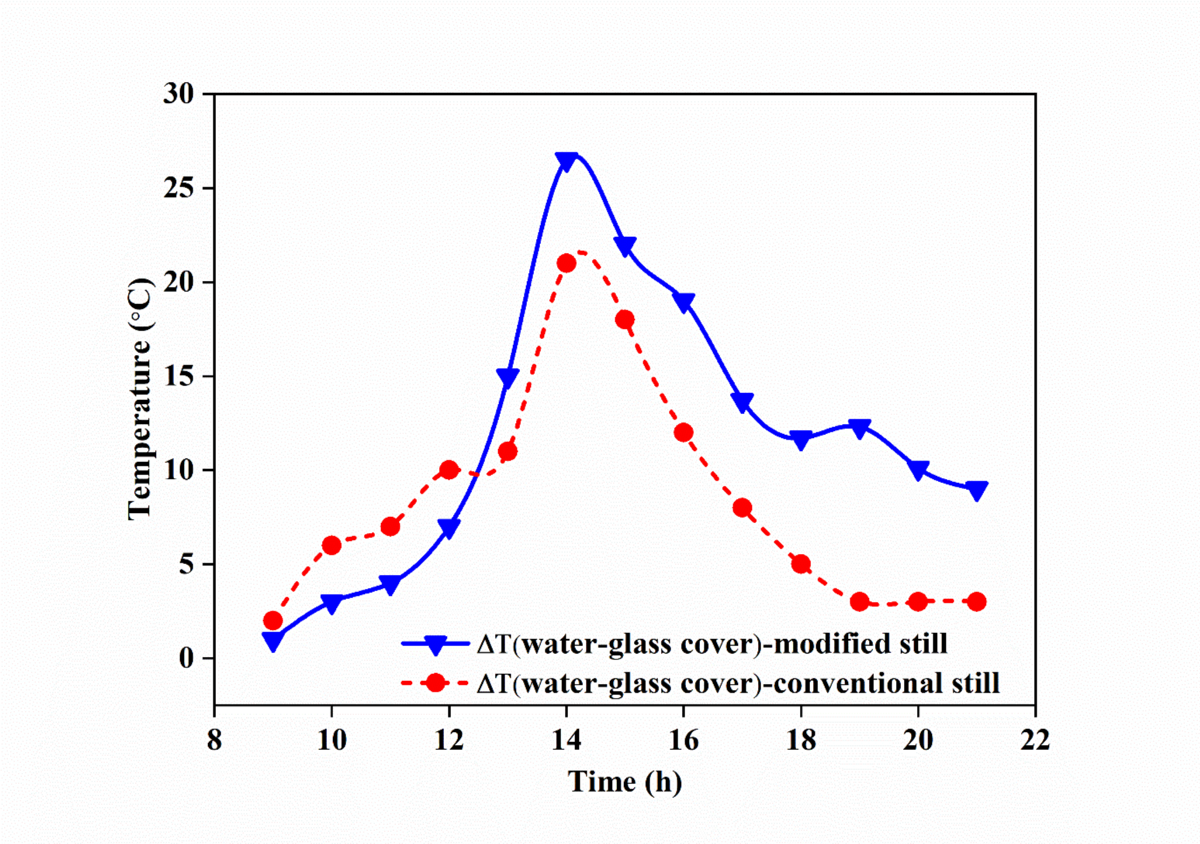

Fig. 9. Comparison of the temperature difference between water and glass cover for the conventional and modified still

At 9:00 h, 10:00 h, 11:00 h and 12:00 h, the temperature difference between water and glass cover was higher in the modified still as compared to the conventional still. There was a 4°C increase observed in the temperature difference of water and glass cover for the modified still over the conventional still from 9:00 h to 12:00 h. The main reason behind this variation was, the energy storage materials were charged during 9:00 h to 12:00 h, where the heat energy of the water was absorbed by the sensible and latent heat energy storage materials which in turn decreased the water temperature in the modified still as compared to the conventional still.

After 12:00 h, there was an increasing trend observed in the temperature difference between the water and glass cover of the modified still. This was because, after 12:00 h, the energy storage materials have released the heat back to the water, thus increasing the temperature of the water in the modified still to be more than that of the conventional still (see Fig. 7) [27,85]. Also, it was the same reason for achieving a higher temperature difference (9°C) even during late evening hours in the modified still. In summary, the temperature difference between water and glass cover was higher for the modified still after 12:00 h due to the integration of paraffin, ferrite magnets and graphite plates – which helped the modified still to achieve better productivity over the conventional still.

4.1.6. Variation of hourly yield and daily productivity

The hourly and daily productivity comparison of the conventional and modified still is depicted in Fig. 10. The hourly yield of the conventional still was slightly higher than the modified still till 12:00 h. After 12:00 h, the hourly yield of the modified still exceeds the conventional still. The maximum hourly yield obtained for conventional and modified still was 0.6 and 0.7 kg/m^2/day, respectively contributing to a 26.6% enhancement in the modified still over the conventional still.

The results show that even in the late evening hours (i.e. from 17:00 h to 21:00 h), there was a constant hourly output achieved in the modified still. The evening time productivity of the conventional and modified still ranged from 0.3 kg/h to 0.02 kg/h and 0.6 kg/h to 0.1 kg/h, respectively. The daily average cumulative yield for the conventional and modified still was found to be 2 kg/m^2/day and 2.7 kg/m^2/day, respectively. The percentage increase in the average cumulative yield of the modified still accounted for 33% as compared to the conventional still. The cumulative yield of conventional and modified still was 3.4 kg/m^2/day and 5.5 kg/m^2/day, respectively. There was a 62% increase in the daily cumulative yield of the modified still as compared to the conventional setup. Evening time productivity (i.e. from 17:00 h to 21:00 h) for the conventional still was accounted for less than one liter whereas it was doubled (nearly 2 liters) for the modified still. There was a 235% increase in the yield observed during evening time in the modified still as compared to the conventional still. This variation was due to the fact that the magnetic field has a positive impact on the evaporation rate due to the change in hydration shells of the water in the modified still [86]. The magnetic field has increased the rate of evaporation, due to which the productivity enhancement was increased to 62%, compared to only 50.3% enhancement in studies using graphite and PCM but without any magnets [24]. This clearly indicates that a 12% increment in the enhancement was due to the magnetic field.

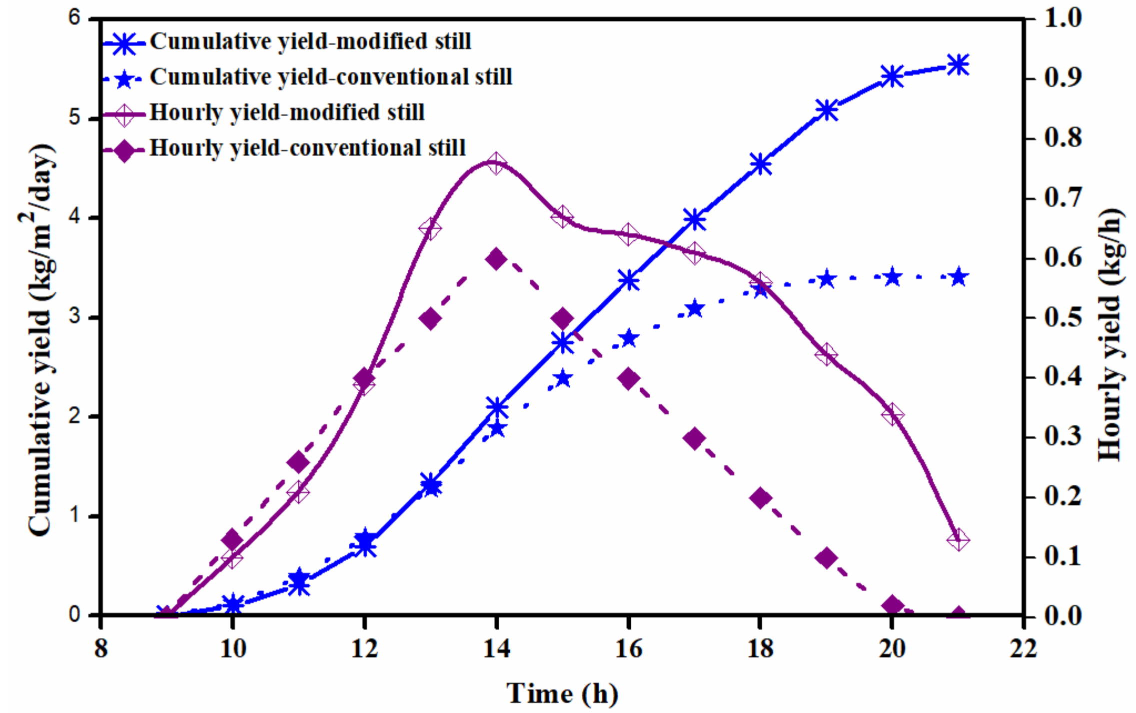

Fig. 10. Variation of hourly and cumulative yield for the conventional and modified still

Effective separation of salt from the water was possible when the solutions were circulated in a magnetic field. The variation in the hourly and cumulative yield was due to the addition of magnets which reduced the surface tension and increased the evaporation rate of the water. And, the integration of composite energy storage materials with the still acted as an additional heat source and helped to maintain the water temperature higher even during late evening and nocturnal hours. Thus, the variation in the hourly yield was because of the combined effect of composite energy storage and magnetizing effect by the thermal energy storage materials (paraffin and graphite plates) and ferrite magnets, respectively.

4.1.7. Productivity comparison of the present study with existing literature

A detailed comparison of the daily yield of the present study with the existing literature is summarized in Table 6. Shalaby et al. (2016) [67] used paraffin as the latent heat storage material under Egyptian climatic conditions and achieved productivity of 3.7 kg/m^2/day which was 46.2% lesser than the productivity of the present study. In the same year, Mousa and Gujrathi (2016) [62] also have performed their study using paraffin as the latent heat storage material in Oman and obtained a daily yield of 2.1 kg/m^2/day which was 61.8% lesser than the productivity achieved by the current study. Rufuss et al. (2018) [27] performed experiments using nanoparticles i.e. titanium dioxide and copper oxide enhanced paraffin under Indian climatic conditions and achieved a daily yield of 4.9 kg/m^2/day and 5.2 kg/m^2/day, respectively which are 4% and 11.3% lesser than the productivity of the present study. Kabeel et al. (2019) [68] have experimented with both latent and sensible heat energy storage materials i.e. by using paraffin and black gravel, respectively under Egyptian climatic conditions and reported a daily yield of 3.2 kg/m^2/day which was 40.5% lesser than the present study's productivity. Diwakar et al. (2020) [56] and Sharshir et al. (2020) [87] have, respectively used gravel coarse aggregate and linen wicks with carbon black nanoparticles as sensible heat storage materials and achieved a daily cumulative yield of 4.2 kg/m^2/day and 5.2 kg/m^2/day, respectively corresponding to 31% and 4.3% less yield than the current study.

To summarise, the productivity of the current study (5.5 kg/m^2/day) is greater than previous results, due to the combined effect of magnets and composite energy storage materials.

Table 6. Productivity comparison of the present study with the existing literature (where data are provided)

Sl. No	Authors and references	Type of energy storage techniques	Type of Energy storage material	Location	Productivity (kg/m^2/day)
1	Shalaby et al. (2016) [67]	Latent heat energy storage	Paraffin	Egypt	3.76
2	Mousa and Gujarathi., 2016 [62]	Latent heat energy storage	Paraffin	Oman	2.1
3	Rufuss et al., [27]	Latent heat energy storage	Paraffin and CuO nanoparticle	India	5.28
4	Diwakar et al. (2020) [56]	Sensible heat energy storage	Gravel coarse aggregate	India	4.21
5	Rufuss et al., 2018 [27]	Latent heat energy storage	Paraffin enhanced with TiO_2 nanoparticles	India	4.94

6	A.E. Kabeel et al. 2019 [68]	Latent heat and sensible heat energy storage	Paraffin and Black gravel	Egypt	3.27
7	Sharshir et al., 2020 [87]	Sensible heat energy storage	linen wicks and carbon black nanoparticles	Egypt	5.26
8	Present study	Latent heat and sensible heat energy storage	Paraffin, Ferrite Magnets, Graphite plates	India	5.5

4.2.Economic investigations

The economic parameters such as capital cost, annual cost, salvage value, annual maintenance cost and cost per liter for the conventional and modified still were discussed in the following section. A detailed cost per liter comparison of the present study with the existing literature was also presented at the end of this section

4.2.1. Economic analysis

Various costs and economic parameters such as fixed annual cost (FAC), annual maintenance and operational cost (AMC), annual productivity (M), productivity percentage and cost per liter (CPL) associated with the experiments were calculated using the following formulae (Eqs. 1-9) suggested in the literature [27,88]

$$\mathrm{FAC} = \mathrm{P} \times \mathrm{CRF} \qquad (1)$$

$$\mathrm{SFF} = \frac{\mathrm{i}}{(\mathrm{i}+1)^{\mathrm{y}-1}} \qquad (2)$$

$$\mathrm{S} = 0.2 \times \mathrm{P} \qquad (3)$$

$$\mathrm{ASV} = \mathrm{SFF} \times \mathrm{S} \qquad (4)$$

$$\mathrm{AMC} = 0.15 \times \mathrm{FAC} \qquad (5)$$

$$\mathrm{AC} = \mathrm{FAC} + \mathrm{AMC} - \mathrm{ASV} \qquad (6)$$

where P, CRF, SFF, S, AC are the present capital cost, capital recovery factor, sinking fund factor, salvage value and annual cost, respectively. The capital recovery factor (CRF) and total years of operation (y) are assumed to be 0.17 and 10 years, respectively [27]. The average productivity (M) was calculated by

$$\mathrm{M} = \mathrm{c} \times \mathrm{n} \qquad (7)$$

where 'c' is the distillate yield per day and 'n' is considered to be approximately 250 days. The productivity percentage can be calculated using the ratio of the product of annual productivity and selling price of water ($0.2/l) to the annual cost [27]. Then, the cost per liter (CPL) of distilled water can be calculated by the ratio of annual cost and average annual productivity

$$\text{Productivity (\%)} = \frac{\text{Annual productivity } \times \text{selling price of the water}}{\text{annual cost}} \quad (8)$$

$$\text{CPL} = \frac{\text{AC}}{\text{M}} \quad (9)$$

The total cost acquired for the conventional and modified still was $82 and $126, respectively which includes the cost of the basin, stand, insulation, adhesives, glass cover, magnets (for modified still only), graphite plate (for modified still only), paraffin (for modified still only), paints and fabrication costs (see details in Table 7). The total cost of the modified still was 55% greater than the conventional still, due to the integration of ferrite magnets, graphite plates and paraffin which contribute to 4.7%, 24% and 6.3%, respectively in the total cost of the modified still. The largest cost component (up to 24%) corresponded to the graphite plates, because of the manufacturing complexity associated with the graphite material. Thus, it is summarized that even though there was a 55% increase in the total cost of the modified still as compared to the conventional still, the other economic parameters like cost per liter and annual productivity are duly important for arriving at a decision about the economic feasibility of the entire experiment.

The various costs associated with the conventional and modified still are shown in Table 8. The fixed annual cost (FAC) and salvage value were $22.2 and $25, respectively which contributed to a 54% increase in the value comparing the conventional still. The increase in FAC and salvage of the modified still was due to the direct accounting of present capital cost in calculating the FAC (see Eq. 1).

Furthermore, the present capital cost was directly proportional to the FAC and salvage value. The AMC of the modified still was 55.3% higher than the conventional still because of the integration of graphite plates and ferrite magnets. This also includes the additional maintenance area/operation cost on the inclusion of PCM materials (paraffin) underneath the basin. The average annual productivity of the modified still was significantly higher (62%) as compared to the conventional still due to the higher distillate yield per day in the modified still (5.5 $kg/m^2/day$) which confirms its advantage in terms of yearly performance. There was a 33% increase in the productivity percentage of the modified still in comparison with the conventional still contributing to 840% and 807%, respectively.

Table 7. Capital cost of the experiment (conversion rate of INR 74.76 per US$ was used)

Components	Conventional still (US$)	Modified still (US$)
Basin	25	25
Insulation	7	7
Stand	12	12
Transparent cover	8	8
Graphite plates	0	30
Ferrite magnets	0	6
Aluminium paint	3.31	3.31
Adhesive gum	2.65	2.65
Foam strap	4	4
Paraffin wax	0	8
Fabrication cost	20	20
Total cost	82	126

Table 8 shows that the CPL of conventional and modified still was $0.018 and $0.017, respectively. The CPL of the modified still was 3.7% lower than the CPL of the conventional still. Even though the total cost of modified still (See Table 7) was 55% higher than the conventional still, the CPL was 3.7% lesser for the modified still as against the conventional still. This variation was due to the combined accounting of annual cost, maintenance cost and average annual productivity in arriving at the CPL. Thus, the modified still gives economically cheaper water as compared to the conventional still. The comparison of CPL of the present study with the existing literature is certainly important to quantify the obtained result and hence the following section compares the CPL of the current study with the literature.

Table 8. Cost analysis of modified still with integrated sensible and latent heat energy storage in comparison with conventional still

Parameters in US$	Conventional still	Modified still
Present capital cost (P)	81	125.9
Capital Recovery Factor(CRF)	0.17	0.17
Fixed Annual Cost (FAC)	14.3	22.2
Salvage value(S)	16.2	25.1

Sinking Fund Factor (SFF)	0.04	0.04
Annual Salvage Value (ASV)	0.7	1
Annual Maintenance Operational Cost (AMC)	2.1	3.3
AC (Annual Cost)	15.7	24.5
M (Average Annual Productivity) in liters	850	1375
Productivity (%)	807.6	840.5
CPL (Cost of distilled water Per Liter)	0.018	0.017

4.2.2. Cost per liter comparison of the present study with existing literature

Table 9 compares the cost per liter (CPL) of the present study with the existing literature. The CPL of the present study was $0.017 which was found to be 78%, 81%, 40%, 37%, 32%, 87%, 71%, 6%, and 0.8%, respectively cheaper than the CPL of freshwater from the solar still with paraffin [67], wick [67], paraffin [60], titanium dioxide nanoparticles enhanced paraffin [27], copper oxide nanoparticles enhanced paraffin [27], graphene oxide enhanced paraffin [27], gravel coarse aggregate [56], paraffin with black gravel [68] and linen wicks with carbon black nanoparticles [87]. This huge range of the percentage difference (min: 0.3% and max: 78%) in the CPL of the present study with other studies may be due to the capital cost of the studies, which includes fabrication cost, availability and price of the materials required for fabrication (basin material, insulation and stand) in the respective location during the year of experimentation. Also, the difference may be due to the rate of interest and years of operation assumed for the economic analysis.

Thus, it is concluded from the above assessment that the CPL of the modified still is considerably cheaper. The main reason is the combined stimulus of the improved daily yield and an annual yield of the modified still due to the integration of magnets, graphite plates and PCM materials.

Table 9. Comparison of CPL of the present study with the existing literature (where data are provided)

Sl. No	Authors and references	Type of energy storage technique	Type of energy storage material	Country	CPL ($)
1.	Shalaby et al., 2016 [67]	Latent heat	Paraffin	Egypt	0.08
2.	Shalaby et al., 2016 [67]	Latent heat and sensible heat	Paraffin and wick	Egypt	0.09

3.	Kabeel and Abdelgaied., 2016 [60]	Latent heat	Paraffin	Egypt	0.03
4.	Rufuss et al., 2018 [27]	Latent heat	Paraffin	India	0.03
5.	Rufuss et al., 2018 [27]	Latent heat	Paraffin enhanced with TiO_2 nanoparticles	India	0.028
6.	Rufuss et al., 2018 [27]	Latent heat	Paraffin enhanced with CuO nanoparticles	India	0.026
7.	Rufuss et al., 2018 [27]	Latent heat	Paraffin enhanced with GO nanoparticles	India	0.13
8.	Diwakar et al. 2020 [56]	Sensible heat	Gravel coarse aggregate	India	0.06
9.	Kabeel et al., 2019 [68]	Latent heat and sensible heat	Paraffin and Black gravel	Egypt	0.01
10.	Sharshir et al., 2020 [87]	Sensible heat	linen wicks and carbon black nanoparticles	Egypt	0.01
11.	Present study	Latent heat and sensible heat	Paraffin, Ferrite Magnets, Graphite plates	India	0.017

4.2.3. Comparison of the CPL from the present study with the cost of bottled water in India

Generally, the cost of bottled water and the selling price of bottled water in India are $0.06 per liter and $0.22 per liter, respectively [27,89]. These values are 69% and 91.6% higher than the CPL of the freshwater obtained from the modified still studied here. Thus, the CPL from the modified still was 69% and 91.6%, respectively cheaper than the bottled water cost and typical selling price of bottled water in India.

4.3.Enviro-economic investigation

The enviro-economic analysis estimates the amount of carbon dioxide, oxides of sulphur and nitrogen emitted for a lifetime from the modified still (Eqs. 10-15). Furthermore, it gives the details about the total embodied energy of the system along with the details of the total carbon dioxide mitigated and the corresponding carbon credit earned. These parameters can be calculated by the following formulae suggested in the literature [90–93]. Various environmental parameters like total embodied energy, emissions (CO_2, SO_2, and NO), the total amount of CO_2 mitigated and the carbon credit earned from the modified still are discussed under the following section:

The total amount of CO_2 emitted for a lifetime is calculated using the following formula

$$\mathrm{CO_2 \text{ emitted for a lifetime} = \text{ Embodied energy } \times 1.58} \tag{10}$$

Similarly,

$$\mathrm{SO_2 \text{ emitted for a lifetime} = \text{ Embodied energy } \times 0.012} \tag{11}$$

$$\mathrm{NO \text{ emitted for a lifetime} = \text{ Embodied energy } \times 0.005} \tag{12}$$

The net carbon dioxide mitigated for the lifetime can be calculated using

$$\mathrm{Net\ CO_2 \text{ mitigation for lifetime}} = [(\text{Embodied energy (out)} \times \text{ n}) - \text{Embodied energy}] \tag{13}$$

where 'n' is the total number of years. The embodied energy of the system and the carbon credit earned by the system is calculated by

$$\text{Embodied energy (out)} = \frac{\text{Annual yield } \times \text{ latent heat}}{3600} \tag{14}$$

$$\text{Carbon credit earned } = \text{Net } \mathrm{CO_2} \text{ mitigation for lifetime } \times 9.99 \tag{15}$$

4.3.1. Total embodied energy

The embodied energy along with the concomitant energy density and mass of various materials used in the modified solar still [56,69,90–96] are tabulated in Table 10. The estimation of total embodied energy is necessary to estimate the CO_2, SO_2 and NO emissions and other enviro-economic parameters. The glass had a total mass of 1.1 kg with the highest energy density of 1127 kWh/kg as compared to the other associated components and it carried the embodied energy of 45 kWh. Mild steel stand, frame and clamp had the maximum embodied energy of 180.5 kWh due to the heavier mass (19 kg) and energy density (of 9.5 kWh/kg) of the individual structures. Both the basin and latent heat energy vessel beneath the basin were made up of aluminium with an equivalent mass, energy densities and embodied energy of 4 kg, 13.5 kWh/kg and 54.2 kWh, respectively. The basin liner had a mass of 0.2 kg with an energy density of 25.1 kWh/kg contributing to 1.6% of the total embodied energy (6.2 kWh/kg). The other components such as insulation gasket and insulators had a total energy density of 8.8 kWh/kg and occupied 2.2% of the total embodied energy. The enhancement techniques additionally used in the modified solar still are graphite plates, ferrite magnets and paraffin wax which contribute embodied energy of 25.4 kWh, 18.3 kWh and 0.48 kWh, respectively. Thus, arriving at the total embodied energy for the whole modified system (of

393.3 kWh) by the summation of the embodied energy of all the individual system components. The estimated embodied energy from this analysis will be taken as an input for estimating the various enviro-economic parameters in the rest of the enviro-economic analysis.

Table 10. The total embodied energy of the modified still [56,69,90–96]

Components	Mass (kg)	Energy density (kWh/kg)	Embodied energy (kWh)
Glass	1.1	11127	45
MS stand + Frame + Clamp	19	9.5	180.5
Basin (Aluminium)	4	13.5	54.2
Basin liner	0.2	25.1	6.2
Insulation gasket	1.8	3.3	5.9
Insulator	1.5	1.9	2.8
Graphite Plate (14 Nos)	2.8	9.0	25.4
Ferrite Magnets (10 Nos)	2	9.1	18.3
Latent heat energy storage material holder beneath the basin (Aluminium)	4	13.5	54.2
Paraffin wax	10	0.04	0.4
Total Embodied energy			393.3

4.3.2. Carbon dioxide emission, mitigation and carbon credit earned

Table 11 presents various details about the emissions (CO_2, SO_2, and NO), CO_2 mitigation, carbon credit, energy payback time and life cycle conversion efficiency of the modified still. The amount of CO_2, SO_2, and NO emitted for a lifetime from the modified still were found to be 621.4 Tonnes, 4.7 Tonnes and 1.9 Tonnes, respectively. The energy payback time will be lesser for the systems with low embodied energy since the embodied energy is directly proportional to the energy payback time and the net CO_2 mitigation. In summary, it is advisable to use materials with less embodied energy value to reduce emissions like CO_2, SO_2, and NO and minimise the energy payback time.

Table 11. Carbon dioxide emission, CO2 Mitigation, Carbon credit earned and energy matrices for the modified still

Sl. No	Parameters	Values
1	Embodied energy	393.3
2	Emission of CO_2 for lifetime	621.4

3	Emission of SO_2 for lifetime	4.7
4	Emission of NO for lifetime	1.9
5	Net carbon dioxide mitigation during 10^{th} year (in Tonnes)	13
6	Carbon credit earned during 10^{th} year (in US$)	130
7	Net carbon dioxide mitigation during 15^{th} year (in Tonnes)	19.8
8	Carbon credit earned during 15^{th} year (USD)	198
9	Energy payback time (Years)	0.4
10	Energy production factor	2.1
11	Life cycle conversion efficiency	0.2

4.3.3. Carbon dioxide Mitigation

The net CO_2 mitigated from the modified still is presented in Fig. 11. Carbon dioxide mitigated increased from 6.2 Tonnes to 40.2 Tonnes over the years (i.e. from 5 years to 30 years), respectively. Also, there was a constant increase of 7 Tonnes in the net CO_2 mitigated in the current year over the preceding year.

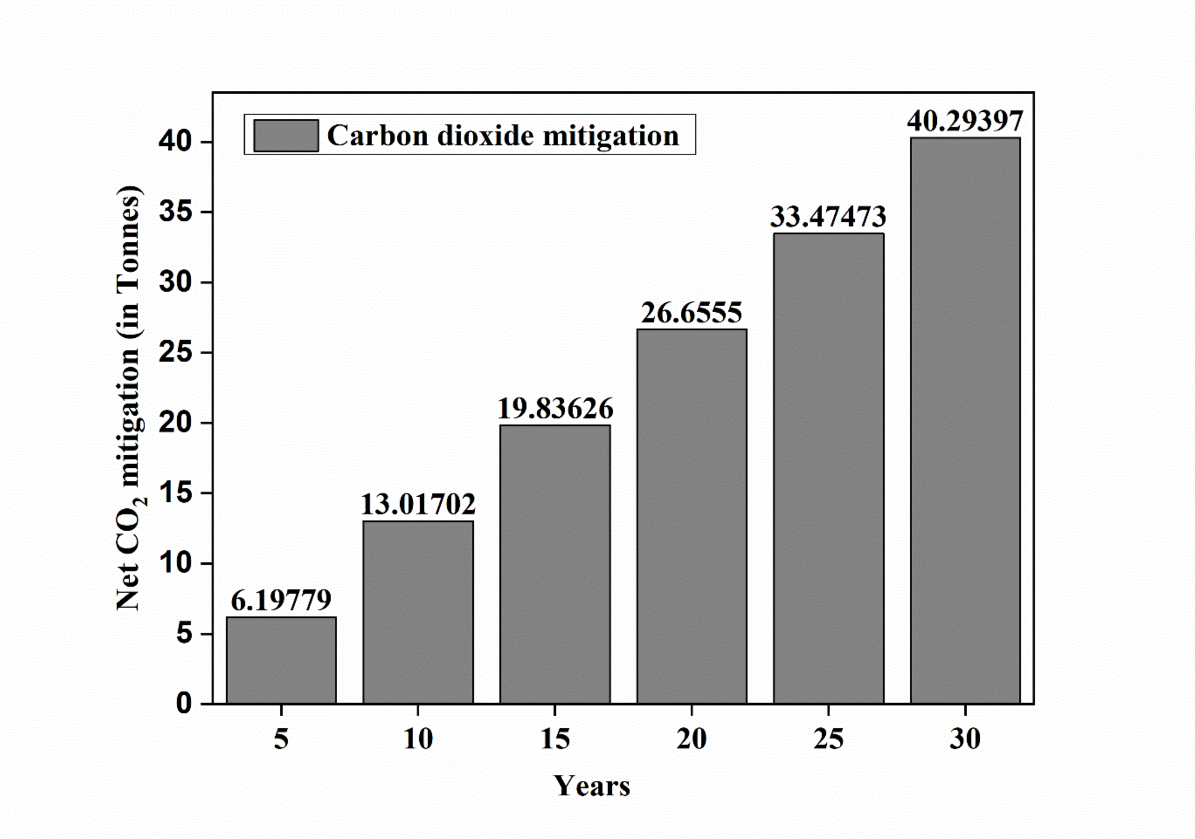

Fig. 11. Yearly variation of the net carbon dioxide mitigated from the modified still

There was a 110% increase in the net carbon dioxide mitigated for the first five years (6.2 Tonnes) as compared to net CO_2 mitigated for the tenth year (13 Tonnes). This percentage further reduced to 52.4%, 34.3%, 25.5% and 20.3% at the end of the 15th, 20th, 25th, and 30th years, respectively corresponding to a net CO_2 mitigated value of 19.8 Tonnes, 26.6 Tonnes, 33.4 Tonnes and 40.2 Tonnes. Ideally, for a solar desalination system, the average total number of years can be considered as 15 years [91] and citing that, at the end of the 15th year, the total CO_2 mitigated from the modified still of the present study will be 19.8 Tonnes.

4.3.4. Carbon credit earned

The overall carbon credit earned for the modified still in the present study is shown in Fig. 12. The carbon credit is the net amount of CO_2 mitigated which can be sold for monetary value. The carbon credit earned for the mitigation of 6.2 Tonnes (during 5th year), 13 Tonnes (during 10th year), 19.8 Tonnes (during 15th year), 26.6 Tonnes (during 20th year), 33.4 Tonnes (during 25th year) and 40.2 Tonnes (during 30th year) of carbon dioxide was \$61, \$130, \$198, \$266, \$324 and \$402, respectively.

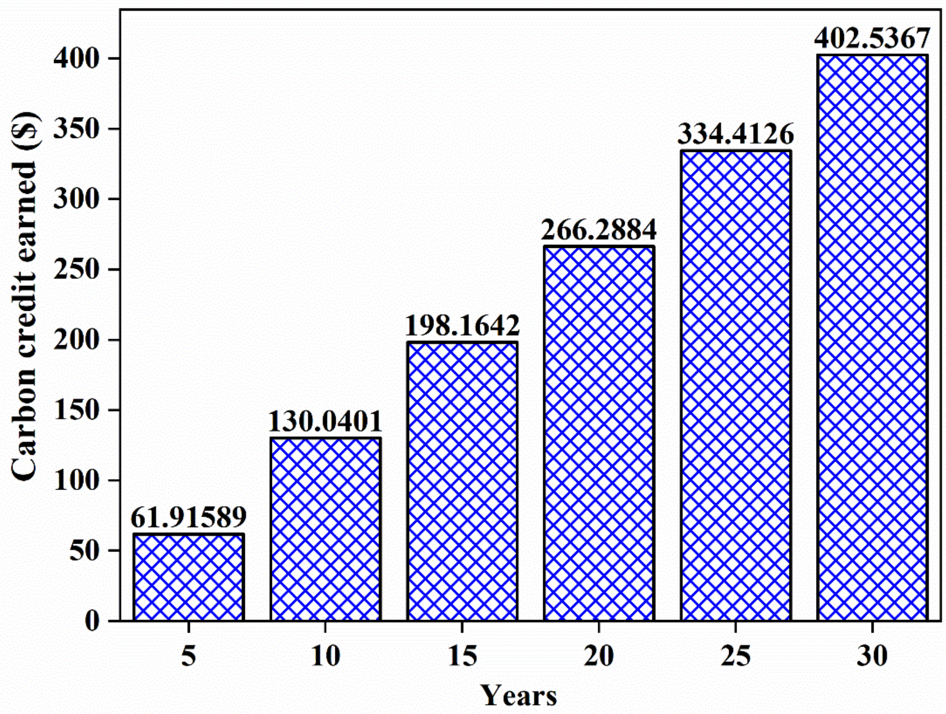

Fig. 12. Yearly variation of the carbon credit earned for the modified still

Thus, the modified still with paraffin, graphite plates and ferrite magnets used in the present study earns \$66 (on average) more than the credit earned in the present year in comparison with the credit earned after the preceding five years.

4.4. Energy matrices analysis

This section includes a discussion about the energy payback time, energy production factor and life cycle conversion efficiency. The various components of energy matrices include energy production factor, energy payback time and life cycle conversion efficiency (Eqs. 16-18). The energy matrices are calculated using the formulae suggested in the studies [56,90–93]. The energy payback time is the period that takes to repay the amount of energy used by the setup. The energy production factor is the inverse of energy payback time.

$$\text{Energy payback time} = \frac{\text{Embodied energy}}{\text{Amount of energy production per year}} \quad (16)$$

Energy production factor is calculated by the formula given below

$$\text{Energy production factor} = \frac{\text{Amount of Energy produced per year}}{\text{Embodied Energy}} \quad (17)$$

The life cycle conversion efficiency can be calculated by

$$\text{Life cycle conversion efficiency} = \frac{\text{Net carbon dioxide mitigated for lifetime}}{\text{Annual solar energy} \times \text{life span of the system}} \quad (18)$$

Parameters like energy production factor, energy payback time and life cycle conversion efficiency are used in energy matrices. A system with higher embodied energy will consume more energy and in turn emits a higher amount of CO_2 to the atmosphere which results in increasing the energy payback time [56,90]. The energy payback time and energy production factor for the modified system were found to be 0.4 years (5.4 months or 164 days) and 2.1, respectively (Table 12). The year-wise life cycle conversion efficiency of the modified solar still is shown in Fig. 13.

The maximum life cycle efficiency achieved for the proposed modified still was 0.52 at the end of the 30th year. The life cycle conversion efficiency of the modified still during the 10th, 15th, 20th, 25th, and 30th year was found to be 0.17, 0.26, 0.34, 0.43 and 0.52, respectively contributing to an increase of 52%, 30%, 29% and 20% in the life cycle conversion efficiency of the modified still for each year, respectively over the preceding five years.

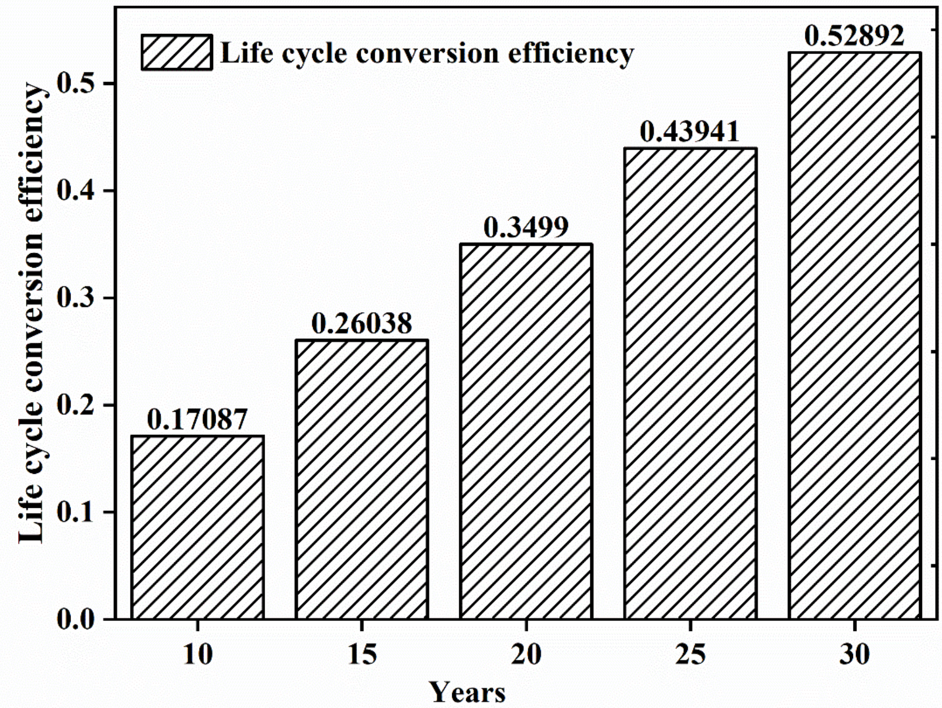

Fig. 13. Yearly variation of life cycle conversion efficiency of the modified still

Table 12. Energy Matrices Analysis

Sl.No	Energy Matrices	Values
1	Energy payback time (Years)	0.45
2	Energy production factor	2.19
3	Life cycle conversion efficiency	0.26

4.5.Water quality test

To estimate the quality of water after desalination, the desalinated water was tested for various quality test parameters. If these quality parameters exceed the safety limits, it may lead to various problems like gas bubbles, heart illness, lung infection, skin disease, laxative effect, somatic damage to the living tissues and neuro affliction in humans [97]. Hence, testing of the water quality after desalination is inevitable. The quality of water before and after desalination was tested at the Environmental and Water Resource Laboratory, VIT University, Vellore, India, and the results are shown in Table 13. The results are compared against the maximum permissible limits of drinking water as per the Bureau of Indian Standards (BIS), New Delhi, India and World Health Organisation (WHO) standards.

Table 13. Comparison of the quality of the water before and after desalination

Water quality parameters	**Before desalination**	**After desalination (conventional still)**	**After desalination (modified still)**	**Maximum permissible limits of the drinking water according to BIS** [98] **and WHO** [98,99]
pH	7.7	7.3	6.9	8.5
TDS (ppm)	330	150	51	500
Hardness (mg/L)	254	81	41	200
Dissolved oxygen (%)	78	62	46	60
Fluoride (mg/L)	1.9	0.9	0.3	1.5
Chloride (mg/L)	31.4	19.3	16.2	250
Electrical conductivity (μs/m)	637	389	227	1500
Calcium ions (mg/L)	29.7	14.3	8.2	200
Magnesium ions (mg/L)	33	9.4	3.7	200
Sodium ions (mg/L)	372	8	1.5	400
Potassium ions (mg/L)	95	3.7	2	250
Sulphate ions (mg/L)	37	3	1.2	12

The pH value of the desalinated water was reduced from 7.7 (saline water) to 7.3 for the conventional still and further to 6.9 for the modified still. There was a 5.4% decrease observed in the pH of the modified still as compared to the conventional still. The total dissolved solids in the desalinated water were reduced from 330 ppm to 51 ppm for the modified still contributing an 84.5% decrease. There was a 66% decrease in the TDS observed in the modified still as compared to the conventional still. The hardness of the conventional still is found to be 81 mg/L which is decreased from 254 mg/L (in saline water) contributing to a percentage decrease of 68%. There was a further decrease of 83% observed in the hardness of the desalinated water from the modified still. The percentage of dissolved oxygen in the saline water was 78% and after desalination, the percentage was reduced to 62% and 46% for the desalinated water in the conventional and modified still, respectively contributing a 20.5% and 41% decrement from the original value. There was a significant reduction observed in fluoride and chloride ions of the desalinated water (0.3 mg/L and 16.2 mg/L) from modified still as compared to saline water (1.9 mg/L and 31.4 mg/L) corresponding to an 84% and 48% decrease from the initial corresponding values.

There was a decrement of 66% and 16% in the fluoride and chloride content of the desalinated water from the modified still, respectively as compared to the conventional still. Similarly, there was a 71%, 88%, 99%, 97% and 96% decrement observed in the calcium, magnesium, sodium, potassium and sulphate ions, respectively in the modified still as compared to the initial value (saline water). Comparing with the conventional still; modified still showed a 42%, 60%, 81%, 45% and 60% decrease in calcium, magnesium, sodium, potassium and sulphate ions, respectively. This decrease in the salt ion has considerably reduced the electrical conductivity of the modified still to 64% and 41% as compared to the saline water and desalinated water in the conventional still.

All the test parameters of the desalinated water sample are within the permissible limits as prescribed by the Bureau of Indian Standards (BIS), New Delhi, India and World Health Organisation (WHO) standards [98,99].

5. Future research potential

The literature shows that the integration of high thermal energy storage materials in solar still needs a judicial selection of material. The material should possess high thermal conductivity, latent heat and it should be environmentally benign. For example, the performance of CNT and their derivatives in solar still would be good enough to use in desalination applications. However, CNT is more dangerous to humans because of their noxious nature, dispersion property and toxic characteristics. Hence, the discovery of an eco-friendly energy storage material would be an important breakthrough. Literature suggests that marine biological shells are one such eco-friendly energy storage material. The use of waste biological shells may earn some revenues to countries that rely on seafood. Hence, it is suggested to research the use of such materials like crab shell, sea shell and oyster shell particles [100] as future energy storage materials in desalination applications. In addition, future research should be carried out into optimising the geometrical arrangement of the magnets and the magnetic field strength.

6. Conclusion

Experimental investigations on the effects of integrated composite thermal energy storage (both sensible and latent heat) and magnetizing effects (ferrite magnets) were investigated on single slope solar still and compared against the conventional still. Economic analysis, enviro-economic analysis and energy matrices analysis were also performed. Furthermore, the desalinated water quality was also tested and compared with the BIS standards. Based on the experiments, the following conclusions were drawn:

The cumulative yield of the modified still was enhanced to 5.5 kg/m^2/day from 3.4 kg/m^2/day (for a conventional still) contributing to a 62% increase in productivity. The evening time productivity (from 17:00 h to 21:00 h) of the modified still increased by 235% due to the addition of integrated energy storage materials and ferrite magnets. The modified still yielded the highest annual productivity of 1375 liters as compared to the conventional still.

The cost per liter (CPL) of the purified water from the modified still was $0.017, which was 3.7% less than the CPL of the purified water from a conventional still. The CPL of freshwater from the modified still was 69% cheaper than the cost of bottled water cost in India. The life cycle conversion efficiency of the modified still was found to be 0.26 and 0.52 at the end of the 15^{th} and 30^{th} years, respectively. There will be 19.8 Tonnes and 40.3 Tonnes of carbon dioxide mitigated from the modified still at the end of the 15^{th} and 30^{th} year, respectively earning a carbon credit of $198 and $402. The water quality test reassures that the quality of the desalinated water is under the permissible limits of the Bureau of Indian Standards (BIS).

The study concludes that the integration of ferrite magnets, graphite plates and paraffin together in a solar still enhanced the performance of the desalination system from technical, economical, enviro-economic perspectives. Thus, the modified still is recommended as a potential candidate in solar desalination application as it outperforms the conventional still in all the aspects (technical, economical, enviro-economic aspects).

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