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Photothermal performance of nanofluids: An experimental study on direct absorption solar energy conversion using graphene oxide and its binary composites for water purification☆

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ABSTRACT

Water scarcity affects two-thirds of the world's population and is one of the most important challenges to human development. Nanotechnology led by solar evaporation is emerging to solve water resource problems by absorbing solar energy to vaporize nanofluid samples, especially in areas where seawater resources are abundant and economical. For this purpose a direct absorption solar collector set-up was constructed to measure evaporation rate under natural solar light, a pyranometer to measure light intensity, a K-thermocouple system to measure temperature and digital balance to measure mass loss. Then, nanofluids were prepared using a standard two-step method, and characterized using scanning electron microscopy and ultraviolet–visible spectroscopy. Photothermal experiments were carried out by weight concentrations (0.02 % and 0.03 %) for ∼ 5h each sunny day. The photothermal performance and specific absorption rate (SAR) of graphene oxide–zinc oxide (GO–ZnO) and graphene oxide–iron oxide (GO–FeO) nanofluids at different mixing ratios were investigated. The contribution of sensible heat based efficiency and evaporative based efficiency was revealed in context of photothermal efficiency. An increase in photothermal efficiency and a decrease in specific absorption rate (SAR) were observed with increasing nanoparticle concentration. 92 % photothermal conversion efficiency in the case of pure (100 %) GO at 0.03 wt% was obtained which is the highest among all the nanofluids used in this work. The best photothermal performance of pure (100 %) GO was achieved due to maximum solar absorption, dark color, highest thermal conductivity and excellent dispersion stability. Such results suggest that the direct adsorption of GO-based nanoparticles to support solar energy conversion may have various promising applications such as clean water production where there is abundant solar energy potential.

Introduction

Currently, with the world's population and industrial development, energy consumption is increasing day by day, whereas existing energy resources are starting to be exhausted [1]. With the rapid increase in population, energy resources known as renewable are considered to be a cheap source of energy to encounter the required energy needs. Among them, the energy generated by natural sun rays is called solar energy, which is the best solution to fulfill the energy requirement in various application sectors. [2]. However, harvesting energy from natural sunlight is challenging [3]. So, for this purpose, various solar thermal collectors capture the sun's rays coming from the natural sun [4]. Solar thermal energy involves harnessing the sun's power to generate thermal energy, which is appropriate to different applications such as

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mechanical to produce steam for water desalination applications [5]. Conventional solar thermal collectors which is also known as surface type solar thermal collectors contain many thermal losses due to heat transfer processes. In this type of solar thermal collector, solar energy is captivated on the black plate and then transported to the nanofluid through heat conduction and convection processes; due to this, temperature losses occur between the plate and channel network where nanofluids are kept [6]. Thus, it is currently needed to produce a solar thermal collector that decreases heat losses and increases the captured energy from the sun. Therefore, a direct absorption solar thermal collector or volumetric-based thermal collector was proposed to reduce these heat losses using nanoparticle suspension and absorbing medium. The working principle of this type of collector is that nanofluids directly absorb the solar radiations from the natural sun. And it also has many advantages over a conventional solar thermal collector. It includes slight losses of heat, low thermal resistance, increased thermal conductivity, also more radiation capturing [7,8]. Thus, all these parameters help to improve this solar collector's overall performance. Volumetric solar thermal collectors achieve high temperatures due to two processes. The first is due to direct or volumetric absorption and the second is the tendency to trap solar radiation [9,10].

Water scarcity, which is a major problem and will affect nearly one-third of the world's total population in the near future [11]. Solar-powered evaporation processes are a promising technology for desalination of seawater (separate waste) to address water scarcity issues in coastal communities through clean evaporation [12]. It is considered to be one of the affordable and environmentally friendly technologies in these areas where sea water is available in abundance but not potable [13]. Although it is an effective, reliable, energy-saving and cost-effective solution to clean water scarcity, it presents several issues that still need to be addressed for large-scale global application [14]. The first problem is its high energy requirement [15] and the second problem is the low production of clean water [16], and the third problem is the maintenance of the system [17]. A fourth problem is that it can be expensive, requiring extensive plant construction and its maintenance on large scale [18]. 5th is that it is also very energy intensive where potential solar flux is limited, making it cost prohibitive in some regions [19]. The 6th problem is that there is also great difficulty in optimizing the solar purification technology to achieve adequate feasibility [20].

Nanofluids, which are mixtures of nanoparticles and base fluids, are considered promising for direct solar absorption with evaporation processes to overcome the current problems in solar desalination techniques [21]. High solar absorption of nanofluids-based solar vapors has been an important academic challenge [22]. Achieving consistent performance under diverse conditions is critical, further research is needed to improve suitable methods to address the low absorption of nanofluids [23]. Current studies have also reported the properties of various mono and hybrid nanofluids, such as solar absorption, dispersion stability, and viscosity to accelerate the evaporation processes for water desalination applications [24,25]. Previously, solar energy associated with evaporation process typically depended on concentrated light, which limited desalination applications for seawater [26,27]. Therefore, in order to optimize the application of solar nanofluidic systems, existing literature also reported that it is important to characterize and study the nanofluids to assess which ones are more efficient [28–30]. Several existing research works reported that composite nanofluids have outperformed mono-nanofluids in solar absorption applications which is useful for desalination of seawater. For example, Milanese et al.[31] Chen et al. [32], Yu et al.[33], Amjad et al.[34], Zeng et al. [35], Malah et al.[36], and Atisham et al.[37] reported the photothermal performance of composites nanofluids of antimony tin oxide-cupric oxide (ATO-CuO), silicon-multiwalled carbon nanotubes(Si-MWCNT), triethylene glycol and potassium doped carbon nanofiber (TEG- KCNF)), copper oxide-silver (CuO-Ag) composite, silicon dioxide-silver (SiO_2-Ag) plasmonic hybrid, ferrous oxide- titanium nitride (Fe_3O_4 −TiN), and copper oxide-aluminum oxide (CuO-Al_2O_3),respectively. All these research works have shown that composites nanofluids are more suitable than mono-nanofluids for testing the photothermal performance, which describes the ability of nanofluids to purify seawater by evaporation.

Solar distillation is a process that produces fresh water by directly evaporating seawater after absorbing sunlight. This process has been used for many years, usually for small-scale applications [38]. Traditional purification methods (such as reverse osmosis, forward osmosis, nanofiltration and electrodialysis) present serious concerns, including high energy consumption, environmental impacts, water quality concerns if chemical methods are used, high treatment and maintenance costs [39,40]. Solar energy is an excellent source of energy that is clean and environmentally friendly compared to traditional cleaning methods that require a lot of energy to run the process and also damage the ecosystem due to its emissions which are harmful to health. It emits no carbon gas, which helps reduce the effects of climate change [41]. Nanofluids are widely used to overcome the limitations of conventional cleaning techniques due to their unusual and unique properties. Current studies show that suitable nanofluids in solar collectors can increase the efficiency of thermal harvesting systems, allowing them to produce more energy with less input [17]. Suspended nanoparticles increase the surface area because of tiny size. Nanofluids with high surface-to-volume ratios have been found to be particularly promising for the preparation of nanofluids that are used to enhance solar absorption heat transfer due to their thermophysical properties [42]. Therefore, the integration of nanotechnology with solar energy for desalination of seawater through evaporation processes has opened up significantly higher efficiency possibilities. Better light absorption, better evaporation rates, and the ability to capture a wider range of solar radiation contribute to more efficient energy conversion to enhance seawater desalination [43,44]. Therefore, performance of nanoparticles based integrated desalination system using solar energy is adequate as compared to simple conventional systems. In various studies, Zhang et al. [45] used titanium nitride nanofluids and investigated that the photothermal efficiency depends on the evaporation rate and concentration of the nanofluids. The photothermal performance improved with the addition of more nanoparticle that demonstrated the potential of titanium nitride nanofluids for solar evaporation-based seawater purification. Analogous outcomes were also described by Beikher et al. [46] using gold/water and multiwall carbon nanotubes/water nanofluid. El-said et al. [47] investigated that nanofluid-based solar evaporation is a great addition to meet the needs of clean water production in arid regions. Syednezhad et al. [48] observed that the addition of nanoparticles to saltwater increases thermal conductivity, which is used to desalinate seawater. Ye et al [49] found that small additions of titanium oxide (TiO_2) nanoparticles increased solar energy absorption, reduced production costs and reduced toxicity in wastewater treatment. Various parallel studies, Rashidi et al. [21], Gajbhiye et al. [50], Sharshir et al. [43], Ohri et al.[51], Ai et al. [52],and Cao et al. [53] have reported that nanoparticles have played an important role in solar desalination techniques through evaporation to produce fresh water for people living in coastal areas. Several prior studies have shown that evaporation rate and evaporation efficiency are two crucial variables in assessing the efficacy of nanoparticles for solar desalination of saltwater. For example, Ni et al. used carbon black/water-graphene/water nanofluids and found an evaporation efficiency of 60 %. Lee et al. used silver titanium oxides (Ag-TiO_2/water) nanofluids and found an evaporation efficiency of 66.9 %. Wang et al. used multi-walled carbon nanotubes and 46.8 % evaporation efficiency was observed. Other similar studies such as Dao et al [54], Kabeel et al. [55], Peng et al. [56], Arunkumar et al. [57], Peng et al. [58], Bait et al.[59], Wilson et al. [60], and Hussein et al. [61] supported the effectiveness of nanofluid-based solar evaporators for portable water harvesting through evaporation processes.

An integrated evaporation of nanofluids through a direct absorption solar collector offers an innovative technique for the development of sustainable water purification due to minimal thermal losses. Direct absorption solar collection systems effectively capture sunlight through various nano-materials. This system not only increases the absorption of solar energy but also increases the conservation of solar energy which is called thermal efficiency. Direct absorption solar collectors are also called renewable energy systems due to their environmentally friendly solar energy capture efficiency. Various optimization methods such as ANN (Artificial Neural Network) and GA (Genetic Algorithm) have been found effective to enhance and improve the design performance of these renewable energy systems [62].These approaches are usually used to optimize hybrid-based systems by analyzing the complex interaction of nanofluids and solar light under different solar intensity conditions. These ANN and GA techniques have proven effective for calibration of operational based parameters that ensure optimum efficiency and effective cost reduction. Applying the same approach to direct absorption solar collectors using nanofluids provides a way to improve design and functionality, allowing the system to be widely adopted in water treatment applications. Furthermore, thermodynamics-based analysis emphasizes the optimization of nanofluids for solar energy systems. Advanced exergy and combined extended-advanced exergy analysis both explore the value of evaluating and improving energy system performance on a joint basis [63]. These analyzes are very interesting for describing energy losses, identifying inefficiencies and identifying areas where improvement is needed. Excellent thermal conductivity and good dispersion stability of nanofluids have been well documented by these advanced methods. These innovative methods offer significant opportunities to maximize the energy conversion of nanofluids using direct absorption solar collectors. With the integration of hybrid and booster-assisted designs, the efficiency and thermodynamic feasibility of the energy system are increased [64].Several research studies have demonstrated how design-assisted development has improved renewable energy systems such as solar power that efficiently meet energy demand. These boosters helped open new avenues for building direct absorption solar collectors to increase solar energy storage that can be used in water purification systems. These hybrid systems have increased efficiency in cooperation with different environmental conditions, which is especially important in regions where solar energy fluctuates. Moreover, reliability considerations play an important role in optimizing renewable energy systems in real-world applications [65]. A resilient system is required to ensure reliable performance of the energy system due to seasonal variations, operational constraints, etc. By applying this concept, a direct absorption solar collector design can be constructed that is useful for maintaining the stability and photothermal efficiency of nanofluids at different solar intensities and temperatures.

A survey of the existing literature reveals that solar water desalination using nanofluids is a new research field with many gaps that still need to be filled. One of the finest methods for harvesting solar energy is nanofluids' absorption of solar radiation to cause evaporation. This approach promises to produce fresh water in desert places with abundant solar energy. Nonetheless, their poor efficiency is a significant obstacle to optimizing and commercializing these energy conversion systems [66]. Widespread energy loss is a serious concern in conventional solar energy harvesting systems. The surface absorber in these systems absorbs solar radiation, transforms it into heat, and then transfers the heat energy to the fluid. As a result, significant radiation and traditional heat losses may result from the absorber temperature being much greater than the surrounding air temperature. Scientists are searching for ways to lower energy losses and boost solar energy harvesting efficiency, which has led to the proposal of several creative techniques. Experiments with existing nanofluids-based solar evaporation for seawater desalination have also shown that some operating problems with existing nanofluids such as their low optical absorption, high cost, low dispersion stability, lower bulk fluid temperature, low evaporation rate, low solar absorption, difficulty in the production process, and their different behavior under different climatic conditions during experimental study. Therefore, there is a need for the development of nanofluids that are low cost, more stable, and have higher absorption capacity and suitable collector to catch the solar rays with minimal losses.

To address the aforementioned issues, composite nanofluids (GO-ZnO, GO-FeO) at varying concentration mixing ratios were suggested and studied under natural sunlight. This research has also produced direct or volumetric solar thermal collection devices. This integrated volumetric solar thermal purification system can improve the system efficiency and reduce the levelized cost of water. Photothermal experiments were conducted outdoors for 5 h on each clear-sky day. This experimental work examined the photothermal transformation behaviour of GO-ZnO and GO-FeO with varying ratio of mixing at two weight concentrations (0.02 % and 0.03 %, respectively) in a direct absorption solar collector. The bulk fluid temperature was measured using three K-type thermocouples and the evaporation rate was determined using a digital weighing scale. Optical absorption, sensible heat efficiency, evaporation efficiency, photothermal conversion efficiency and specific absorption rate (SAR) were used for comparison and possible mechanisms were evaluated.

Materials and methods

Nanomaterials selection

Nanoparticles are an emerging topic of research these days because of their wide range of applications in every field, especially in heat transfer applications. The selection of nanomaterials for making composite nanofluids is very important to obtain the best properties such as uniform and fine particle size, low particle agglomeration, good stability in base fluids, high thermal conductivity, high specific heating value, high solar absorption and most important is low cost affordability. All these properties are essential for any research study using composite nanoparticles. The thermophysical properties of nanoparticles used to make (GO- FeO and GO- ZnO) composites are given in Table 1. By mixing these nanoparticles in water and then transferring the nanofluids to volumetric or direct absorption solar collectors, various samples of composite nanofluids were prepared to evaluate their ability to purify seawater. The composite nanoparticles used in this study have different thermophysical properties, because of this all composite nanofluids displays diverse temperature rise trends, different evaporation rates. Thermophysical properties which are density (ρ), thermal conductivity (κ), specific heat (Cp) are given in Table 1. On the basis of these properties, the nanomaterials are selected to form composites (GO-ZnO and GO-ZnO).

Preparation of nanofluids

Composite nanofluids at different concentration mixing ratios are prepared through two-step technique. In the initial step, composite nanoparticles (GO-ZnO and GO-FeO) are synthesized with hydrothermal approach, then these particles are dissolved in deionized water to form nanofluid samples using ultrasonication and magnetic stirring techniques which helps to avoid agglomeration of the nanoparticles [71]. For the synthesis of GO-ZnO nanocomposites using hydrothermal methods, ZnO nanoparticles, GO nanoparticles, and ethanol were used as starting materials. The required amount of GO is dissolved in 100 mL of ethanol and is defined as GO solution. The desired amount of ZnO nanoparticles was also mixed in 100 mL of ethanol and defined as ZnO

Table 1
Thermophysical properties of nanoparticles and base fluid to form nano-composite nanofluids.

Material	ρ ($kg\ m^{-3}$)	k ($Wm^{-1}\ K^{-1}$)	Cp ($kJ\ kg^{-1}\ K^{-1}$)	References
GO	2266	2000–5000	0.70	[67]
ZnO	5600	29	0.490	[68]
FeO	5730	2.20	0.440	[69]
DI water	1000	0.60	4.18	[70]

solution. Then these two solutions were uniformly mixed using technique of ultrasonication for one hour under constant stirring. Then transfer the mixture solution to a 100 ml Teflon-lined autoclave at temperature of 180 °C for period of 18 h for hydrothermal treatment. After the hydrothermal reaction, the mixture was cooled and the nanocomposites were assembled. Then, the collected precipitate was centrifuged to separate the solid nanocomposites from the rest of the composite solution and then washed for several times with ethanol and deionized water to clear the remaining residuals. Then, the final product was dried under temperature of 60 °C for 10 h in oven to obtain GO- ZnO nanocomposites. A similar hydrothermal method was used to synthesize GO-FeO nanocomposites.

For preparation of composite nanofluids (GO-ZnO and GO-FeO) samples with weight concentrations of 0.02 % and 0.03 %, 0.02 g, and 0.03 g of nanoparticles in 100 g of DI water with help of stirring processes. The sonication of combination then carried out till 60 min in before start of the photothermal performance experiment. Fig. 1 illustrates the two-step process [72] scheme for preparing the nanofluid in this study.

SEM Characterizations of nanocomposite at different concentration mixing ratios

The successful synthesis of GO-ZnO and GO-FeO nanocomposites at various weight mixing ratio was confirmed by the scanning electron microscope (SEM) images. Their size that was measured with IJ image software. SEM images GO-ZnO nanocomposites at different portion is given in Fig. 2 (a–e). 100 % ZnO-0 % GO nanoparticles showed spherical shapes having diameter of 49.65 nm and 100 % GO −0% ZnO nanoparticles showed a two-dimensional sheet like structure with an average length of 88.59 nm. GO-ZnO nanocomposites at different concentration mixing ratios show nanorod structures with spherical shapes. Their average length and average diameter are given in Table 2. As a result of the hydrothermal treatment during the synthesis process of GO-ZnO, ZnO was found to be spherically deposited on the surface of GO nanosheets which is clearly shown in the SEM image.

Morphological characterization of the nanocomposite containing (GO-FeO) at different mixing ratio given in Fig. 3(a-e) where Fig. 3 (a) displays that of 100 % GO −0% FeO nanoparticles with average length of 88.59 nm without the aggregation of particles and nanosheets shape was observed. Fig. 3 (e) shows the SEM image of 100 % FeO-0 % GO nanoparticles having average diameter of 52.79 nm with spherical shape. The GO-ZnO binary nanocomposites at different concentration mixing ratios show nanorod structures with spherical shapes. Nanocomposites display rod shape of spherical particles at different mixing weight rations. A synergistic effect between GO-ZnO and GO-FeO composites and declining GO amount was discovered to regulate the production of dimensional ZnO and FeO upon stabilization of ZnO and FeO structures in nanorod form.

During the experiment using SEM analysis, it was observed that all types of nanocomposites exhibit a size below 100 nm and reduce the probability of particle aggregation, which, in turn, highlights the nanoparticles as a potential candidate for developing nanofluids with good dispersion stability that is useful in absorbing more solar radiation for purification of seawater.

The average length, average diameter probes of GO-ZnO and GO-FeO nanocomposites are shown in Table 2, with particular attention to the properties noted at different mixing ratios. The results show that the GO-ZnO and GO-FeO nanocomposites exhibit better stability as indicated by the lower diameter and length values at different mixing ratios. The minimum size of GO-ZnO and GO-FeO nanocomposites is obtained at different mixing ratio. This finding is particularly important because it suggests that GO-ZnO and GO-FeO nanocomposites may find applications in many different fields. For example, it can be used to develop new materials that are useful in solar energy absorption applications to purify water through evaporation.

Experimental setup

The photothermal performance of the different composite (GO-FeO and GO-ZnO) nanofluids at various concentration mixing ratio were investigated under natural sunlight.

A petri dish with a diameter of 4 cm was employed for holding nanofluids samples. The bulk fluid temperature measurement was done with TC1, TC2 and TC3 thermocouples mounted at three representative depths at an angular position of 120°: TC1, TC2 and TC3 (omega 4TC-TT-K-35–35) measure the temperature of the nanofluids in contact with the top surface, middle surface and bottom surface of the sample. TC4 was used to measure ambient temperature. The natural sunlight irradiance was measured using a solar intensity meter i.e. pyranometer (SR30-D1). The evaporation rate was measured with a digital scale (Cornell, Germany). All photothermal experimental data were recorded with the help of data logger devices (NI SCXI-1303 Experimental setup to test the photothermal and vaporization performance of various composite nanofluids given in Fig. 4. To achieve steady-state heating of the nanofluids samples, Insulating material was applied against the away from sunlight and special thermocouple holders were used to avoid heat dissipation and ensure that the thermocouple top, middle and bottom are positioned correctly. The photothermal experiment was performed only on days with clear sky conditions. In order to obtain

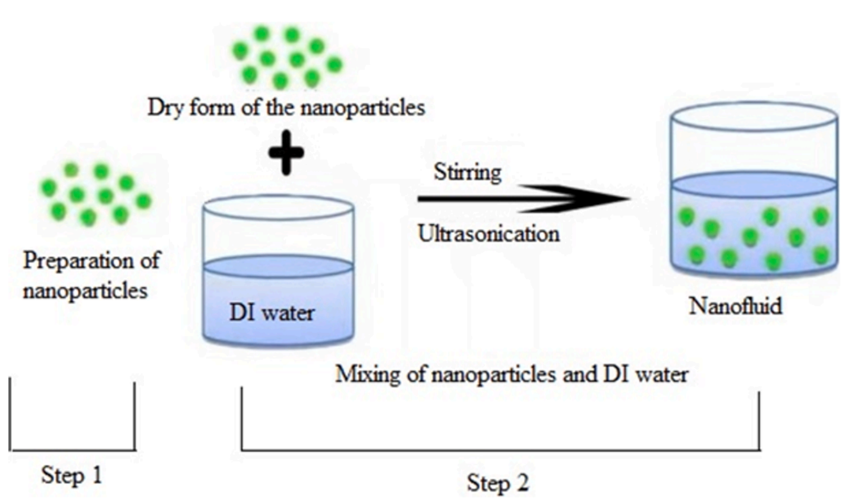


Fig. 1. Process to prepare the nanofluids using two step methods [72].

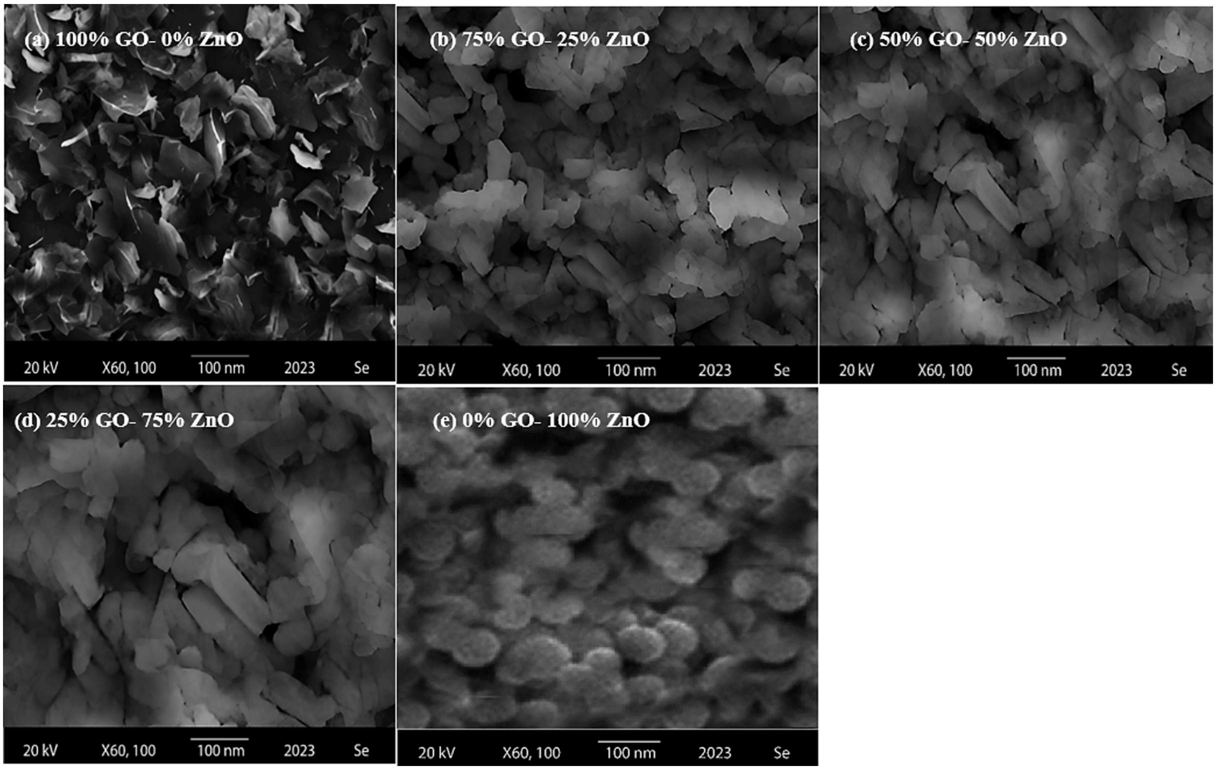


Fig. 2. The SEM images of GO-ZnO at different mixing ratio with 0.03 wt% concentration.

Table 2
Average diameter, length, of GO-ZnO and GO-FeO nanocomposites for various weight mixing ratio.

Sr. No.	Sample	Diameter (nm)	Length (nm)	Shape
1	100 % GO + 0 % ZnO	–	88.59	nanosheet
2	75 % GO + 25 % ZnO	49.05	91.89	nanorod
3	50 % GO + 50 % ZnO	47.26	90.19	nanorod
4	25 % GO – 75 % ZnO	45.52	89.08	nanorod
5	0 % GO + 100 % ZnO	49.65	–	spherical
6	75 % GO + 25 % FeO	51.97	92.42	nanorod
7	50 % GO + 50 % FeO	49.61	92.78	nanorod
8	25 % GO + 75 % FeO	47.92	94.02	nanorod
9	0 % GO + 100 % FeO	52.79	–	spherical

accurate and precise photothermal experimental data, all types of composites nanofluids were continuously tested for four days at constant concentrations. The stability of the composite nanofluids was determined using UV–visible spectroscopy as described in Section 3.1. Photothermal experiments were performed for different composite nanocombinations (GO-FeO,GO-ZnO) at altered mixing ratio using direct solar absorption collector for solar desalination with 0.02 wt%, and 0.03 wt%, concentrations. Table 3 presents the photothermal experimental settings for GO-FeO and GO-ZnO composite nanofluids at 0.02 wt% concentrations. Each sample has a different quantity of GO. Still, because different amounts of the other nanoparticles (FeO and ZnO) were utilized in this study, the overall number of hybrid nanoparticles stayed constant.

A similar matrix of nanofluid samples was followed to perform the photothermal experiment for 0.03 wt%. Only the amount of nanoparticles is different which is 0.03 g.

This research work clearly demonstrated the effect of nanoparticle concentration (0.02 wt% and 0.03 wt%) and time on photothermal performance for composite (GO-ZnO and GO-FeO) nanofluids with different mixing ratios. Key metrics analyzed include: temperature rise over time (measured using a Type K thermocouple) described in Section 3.2; The mass loss of the nanofluid samples due to evaporation (measured with a digital scale) is shown in Section 3.3. The efficiency based on sensible heat and the efficiency based on evaporation and the photothermal efficiency (according to Equations (1), 2, 3) are described in Section 3.4, respectively. Specific absorption rates (calculated using Equation (4) are described in Section 3.5. This study investigates that as the nanoparticle concentration increases from 0.02 wt% to 0.03 wt%, it enhances solar absorption and photothermal efficiency. The study also observed the effects of time on moss loss due to evaporation and temperature rise. This research study not only focuses on concentration and time but also considers other effects on objective factors or variable parameters including ambient temperature, solar radiation (insolation), wind speed, and dispersion stability. Ambient temperature: The ambient temperature was observed to be almost constant in this study during the photothermal experiments. This ensures that differences in ambient temperature do not significantly affect the results of this practical study. Solar Irradiance (isolation): Fluctuations in the intensity of solar energy are observed. However, in this experimental study, average solar irradiance was used to calculate evaporation efficiency, sensible heat efficiency, photothermal efficiency and specific absorption rate. Solar radiation was measured using a pyranometer. Wind Speed: Wind speed is not considered in this work. But, it can cause thermal loss through the convection mode of heat transfer which can slightly affect the temperature and mass loss readings. Dispersion stability: The dispersion stability of all nanofluids used in this study was evaluated by UV–visible spectrometry and visual inspection. A visual inspection method ensures that there is no nanoparticle sedimentation in the base fluid (DI water). UV–visible spectroscopy provides a platform to note the optical absorbance versus concentration of nanoparticles. The optical absorption of all nanofluids used is enhanced with increasing concentration of nanoparticles. This confirmed the Barrett-Lambert law which shows that all nanofluids are stable.

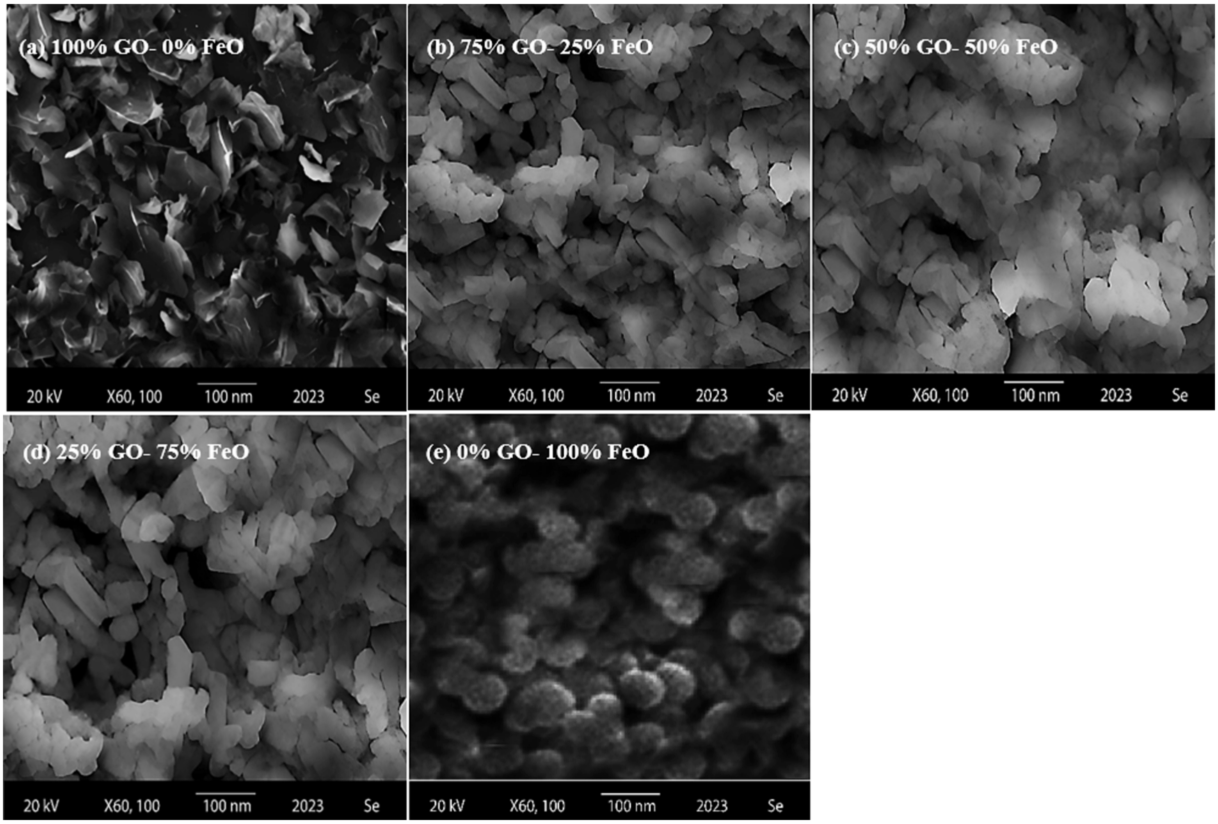


Fig. 3. The SEM images of GO-FeO at different mixing ratio with 0.03 wt% concentration.

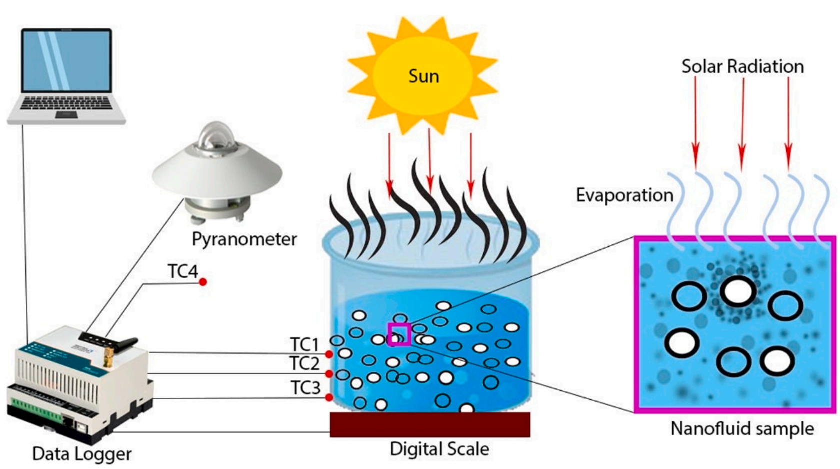


Fig. 4. Experimental setup to test the photothermal and vaporization performance of various composite nanofluids.

Results and analysis

Uv–visible absorption spectra and stability investigation of nanofluids

The composite nanofluids with high optical absorption are applicable for solar absorption application. The efficient absorption of composite nanofluids indicates optimal solar absorption in natural sunlight to generate heat which is interconnected with photothermal applications. This is why optical absorption using UV–visible spectroscopy is essential to evaluate absorption properties of composite nanofluids. The optical absorption spectra of different composite (GO-FeO and GO-ZnO) nanofluids at different concentration mixing ratio with 0.02 wt% and 0.03 wt% concentration is given in Fig. 5 and Fig. 6 respectively. Composite nanofluids (GO-ZnO) containing both ZnO, and GO nanoparticles with 0.02 wt% and 0.03 wt% concentration is given in Fig. 5(a, b). The 100 % GO-0 % ZnO nanofluid sample consists entirely of GO which represents pure graphene oxide displayed maximum absorbance. 75 % GO – 25 % ZnO sample shows that the presence of ZnO reduces the absorption because ZnO does not absorb light as strongly as GO. The 50 % GO – 50 % ZnO sample contains equal amounts of GO and ZnO and the optical absorption is affected by both nanoparticles. Since ZnO does not absorb light as strongly as GO. Therefore, this 50 % GO – 50 % ZnO sample shows a lower absorption value compared to 100 % GO-0 % ZnO and 75 % GO – 25 % ZnO. In 25 % GO – 75 % ZnO, the optical properties of ZnO are more dominant than those of GO, but still GO affects the absorption. Higher amounts of ZnO lead to lower overall absorption

Table 3
Various composite nanofluids at different concentration mixing ratio.

S. No.	Samples/%	Weight of GO /g	Weight of ZnO /g	Weight of FeO /g	Sample Concentration/ wt. %
1	100 % GO	0.02000	0.00000	–	0.02
2	75 %GO + 25 % ZnO	0.00750	0.00250	–	0.02
3	50 %GO + 50 % ZnO	0.00500	0.00500	–	0.02
4	25 %GO + 75 % ZnO	0.00250	0.00750	–	0.02
5	100 % ZnO	0.00000	0.02000	–	0.02
6	75 %GO + 25 % FeO	0.00750	–	0.00250	0.02
7	50 %GO + 50 % FeO	0.00500	–	0.00500	0.02
8	25 %GO + 75 % FeO	0.00750	–	0.00750	0.02
9	100 % FeO	0.00000	–	0.02000	0.02

in 25 % GO − 75 % ZnO compared to samples with higher GO content. The 0 % GO − 100 % ZnO nanofluid sample consists entirely of ZnO nanoparticles. ZnO can absorb UV light at a different wavelength than GO and because of the wide band gap, ZnO does not absorb light more strongly than GO in the visible region. The decreased value in optical absorbance is attributed to the different absorbance of GO and ZnO in (GO-ZnO) with decreasing GO content. As ZnO grows in (GO-ZnO) and GO decreases in that ratio, it shows the dominance of ZnO, which cannot absorb light as strongly as GO, causing the nanofluidic samples as a whole less absorbent of light. Optical absorption of GO −ZnO composites with 0.03 wt% concentration is given in Fig. 5 (b), which provides evidence that the optical absorbance increases with increasing concentration. A higher optical absorbance was obtained at 0.03 wt% for (GO-ZnO) nanofluids at different mixing ratios than the optical absorbance obtained at 0.02 wt%.

Fig. 5(c, d) shows absorption peak for GO-FeO at different mixing ratio of GO and FeO at 0.02 wt% and at 0.03 wt% concentration. In both composite at various mixing proportion, 100 % GO showed highest optical absorption at both 0.02 wt% and 0.03 wt% concentrations. 100 % GO nanofluids achieved a significant optical absorption compared to all other composite (GO-FeO and GO-ZnO) nanofluids at different concentration mixing ratio in this study, demonstrating the potential of GO −based nanofluids in absorption of solar energy which can be used to purify the seawater through evaporation processes. This is because of carbon-based structure with sp2 bonding network, π-rich electronic structure, unique optical band gap, dark color, good suspension in base fluids, high optical absorption, high thermal conductivity, excellent dispersion stability. Moreover, the 2-D honeycomb structure, other functional groups containing oxygen atoms such as hydroxyl groups, epoxy groups, and carboxyl groups and its unique electronic structure with unique bandgap make it a highly light absorbing material.

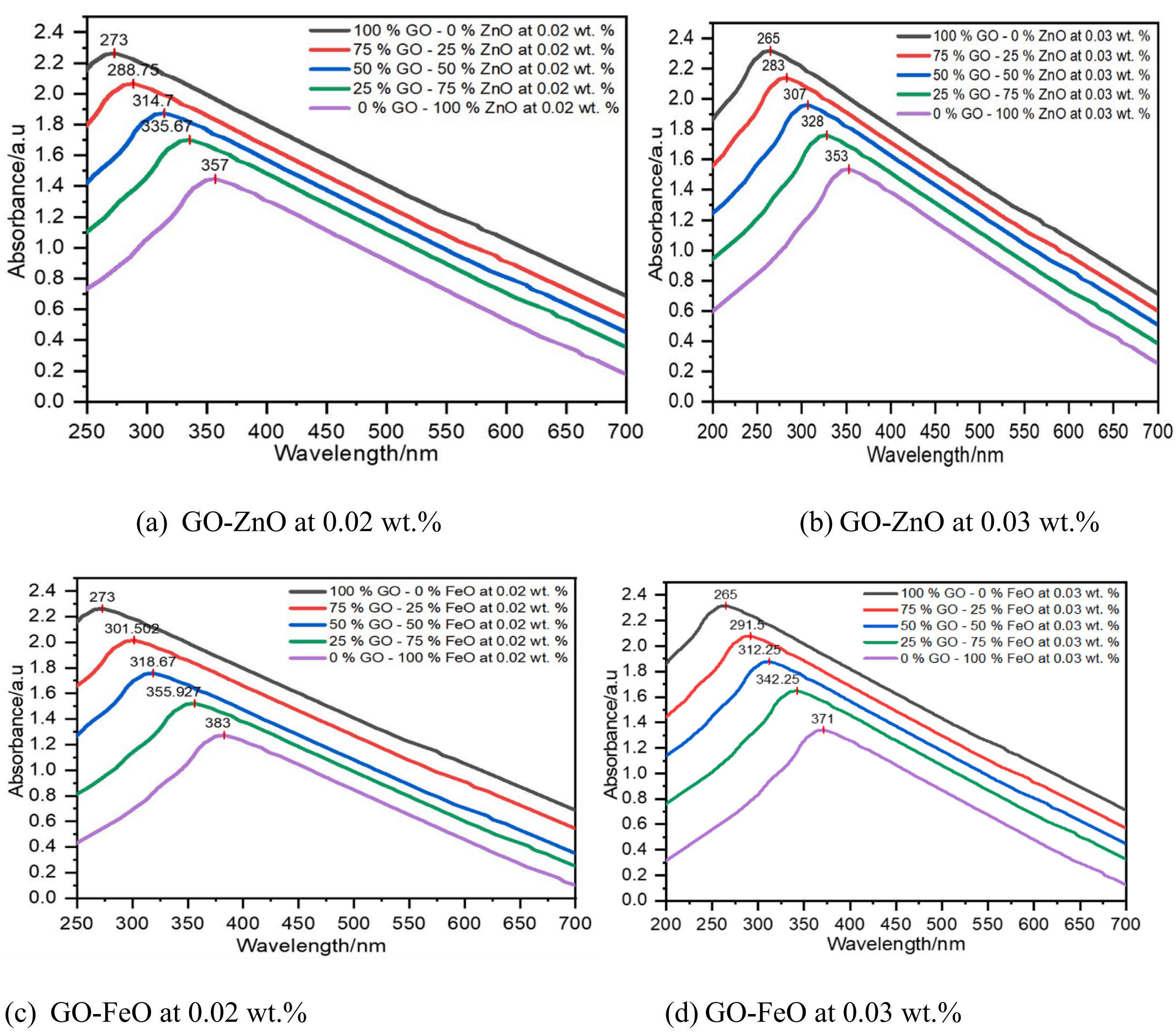
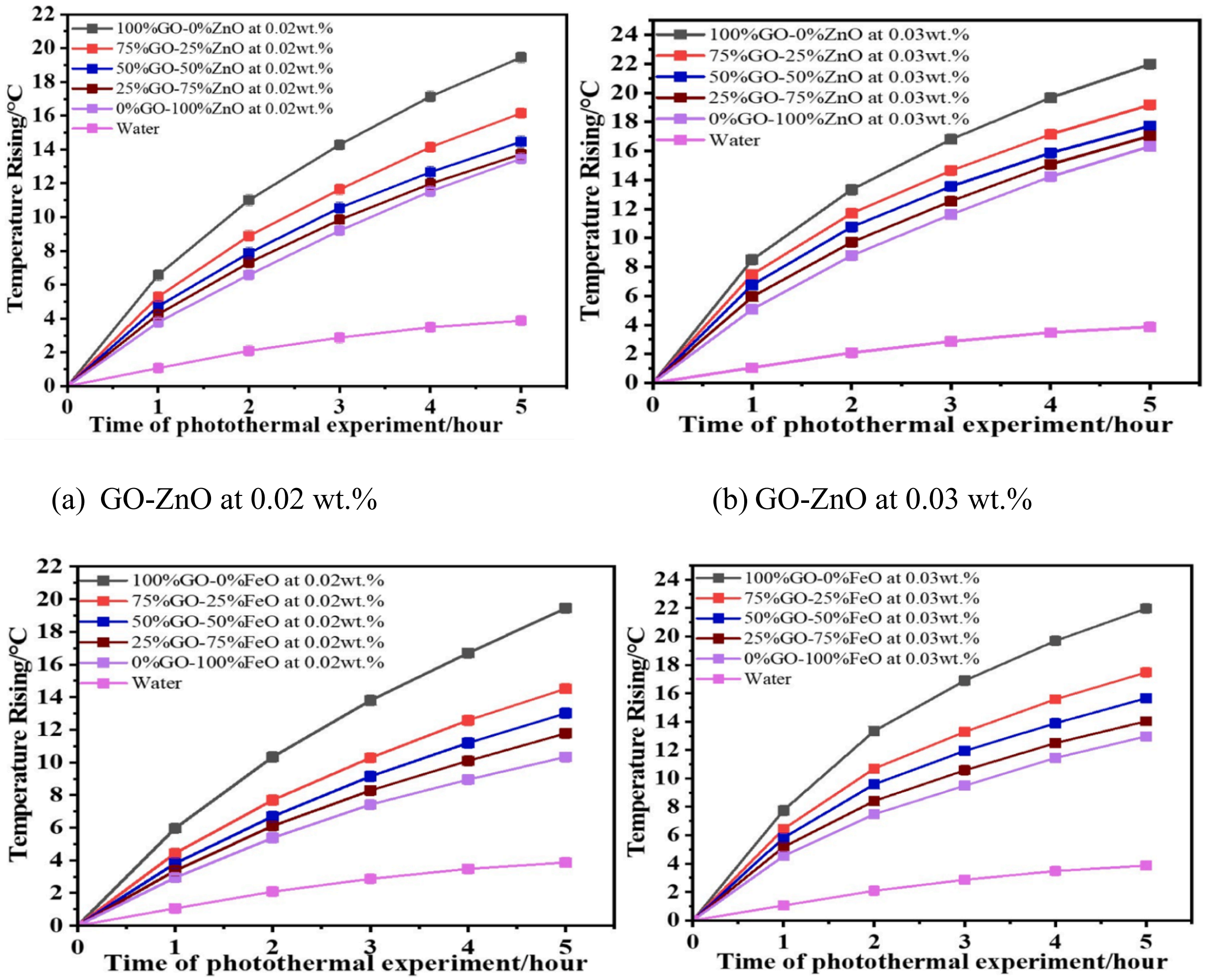


Fig. 5. Optical absorption of GO-FeO, GO-ZnO composite nanofluids with different mixing ratio at 0.02 wt% and 0.03 wt% concentration.



(a) GO-ZnO at 0.02 wt.%

(b) GO-ZnO at 0.03 wt.%

(c) GO-FeO at 0.02 wt.%

(d) GO-FeO at 0.03 wt.%

Fig. 6. Average temperature rising of GO-FeO, GO-ZnO composite nanofluids with different mixing ratio at 0.02 wt% and 0.03 wt% concentration.

Dispersion stability of nanofluids is defined as nanoparticles capabilities to remain in suspended position in a base fluid without agglomeration or settling over time. In GO-FeO and GO-ZnO composite nanofluids at various concentration mixing ratios, it is found that the absorbance values increase with enhance in weight concentration indicating better dispersion stability of GO-FeO and GO-ZnO, also indicates less accumulation of particles. To test the dispersion stability of GO-FeO and GO-ZnO composite nanofluids using UV–visible spectroscopy, the Beer-Lambert principle is used. Beer-Lambert's principle states that the concentration of nanoparticles is directly related to the absorption of samples of nanofluids. A higher optical absorbance value, indicating higher stability and inhibition of nanoparticle aggregation, is explained by increasing nanofluid concentration with increasing nanofluid absorbance. Fig. 5 represents the UV–visible absorption spectra of GO-FeO and GO-ZnO nanofluids at different mixing ratio with 0.02 wt% and 0.03 wt% concentration.From this Fig. 5 it can easily see that, the optical absorption of GO-FeO and GO-ZnO composite nanofluids increased with increasing concentration which satisfies Beer-Lambert's principle so it is considered that all composites nanofluids in this study are stable.A pure (100 %) GO showed the maximum optical absorbance. For this reason, graphene oxide (GO) nanofluids are considered more reliable as compared to all nanofluids in this work.

The optical absorption properties and stability of different composites combinations were noted using Shimadzu 1800 Japanese spectrometer with a wavelength range of 200–1000 nm. Stability was analyzed using the Beer-Lambert law, which expresses the relationship between absorption and concentration. Their linear relationships indicate well-stabilized nanoparticles in base fluids. (GO-ZnO and GO-FeO) composite nanofluids with various mixing propotion show different absorption trends. 100 % GO showed a strong absorption peak at 273 nm with 0.02 wt% concentration and 265 nm at 0.03 wt% concentration. 100 % ZnO showed an absorption peak at 357 nm with 0.02 wt% concentration and 353 nm at 0.03 wt% concentration. 100 % FeO showed an absorption peak at 383 nm with 0.02 wt% concentration and 371 nm at 0.03 wt% concentration. Moreover, different mixing ratios of composite nanofluids presented different absorption peaks. In both nanofluids, the absorbance declined as declining amount of graphene oxide. It was also noted that the absorbance of composites nanoparticles increased with the concentration increased from 0.02 wt% to 0.03 wt%. The strongest absorption peak in 100 % GO compared to 100 % ZnO and 100 % FeO makes it efficient in light absorption of UV light. Higher optical absorption with increasing concentration is due to higher nanoparticle density which enhances scattering and light interaction. GO proved to be the dominant nanoparticle in both combinations. Lower concentration of GO in both nano-composites leads to lower absorption efficiency. GO has also been shown to be a good candidate for improving light absorption in both mixtures, which have been described to absorb more light in the UV–visible spectrum. GO is an excellent absorber of optical lights due to its exceptional dispersion stability, high thermal conductivity and strong absorption in a wide range of wavelengths especially in the UV region. All these properties make GO nanofluids excellent candidates for solar absorption applications. ZnO and FeO showed relatively low optical absorption because their thermal conductivity, diffusion stability, and absorption properties are not as high as GO, leading to lower efficiency.

Evaluation of bulk fluid temperatures for nanofluids

A bulk-fluid temperature technique was used to assess the capabilities of composite nanofluids for solar absorption to evaluate photothermal efficiency. The average temperature rising of different composite nanofluids (GO-FeO and GO-ZnO) with various mixing proportion at 0.02 wt% and 0.03 wt% concentrations has been evaluated under natural sun for the period of five hours using a direct solar thermal collector.

The temperature rise profiles at concentrations of 0.02 wt% and 0.03 wt% for two distinct composite nanofluids (GO-FeO, GO-ZnO) with varying mixing ratios are shown in Fig. 6(a-d). Experimental research revealed that the concentration mixing ratio of the nanoparticles significantly influences the average temperature rise of composite nanofluids (GO-FeO, GO-ZnO). Furthermore, a high ZnO/FeO ratio in individual nanoparticles reduced the overall temperature rise. According to the experimental results, as ZnO and FeO concentrations rose, for the composite nanofluids of GO-FeO and GO-ZnO, the average temperature rise first climbed and then decreased. The binary nanocomposites of GO-FeO and GO-ZnO performed better than the individual components FeO, ZnO, and water at concentrations of 0.02 and 0.03 wt%, respectively.

The increase in average temperature rising for GO-FeO, GO-ZnO was obtained at particle concentration of 0.03 wt% concentrations which is shown in Fig. 6(c-d) as compared to temperature rising at 0.02 wt% concentrations. It shows that temperature rising increases with increase the concentrations. It means higher concentration allows more absorption. The maximum average temperature rising was found in the case of 100 % GO at 0.03 wt% concentrations due to the maximum absorption amongst all the composite (GO-FeO, GO-ZnO) nanofluids at different concentration mixing ratio using direct solar absorption collector for solar desalination. The following three properties of GO are also responsible for the increase in temperature (1) GO has a carbon-based structure (2) the carbon nanostructures and dark color of GO are responsible for enhancing its solar absorption (3) Excellent dispersion stability of this nanoparticle in water due to oxygen atoms attachment.

An increase in temperature is observed in both composites with various mixing proportion at (0.02 wt% and 0.03 wt%) concntrations. The average temperature decreases with time as GO concentration decreases and ZnO, FeO increases. There are several reasons for the decrease in temperature rise trends. The first reason is the low thermal conductivity of zinc oxide and iron oxide than that of graphene oxide, which lowers heat transfer capability, leading to a decrease in thermal efficiency due to their content in both nano-composites. High thermal conductivity of GO helped towards increase heat transfer capacity of GO compared to zinc oxide and iron oxide. The second reason is that strengthening effect of GO is reduced by the growth of zinc oxide and iron oxide nanoparticles in both hybrid nanofluids. This attenuation effect reduces the overall solar absorption from natural sunlight. The third reason is related to particle aggression. The high content of metal oxides (ZnO and FeO) nanoparticles in GO-ZnO, GO-FeO enlarges the particles which reduces the surface area available for solar absorption, further reducing the solar absorption efficiency. The fourth reason is related to the coordination effect that describes the interaction of GO with ZnO and FeO. This complex interaction reduces the synergy effect which increases the heat transfer capabilities. When GO interacts with metal oxides (ZnO and FeO) nanoparticles, ZnO and FeO inhibit the ability of GO to interact with solar radiation. Because of this, the overall solar absorption of the nanofluid is reduced. Despite these challenges, GO-ZnO and GO-FeO binary nanofluids outperformed DI water due to the synergistic effect of GO with different mixing ratios. GO's strong solar absorptivity, highest thermal conductivity, highest surface area to absorb photons, least particle aggressiveness, efficient interaction of solar radiation, excellent heat retention properties make it an efficient absorber of solar energy. ZnO and FeO have low thermal conductivity, moderate solar absorption, low dispersion stability, low heat retention, low surface area, and low UV light absorption, making them less efficient nanoparticles in energy absorption and heat retention than GO.

Mass loss (evaporation rate) of nanofluids

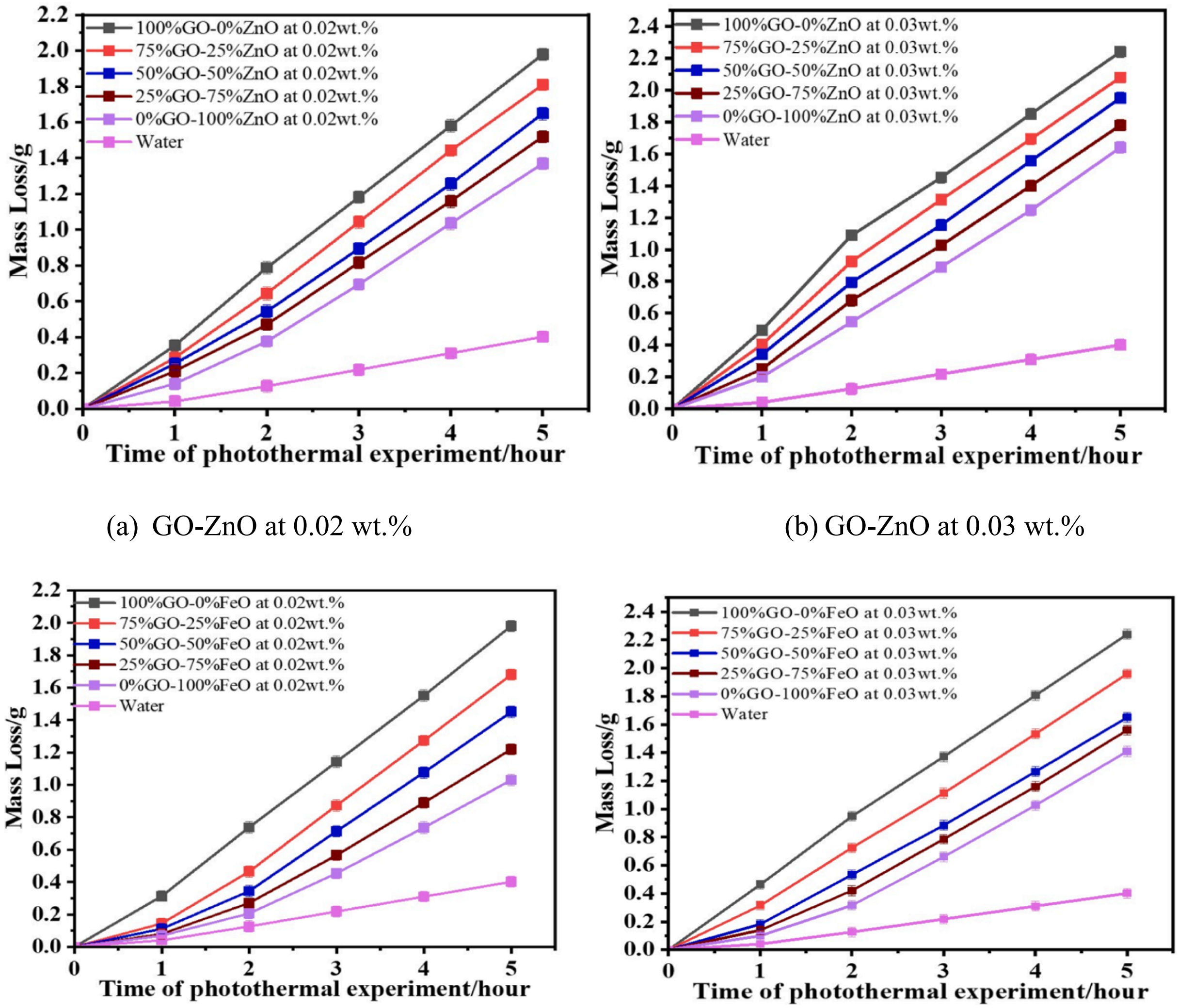
The nanofluids capabilities for solar energy harvesting can be assessed by considering mass loss of nanofluids samples and evaporation efficiency under natural sun. Nanofluids efficiently absorb solar radiations and generate the steam or vapors is interrelated to photothermal performance. That's why mass loss due to evaporation is compulsory for solar absorption evaluations. In binary nanofluids of (GO-FeO, GO-ZnO) 100 % GO at 0.02 wt% concentrations, showed the maximum mass loss due to evaporation in comparison with all other nanofluids samples as shown in Fig. 6 (a, b). In the nanofluids sample of (75 % GO-25 % ZnO, 75 % GO-25 % FeO) due to presence of FeO and ZnO mass loss reduces which is not an effective absorber of solar energy than pure graphene oxide (GO) samples in both of nanocomposites.

The nanofluid sample of (50 % GO-50 % ZnO,50 % GO-50 % FeO), both GO, FeO and GO, ZnO equally participated in solar absorption which is described by mass loss due to evaporation. But graphene oxide (GO) still gives a prominent mass loss in both of combination due to evaporation but the contribution of FeO and ZnO reduced the overall mass loss as compared to 100 % GO and 75 % GO-25 % ZnO, 75 % GO-25 % FeO. In 25 % GO-75 % ZnO, 25 % GO-75 % FeO sample, ratio of graphene oxide (GO) more decreases and amount of FeO and ZnO increases. Because of this, mass loss in this sample is decreased but not prominent as in those sample where GO has higher concentration mixing ratio. In the mixture of 100 % ZnO and 100 % FeO, graphene oxide (GO) is not present, only FeO and ZnO nanoparticles are existing which shows minimum mass loss due to less solar absorption which is not as strong as graphene oxide (GO). As a result, the overall mass loss and evaporation efficiency for 100 % ZnO and 100 % FeO sample is observed due to least solar absorption under natural solar flux.

Fig. 7 (a-d) shows that as amount of GO is decreases the amount of FeO and ZnO increases the mass loss is decreases in various maxing ratio of GO, ZnO and GO, FeO in respective binary combination at 0.02 wt% and 0.03 wt% concentrations. Different samples of GO-ZnO, GO-FeO have different mass loss trend under natural sun due to evaporation. The mass loss profile exaggerated through several aspects such as the interaction of sun radiations with material nature, its band gap, and electronic structure as well.

The mass loss due to evaporation is directly dependent on the concentration. As the concentration of GO-ZnO, GO-FeO increases leading to an increase in the mass loss. Due to this binary nanofluids of GO-ZnO, GO-FeO at 0.03 wt% showed higher mass loss in comparison of 0.02 wt %. At higher concentrations, more absorbing nanoparticles are present in the sample which increases absorbing capacity of solar radiations and causes more evaporation. Due to more evaporation more, mass loss was found. Higher concentrations of nanofluids (0.03 wt% concentrations) enhance the mass loss from the evaporation of samples of nanofluids under natural solar flux because higher concentrations of nanoparticles increase the particles' availability for interface with the solar radiations. Solar absorption from the sun causes mass loss in nanofluid samples, which is influenced by the interactions between GO, ZnO in GO-ZnO, and GO, FeO in GO-FeO samples. The combined action of GO, FeO in GO-FeO, and GO, ZnO in GO-ZnO increased solar absorptivity. The basic structures of FeO, ZnO, and GO also have a major impact on solar absorptions.

Because of carbon-based electronic structure, 100 % GO exhibits maximal mass loss. Its high surface area, high thermal conductivity, and



(a) GO-ZnO at 0.02 wt.% (b) GO-ZnO at 0.03 wt.%

(c) GO-FeO at 0.02 wt.% (d) GO-FeO at 0.03 wt.%

Fig. 7. Average mass loss of GO-ZnO, GO-FeO composite nanofluids with different mixing ratio at 0.02 wt% and 0.03 wt% concentration.

superior absorption of solar radiation further contribute to increased evaporation. GO has good thermal conductivity, its carbon-based atomic structure and its covalent bonding with various functionalizing groups. The sp2-based structure, the π-rich electronic structure is responsible for its good performance in solar absorption.

The reduction of mass because of evaporation of GO-ZnO and GO-FeO nanofluids at concentrations (0.02 wt% and 0.03 wt%) can be explained by several factors. With high solar absorptivity and high thermal conductivity, GO exhibited optimal mass losses resulting in efficient absorption and evaporation rate. ZnO and FeO showed low mass loss due to moderate solar absorption and low thermal conductivity. Low solar absorptivity and low thermal conductivity reduce the ability of ZnO and FeO to absorb and transmit solar radiation, leading to less evaporation. It was also observed that as the concentration of nanoparticles increased from 0.02 wt% to 0.03 wt%, mass loss increased because of better absorption of sunlight. The mass loss of GO-ZnO and GO-FeO nanofluids with various mixing proportions decreases with decreasing GO and increasing ZnO and FeO. This is due to the accumulation of particles that reduce the surface area for solar absorption, thereby limiting heat transfer efficiency. Less solar absorption produces less mass loss due to evaporation. Moreover, the synergistic effect describes the interaction of GO with ZnO and FeO, which increases the efficiency of GO-ZnO and GO-FeO because presence of GO increases the overall solar captivation.

Photothermal conversion efficiency of nanofluids

Photothermal conversion efficiency is used to assess feasibility of nanofluids for desalination of seawater by evaporation. Sensible heat efficiency and evaporation efficiency are combined to form photothermal conversion efficiency. Evaporation efficiency can be calculated using equation 01 [73].

$$\eta_{(\text{evaporation})} = \frac{L_v m_{loss}}{I.A.t} \tag{1}$$

where *η (evaporation)* is evaporation efficiency, A nanofluid is expected to have the same latent heat of vaporization as water at one pressure atmosphere, represented by the symbol Lv. m_{loss} is evaporation rate of the nanofluid sample. A is surface area of the petri dish. I shows solar irradiance.t is the time of photothermal experiment under natural sunlight.

The sensible heating efficiency $\eta_{(sensibleheating)}$ describes the thermal sensitivity of nanofluids under natural sun lights and can be used for evaluation of the solar absorption by evaporation of nanofluid samples for desalination of seawater. The sensible heating efficiency can be calculated using equation 02 below [73].

$$\eta_{(sensibleheating)} = \frac{(C_w m_w).\Delta T}{I.A.t} \tag{2}$$

In equation (2), Water's specific heat capacity is Cw. m_W is the water's initial mass. Using three thermocouples, the average temperature change is calculated as $\Delta T = (\Delta TC1 + \Delta TC2 + \Delta TC3)/3$.

Equation 03, which adds the sensible heating and vapour production efficiency, is used to determine the further photothermal conversion efficiency. [73].

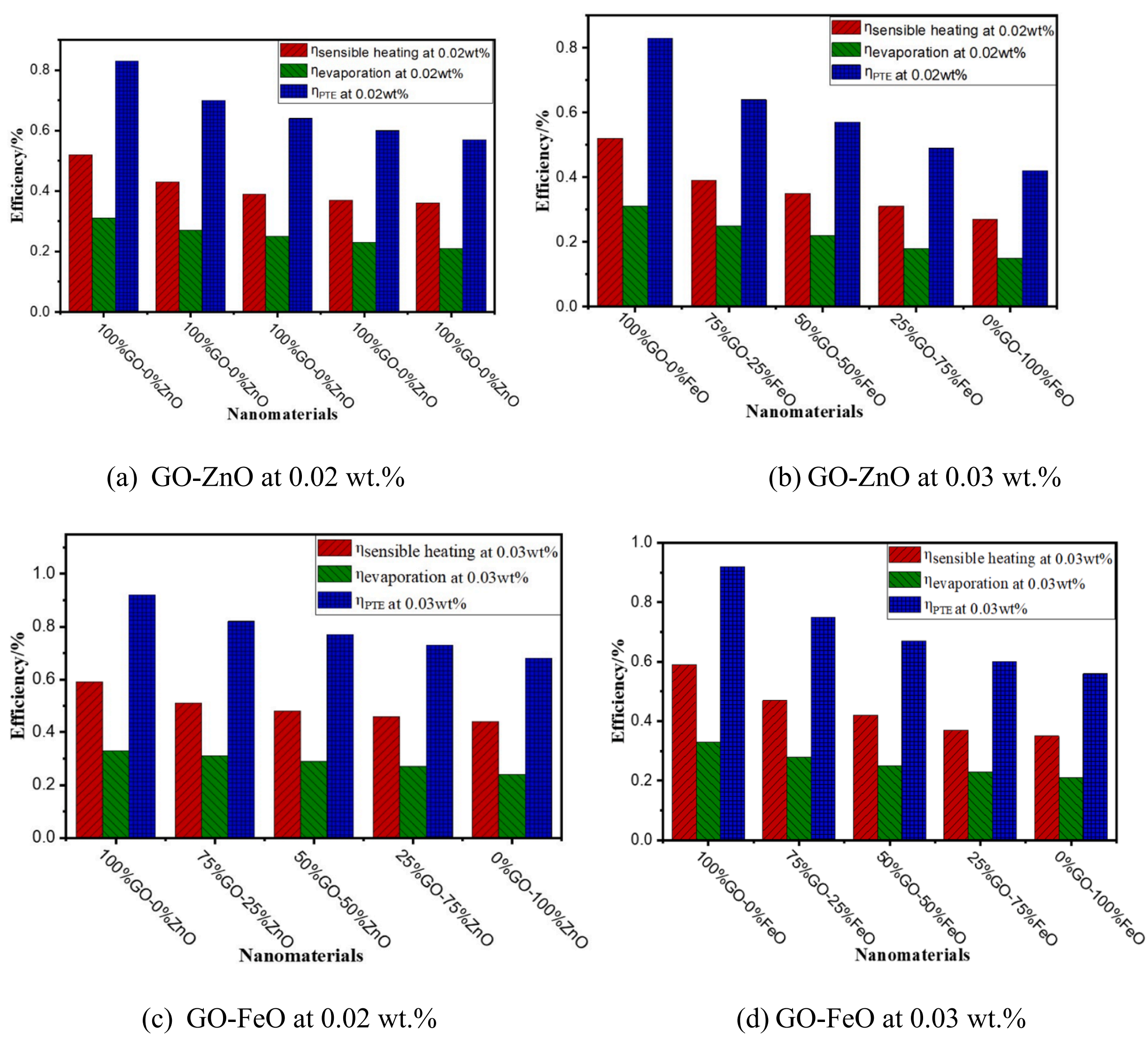
$$\eta_{PTE} = \eta_{(evaporation)} + \eta_{(sensibleheating)} \tag{3}$$

The sensible heat based efficiency and evaporative based efficiency, and photothermal conversion efficiency of two distinct nanofluids, GO-FeO and GO-ZnO, at varying mixing ratios with concentrations of 0.02 wt % and 0.03 wt%, are shown for five hours under natural solar irradiation in Fig. 8(a–d).

High sensible heat based efficiency and evaporative based efficiency, and photothermal conversion efficiency nanoparticles are considered stable and have a high potential for sun absorption because they are less prone to clump together. GO-FeO, and GO-ZnO, was shown to have greater sensible heat efficiency, evaporation efficiency, and photothermal conversion efficiency at concentrations of 0.02 wt% to 0.03 wt%.

This shows that the solar absorption is also depends on concentration of nanoparticles which increases with increasing concentration which is also consistent with Beer-Lambert's law (A = εcl), which states that the solar absorptivity and particle concentration show a direct relationship. On statistical analysis, it was observed that the increase in temperature and evaporation rate on which the thermal sensitivity, evaporation efficiency and photothermal conversion efficiency depended were higher for 100 % GO compared to all other nanofluids used in this work. This is due to GO properties such as carbon-based structure with sp2 bonding network, π-rich electronic structure, unique optical band gap, black color, good suspension in base fluids, high optical absorption, high thermal conductivity; and the oxygen-bonded functional groups make it a highly solar radiation absorbing material for water purification based on solar evaporation.

There are several shortcomings of previous studies that led to this article. Low thermal efficiency of conventional solar thermal collectors is a major concern due to extensive heat losses. Existing studies have shown several problems with existing nanofluids due to high cost, low solar absorption and low stability. Moreover, early studies mainly focused on individual nanofluids that suffer from limited photothermal performance due to low absorption of solar energy, and poor radiation



(a) GO-ZnO at 0.02 wt.% (b) GO-ZnO at 0.03 wt.%

(c) GO-FeO at 0.02 wt.% (d) GO-FeO at 0.03 wt.%

Fig. 8. Evaporation efficiency, photothermal efficiency, and sensible heating efficiency of GO-FeO and GO-ZnO composite nanofluids with different mixing ratio at 0.02 wt% and 0.03 wt% concentrations.

trapping. This drawback limits the efficient use of nanofluids in solar energy applications. Individual nanofluids often exhibit dispersion stability problems due to weak interparticle repulsive forces such as nanoparticle aggregation in the base fluid leading to reduced heat transfer capacity and unbalanced performance over time. This hinders the application of these nanofluids in sustainable energy conversion systems. Solar energy comes directly from the sun's rays and can be converted primarily into heat. Conventional surface-based tube/flat plate solar thermal collectors first absorb the solar radiation incident on the black plate and then transfer it to the heat transfer fluid (HTF), which results in high heat loss. Existing plant experiences have shown that some operating problems with existing nanofluids are due to their low specific heat, high cost, difficulty in their production process. These nanofluids show different behavior under different climatic conditions during their experimental study. Furthermore, these solar-powered nanofluids were not suitable for water purification because they relied on intense sunlight through the evaporation process and were not designed for saline environments. Previously, photothermal experiments were conducted under controlled laboratory conditions that did not reflect real-world operational issues such as temperature fluctuations and solar intensities. Prior studies have also shown that some nanofluids are incompatible with conventional solar thermal collector designs for capturing solar radiation due to low evaporation efficiency and heat transfer efficiency. Additionally, synergistic effects for combining different types of nanoparticles to enhance solar absorption and thermal performance are not fully developed due to limited understanding of the complex interdependencies.

Existing literature studies on solar energy absorption by nanofluids have revealed several notable research gaps that are addressed in this study. An important research gap concerns the lack of comprehensive comparisons between different types of nanofluids for efficient solar absorption under the same experimental conditions. Most previous research studies have focused on monotype nanofluids and theoretical models to analyze the optical and thermal performance of confined nanofluids under controlled laboratory conditions such as a sun simulator. It limits the actual solar applications associated with various solar conversion processes such as water purification and thermal energy storage systems. Research studies on solar absorption of nanofluids conducted under controlled laboratory experiments ignore real conditions such as ambient temperature variations and fluctuations in sunlight intensity. Furthermore, nanoparticle aggregation is another major problem that significantly affects the dispersion stability and thermal conductivity leading to low photothermal efficiency of nanofluids. Nanoparticle aggregation limits the use of nanofluids in large-scale absorption applications and high-concentration scenarios. Moreover, current studies showed a limited synergistic effect for combinations of binary nanoparticles, especially carbon-based nanoparticles and metal oxide-based nanoparticles. A less-explored synergistic effect does not elucidate in depth how combinations of nanofluids enhance photothermal efficiency by coupling optical and thermal properties. Also, most of the previous research works were carried out using conventional surface-based solar thermal collectors which are ineffective due to large heat losses, high thermal resistance, low effective heat absorption, low transmittance and limited temperature operational conditions. These parameters particularly hinder the absorption performance of nanofluids for water purification. The cost of nanofluids is also a significant challenge for their large-scale scalability. Most of the nanofluids used in early research work are expensive due to their expensive synthesis procedures and the functionalization of nanoparticles. Complex manufacturing procedures, availability of stable nanoparticles and advanced processing methods increase the cost of nanoparticles for commercial applications. Therefore, cost is considered a major obstacle in the exploration of nanofluids for various practical applications such as water vapor-based purification.

This research work addresses the aforementioned problems in existing nanofluids. It presents a comprehensive comparative study on composite nanofluids (GO-ZnO and GO-FeO) with various mixing proportions and identifies the most efficient nanofluids for photothermal applications. All types of nanofluids are tested under natural sunlight rather than under controlled laboratory conditions. This demonstrates the applicability of nanofluids for real-world applications. Aggregation of nanoparticles at different weight concentrations (0.02 wt% and 0.03 wt%) is analyzed by optical absorption spectra via Uv–visible spectroscopy. The optical absorbance of all types of nanoparticles used in this study increases with increasing concentration of nanoparticles. This shows that the nanoparticles are stable according to the Beer-Lambert law which ensure the dispersion stability problem that limits the scalability of nanofluids. Synergistic effects are explored for the binary combination of carbon-based nanoparticles (GO) with metal-based nanoparticles (ZnO and FeO) to enhance the solar energy absorption efficiency under natural solar flux. Synergistic effects show how both composites nanofluids can achieve better photothermal performance than that of pure metal oxide nanofluids (100 %Zno and 100 %FeO), thereby absorbing broaden the spectrum. Additionally, this study utilizes low-cost nanofluids focusing on economical production methods and materials suitable for wide-scale adoption in solar energy conversion applications. GO nanoparticles are prepared using a modified Hummer method, which is a simple and low-cost method. ZnO and FeO are synthesized by co-precipitation method which is an efficient, effective and cheap method to obtain stable nanoparticles. This approach overcomes the cost barrier to scaling nanofluids technology to reduce the economic challenges associated with earlier nanomaterials. In this research study, a direct absorption solar thermal collector is used to overcome the limitation of conventional surface-based collectors to capture solar radiation. In this collector, the nanofluids are directly heated which minimizes thermal losses. This type of thermal collector absorbs solar energy uniformly in the medium due to its design support compared to surface-based solar thermal collectors. A high operating temperature is achieved making it ideal for advanced thermal applications. The nanofluids in these collectors naturally increase thermal efficiency by trapping direct radiation from sunlight. The compact design of these collectors allows for space-efficient installations, making them ideal collectors for both the industrial sector and the residential sector.

This research study is progressive because it focuses on real-world application that is often overlooked in similar studies. This work bridges the gap between theoretical potential and real-life application by conducting an experiment under natural sunlight for over five hours using a direct absorption solar collector. Most of the previous research studies have relied on surface-based solar thermal collectors under controlled laboratory settings, which is a serious concern due to extensive heat losses. But this work uses volumetric solar collectors to achieve higher photothermal efficiency by heating the fluid volume and improving solar energy absorption. This study uses advanced nanofluids consisting of GO-ZnO and GO-FeO with various mixing proportions to enhance the thermal efficiency through maximum volumetric solar absorption. These nanofluids showed superior solar absorption properties and dispersion stability under different intensities of sunlight. The combination of real-world testing, advanced nanofluids and efficient collector design establishes this research as a significant breakthrough in the optimization of solar thermal systems for practical and sustainable energy solutions.

Table 4 contains two types of results in terms of photothermal conversion efficiency. One type of result is the actual value of photothermal efficiency obtained in this work. The other results are the photothermal efficiency of the published results. This comparison provides the effectiveness of research to meet worldwide research demands. The photothermal efficiency in the present work is calculated at a concentration of 0.02 wt% and the published efficiency is calculated with 0.0004 wt% concentration. This is reason why this study achieves high photothermal efficiency. In this study, the photothermal efficiency of nanofluids also increased with increasing concentration of nanofluids shown in Fig. 8(a-d). So, it is consistent with other published research work [70–72].

Table 4
Comparison of photothermal efficiency for the nanofluids used in this study with published studies.

Current study		Published study		
Nanofluids samples	η_{PTE}	Nanofluids samples	η_{PTE}	Reference
100 % GO	83 %	100 % GO	~42 %	[74]
75 % GO −25 % ZnO	70 %	80 %GO + 20 % ZnO	~39 %	
50 % GO −50 % ZnO	64 %	60 %GO + 40 % ZnO	~34 %	
25 % GO-75 % ZnO	60 %	20 %GO + 80 % ZnO	~27 %	
100 % ZnO	57 %	100 % ZnO	~23 %	
75 % GO −25 % FeO	63 %	NA		
50 % GO −50 % FeO	58 %			
25 % GO-75 % FeO	49 %			
100 % FeO	42 %			

Below is a summary of this experimental research that pertains to the recent findings of this study.

I. Under natural sunlight, our experimental studies have shown a noteworthy trend in improving the photothermal efficiency of different nanofluids and their hybrids, particularly GO-based nanofluids. As opposed to every other nanofluid in this investigation, 100 % GO nanofluids showed a noteworthy 92 % improvement in photothermal efficiency, highlighting the promise of nanotechnology (nanofluids) in the development of solar thermal harvesting systems. This is due to carbon-based structure with sp2 bonding network, π-rich electronic structure, unique optical band gap, dark color, good suspension in base fluids, high optical absorption, high thermal conductivity; and oxygen linked functional groups make it a highly solar radiation absorbing material for water purification based on solar evaporation. Furthermore, contrary to existing studies, the results of this work revealed that pure (100 %) GO-based nanomaterial are the most photothermal by efficiently absorbing solar energy and converting this solar energy into heat under natural solar flux. Although existing research studies have explored various nanoparticles in base fluid to improve photothermal efficiency, none of the studies achieved the 92 % significant improvement as found in this study. This reflects the high potential of GO based nanotechnology and advanced evaporation processes for water purification, which was limited by poor solar energy absorption and high energy requirements. It also suggests sustainable and economical techniques to obtain clean water through solar evaporation process as compared to conventional techniques which are expensive and energy intensive.

II. This research study illustrates the trend towards integration of solar vapor based nanofluids with solar thermal energy storage technology which is also known as volumetric based absorption technology to address the challenge of low solar energy for continuous clean water production. To address the main issue facing the saltwater desalination industry, this signals a critical transition towards a greater dependence on solar-based purification under natural solar flux. The results of this study can allow the storage of solar energy during the peak solar hours of the day, especially during the hours when the solar energy is high using volumetric based solar energy storage technology to run the evaporation process continuously. This is due to better heat transfer properties, better thermal conductivity, higher optical absorption, higher solar absorptivity and higher evaporation rate of nanofluids compared to base fluid. The results of this study show that more solar energy can be stored during high absorbing solar energy nanofluids and can be used for continuous evaporation process to purify water during low intensity hours. It also increases the efficiency of the evaporation which is 33 % in this study and its reliability for solar-based purification under natural solar flux. Although existing research studies have explored various techniques to overcome the lower solar availability, but most existing research work hase been performed using sun simulators with very small nanofluids samples which may not reflect the actual application environment with the through volumetric collection energy storage technology to address the challenge of low solar energy for continuous clean water production. This technology uses natural solar radiation to enhance the evaporation tendencies of nanofluids under realistic rather than controlled conditions us for sustainable clean water production and also resolved the low intensity challenge.

III. This research study explored and improved access to solar absorption performance of material systems using highly absorbent nanomaterials to drive evaporation processes for water treatment. The findings of this experimental study can be used to assess the absorption performance of material systems. Specifically, as defined by sensible heating and evaporation efficiencies, the base fluid dramatically benefits from adding small nanoparticles to increase solar energy absorption. This enhancement suggested a new approach towards the design of new nanofluids. By controlling the concentration of nanoparticles in the base fluid, optimal solar absorption and heat production are achieved, which is important in nanofluidic systems. These useful findings highlight the importance of focusing on fine-tuning the properties of nanofluids in volumetric solar thermal collectors to achieve optimal solar absorption and evaporation rates in nanofluid-based evaporation systems for water purification. This increases the feasibility and scalability of both the collector and the nanofluid for efficient evaporation processes for cleaning of seawater.

IV. This research investigation compares the photothermal performance of different nanofluids considering evaporation rate, optical absorption, high bulk fluid temperature and high evaporation rate for water treatment applications. This research study also presents a decreasing order of nanofluids considering specific absorption rates for water treatment applications. In this study with respect to photothermal performance and specific absorption rate, decreasing order as 100 %GO, GO-ZnO, GO-FeO, 100 %ZnO and 100 %FeO was observed. Experimental results show that binary nanofluids proved to be the best except for 100 % GO due to its strong solar absorbing nature. These new findings support optimization and customization of various nanofluids and their hybrids to achieve optimal evaporation rates under realistic conditions and improve overall system performance. The system's overall increased efficiency makes a difficult task possible for the evaporation process to proceed to create clean water.

In this study, the photothermal performance of GO-ZnO and GO-FeO with various mixing proportions was evaluated at two concentrations (0.02 wt% and 0.03 wt%). The photothermal performance of GO-ZnO and GO-FeO with different mixing ratios increases with increasing nanoparticle concentration. High photothermal efficiency was obtained at 0.03 wt% concentration. As the amount of GO in GO-ZnO and GO-FeO decreases, the photothermal peformance decreases. The superior solar absorptivity, high thermal conductivity, carbon composition, and high surface area make 100 % GO highly photothermal. This element allows more absorption of solar energy and efficiently converted into heat. Furthermore, the sheet based two-dimensional structure of GO presents better heat transfer in all nanofluid combinations used in this study. GO is a material that transfers heat efficiently due to its high thermal conductivity which can be justified by Fourier's law of heat conduction. 100 % ZnO and 100 % FeO showed lower photothermal efficiency due to lower thermal conductivity, lower surface area, lower solar absorption and lower heat retention. A larger surface area of GO enhances the photon interaction of light compared to ZnO and FeO. The carbon structure for graphene oxide attributed to high temperature and mass loss contributed to the high photothermal efficiency.

Specific absorption rate (SAR)

SAR can be stated as solar energy absorbed in unit mass of nanoparticle. SAR is a critical factor that indicates the solar absorptivity of various nanofluids to evaluate their ability to treat water purification application.

$$\mathrm{SAR} = \frac{(\mathrm{C_W m_W})(\Delta\mathrm{Tn} - \Delta\mathrm{Tw}) + \mathrm{L_V m_{loss}}}{1000\,\Delta\mathrm{t}\,\mathrm{m_n}}\,\mathrm{SAR} = \frac{(\mathrm{C_w m_w})(\Delta\mathrm{T_n} - \Delta\mathrm{T_w}) + \mathrm{L_v m_{loss}}}{1000\,\Delta\mathrm{t}\,\mathrm{m_n}} \tag{4}$$

In equation (4), C_w is the specific heating value for base fluid..m_w is the mass of water used for preparation of nanofluids. ΔT_n and ΔT_w are the rising in temperature for the nanofluid sample and for DI water, correspondingly. m_n is mass of nanoparticles.

Fig. 9(a, b) showed the SAR profiles of GO-FeO, GO-ZnO against two different weight concentrations.

In the binary combination of GO-FeO, GO-ZnO the specific adsorption rate strongly depends on the GO content. Higher contents of GO in GO-FeO, GO-ZnO increase the specific rate. As the GO content decreases in GO-FeO, GO-ZnO it decreases the specific absorption shown in Fig. 9 (a, b) at two different weight concentrations. It was also observed that as concentrations of nanoparticles increases from (0.02 wt% to 0.03 wt%), it decreases the specific absorption which is according to the Equation (4).

The 100 % GO nanofluid had the most dispersion stability, the maximum solar absorption, the highest thermal conductivity, and a carbon-based structure. It outperformed all the other nanofluids employed in this investigation at various weight percentage concentrations. The highest specific absorption of GO nanofluids also indicates that they are an excellent nanomaterial that can be used in photothermal applications including seawater desalination applications.

100 % GO nanofluids achieved a significant specific absorption (SAR) among all nanofluids in this study, demonstrating the potential of GO −based nanofluids in absorption of solar energy under natural sun using technique of direct absorption solar collection which can be used to purify the seawater through evaporation processes. This is because of carbon-based structure with sp2 bonding network, π-rich electronic structure, unique optical band gap, dark color, good suspension in base fluids, high optical absorption, high thermal conductivity, excellent dispersion stability. Moreover, the 2-D honeycomb structure, other functional groups containing oxygen atoms such as hydroxyl groups, epoxy groups, and carboxyl groups and its unique electronic structure with unique bandgap make it a highly light absorbing material.

SAR of GO-ZnO and GO-FeO with various mixing proportions revealed that 100 % GO showed maximum specific absorption compared to various combinations of both nanocomposites. This is due to the structure and specific properties of GO. GO has carbon structure which promotes high electron mobility, which is associated with efficient energy conversion in natural sunlight. Broad optical absorption of GO increases its SAR. Other factors such as surface plasmonic resonances that enhance the electromagnetic properties effectively generate heat. The low thermal loss in GO is due to its sheet-like structure which leads to energy trapping. The sheet-like structure of GO enhances the light-photon interaction compared to the compact spherical shape of ZnO and FeO, which allows efficient energy conversion. The excellent dispersion stability of nanofluids stabilizes the solar absorption which increases the SAR. Because of GO existence in GO-ZnO and GO-FeO, SAR is increased than that of pure ZnO and pure FeO. Low SARs are observed in 100 % ZnO and 100 % FeO due to narrow range of optical absorption spectrum, low electron mobility, high thermal losses and low dispersion stability.

Uncertainty analysis

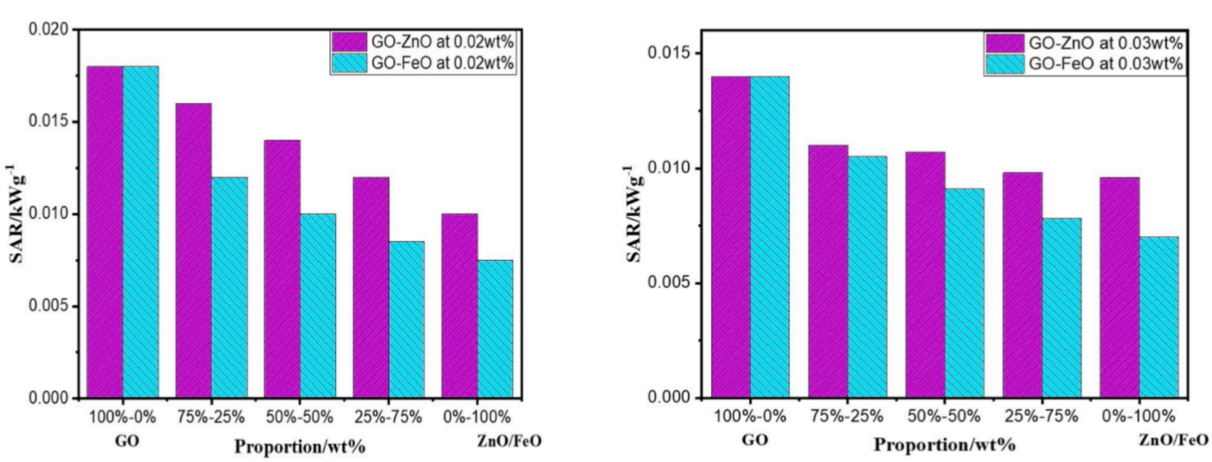
Uncertainty analysis for photothermal conversion efficiency and specific absorption rate is done with the help of Equations (5), 6, respectively.

$$(U_\eta)^2 = \left(\frac{\partial\eta}{\partial m_w}Um_w\right)^2 + \left(\frac{\partial\eta}{\partial\Delta T}U\Delta T\right)^2 + \left(\frac{\partial\eta}{\partial m_{loss}}Um_{loss}\right)^2 + \left(\frac{\partial\eta}{\partial I}UI\right)^2 \tag{5}$$

$$(U_{SAR})^2 = \left(\frac{\partial SAR}{\partial m_w}Um_w\right)^2 + \left(\frac{\partial \mathrm{SAR}}{\partial\Delta Tn}U\Delta T_n\right)^2 + \left(\frac{\partial \mathrm{SAR}}{\partial m_{loss}}Um_{loss}\right)^2 + \left(\frac{\partial \mathrm{SAR}}{\partial\Delta \mathrm{Tw}}U\Delta T_w\right)^2 \tag{6}$$

Table 5 illustrates the accuracy of the experimental equipment's used to measure the various parameters that contribute to the calculation of the photothermal conversion efficiency and specific absorption rate.

According to Equations (3) and (4) which show the photothermal conversion efficiency and specific absorption rate, these equations are dependent on several parameters whose measurement uncertainties are given in Table 6.



(a) GO-ZnO and GO-FeO at 0.02 wt.% (b) GO-ZnO and GO-FeO at 0.03 wt.%

Fig. 9. Specific absorption of GO-ZnO, GO-FeO composite nanofluids with different mixing ratio at 0.02 wt% and 0.03 wt% concentrations.

Table 5
Measurement accuracy of the instruments used in this study.

Equipment	Accuracy
Thermocouple	± 0.02 °C
Pyranometer	± 5 W/m^2
Digital scale	± 0.0002 g

Table 6
Uncertainty in measurement parameters.

Parameter	Uncertainty (%)
ΔT	±1.2 %.
m_{loss}	±1.25 %.
I	±3 %.
η (evaporation)	±1.10 %.
$\eta_{(sensible\ heating)}$	±1.21 %.
η_{PTE}	±2.31 %.
SAR	±0.24 %.

Note: Author Footnote 1 information missing.

Conclusion

T This study experimentally investigated the photothermal properties of two composite nanofluids (GO-ZnO G and GO-FeO) at concentrations (0.02 wt% and 0.03 wt%) under natural sunlight in the context of water p purification applications. These nanofluids were tested via direct absorption solar thermal collectors and thfollowing conclusions are drawn.

1) This research study demonstrated that composite nanofluids (GO-FeO and GO-ZnO) with different mixing ratios exhibit significant optical absorption in the UV region. Pure (100 %) GO showed the highest optical absorption among all composite nanofluid compositions. This is due to its excellent dispersion stability, unique carbon electronic structure, oxygen-based functional group, sp2 hybridization and high surface area. These results are very supportive for evaluating the solar absorption of nanoparticles for practical applications that require efficient UV absorption such as purification of seawater.
2) The addition of nanoparticles to the base fluid increases the ability of the nanoparticles to absorb solar radiation at a faster rate, which is reflected by rising temperature and mass loss due to evaporation. Additionally, the photothermal efficiency of nanofluids has been found to increase with increasing nanoparticles concentration from 0.02 wt% to 0.03 wt%. This is because nanoparticles have a high free electron density and a high surface-to-volume ratio, which enables localized surface plasmon resonance that enhances solar absorption. However, this increase in solar mass absorption is far outweighed by the benefits of improved thermal efficiency. This is the best analysis to select the optimal concentration to evaluate the photothermal performance of different types of nanofluids for seawater desalination.
3) Pure (100 %) GO achieved a remarkable 92 % photothermal efficiency compared to all other composite ratios of GO-ZnO and GO-FeO. This is because GO has carbon structure with sp2 bonding network, π-rich electronic structure, unique optical band gap, dark color, good suspension in base fluids, high optical absorption, high thermal conductivity; and oxygen linked functional groups make it a highly solar radiation absorbing material for water purification based on solar evaporation. Furthermore, a synergistic effect was established to improve the photothermal performance in GO-FeO and GO-ZnO. The composites (GO-FeO and GO-ZnO) nanofluids showed an increasing trend in photothermal efficiency with increasing GO concentration and decreasing FeO and ZnO. This is of great importance for optimizing nanofluids, as it depends on several aspects, such as size, concentration, nature of nanoparticles, material composition and atomic structure of nanoparticles.

Finally, a detailed experimental analysis on the optical and photothermal properties of various nanofluids and their hybrids revealed that nanoparticles based on amorphous carbon i.e. GO and its binary compounds (GO-FeO, GO-ZnO) are particularly suitable compared to pure metal oxides (100 % ZnO and 100 % FeO) for solar thermal application. These results are vital for the exploration of several photothermal applications such as water purification, steam generation, electricity generation, and photothermal catalysis etc.

Nomenclature

Abbreviations	
DASC	Direct Absorption Solar Collector
DI	Deionized
NPs	Nanoparticles
PTE	Photothermal Conversion Efficiency
SAR	Specific Absorption Rate
TC	Thermocouple
SEM	Scanning Electron Microscopy
UV	Ultraviolet
Symbols	
C_W	Specific heat capacity of water (J/kgK)
L_V	Latent heat of vaporization at pressure of 1 atm (J/kg)
m_{loss}	Mass loss of the nanofluid sample (kg)
I	Solar irradiance (W/m^2)
m_w	Mass of water (kg)
A	Illumination area of the nanofluid sample (m^2)
ΔT	Average change in temperature (°C)
ΔT_n	Change in temperature of nanofluid (°C)
ΔT_w	Change in temperature of base fluid (°C)

CRediT authorship contribution statement

Abdul Sattar: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Bai Bofeng:** Writing – review & editing. **M. Adeel Munir:** Formal analysis. **Muhammad Farooq:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Conceptualization. **S. Bilal:** Investigation, Visualization, Writing – review & editing. **M. Imran Khan:** Data curation. **Noreen Sher Akbar:** Writing – review & editing, Software, Investigation. **Mohammed Ilyas Khan:** Investigation, Resources, Writing – review & editing. **Mohammad Rehan:** Formal analysis, Resources, Writing – review & editing. **Fahid Riaz:** Writing – review & editing, Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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