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Experimental investigation of photothermal performance in nanofluid-based direct absorption solar collection for solar-driven water desalination

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HIGHLIGHTS

- Experimental analysis of optical properties of various nanofluids and their hybrids.
- Photothermal investigation of nanofluids under natural solar flux.
- Enhancement in photothermal performance using low cost nanofluids.
- Potential working fluid for solar energy-based applications.
- A sustainable solution for solar-based water purification applications.

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ABSTRACT

As the demand for energy continues to rise unabated, an examination of the constraints posed by finite fossil fuel reserves becomes crucial. There is need to explore and underscore the imperative shift towards renewable energy resources, where, solar energy is widely available and can readily be used in different applications, especially in water desalination applications. In the present research, photothermal performance of water based nanofluids containing graphene oxide (GO), zinc oxide (ZnO), iron oxide (FeO), and their composites (GO-ZnO and GO-FeO) have been studied under the natural sun to determine the potential for water desalination applications. All type of the nanofluid are prepared through a two-step method and are characterized morphologically using a scanning electron microscope (SEM). UV–visible spectroscopy is used to assess the optical absorbance of prepared nanofluids. The outcomes of this study show that pure GO nanofluids exhibited excellent absorption in the visible and near-infrared regions as compared to other nanofluids used in this research study, which makes them efficient nanofluids in converting solar energy into heat. For more assessment, a direct or volumetric solar thermal collector was used to evaluate the photothermal efficiency of water based nanofluids GO, ZnO, FeO, and their binary composites of GO-ZnO, and GO-FeO under natural solar flux at weight concentrations (0.01 wt%). The sensible heating efficiency due to the rise in temperature and latent heat of

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evaporation efficiency due to mass loss of nanofluid samples contributed towards photothermal efficiency. Pure GO nanofluids showed the highest photothermal efficiency, which is 71 % among all the nanofluids used in this study due to their carbon-based structure, highest optical absorption peak, excellent dispersion stability, and highest thermal conductivity. This experimental work also revealed that binary nanofluids containing composites of (GO-ZnO) and (GO-FeO) showed higher photothermal efficiency as compared to individual nanofluids ZnO and FeO except graphene oxide GO. According to the results and observation of this experimental work, pure GO-based nanofluids are potential candidates for direct absorption solar collection used in water desalination applications.

1. Introduction

With increase in population and depletion of fossil fuels, demand of energy is increasing day by day which is main issue for industries and economy. Renewable energy resources are considered best solution to meet the energy demand [1]. Solar energy is widely available, abundant, renewable and alternative energy source for the elimination of consequences of fossil fuels and has been used in many applications such as water desalinations for the production of drinkable water [2]. Existing water desalination techniques are very expensive and energy intensive. But, solar energy is economical and widely available energy source which can be used for water desalination applications [3]. For water desalination applications, solar energy is harvested with the help of solar thermal collectors. In conventional or traditional solar thermal collectors, first, radiation is absorbed by the black surface, and then this absorbed heat is transferred to the working fluids. Therefore, conventional solar thermal collectors are not effective for capturing radiation because there are three thermal resistances between the incident solar radiation and the working fluids. The first radiation is absorbed by the black surface plate, the second heat is transferred to the tube using conduction mode, and the third heat is transferred from the tube to the working fluids by convection heat transfer [4]. To minimize these thermal losses, a volumetric or direct absorption Solar Collector (DASC) was developed for direct absorption solar collection. In a volumetric solar thermal collector, solar radiation falls directly on the working fluids. Therefore, there is no thermal resistance between the solar radiation and the working fluid [5]. Nanofluids are an important area of research that is used in my applications of heat transfer because of exceptional heat transfer capabilities [6]. So, nanofluids expanded their importance towards water desalination applications for the production of clean water under natural solar radiations [7]. Existing literatures describes the different properties of different nanofluids including individual nanofluids and binary nanofluids [8]. However, many numerical and experimental research studies have revealed that individual nanofluids have lower dispersion stability, lower solar absorption, higher cost and poorer heat transfer properties than binary nanofluids for water desalinations is given low priority [9]. So, problems arise using individual nanofluids can be overcome with binary nanofluids for effective and economical water desalination [10].

The nanofluids have great potential for effective utilization of solar energy to produce fresh clean water which is promising one [11]. In recent times, binary nanofluids by combining two different particles received great focus because of exceptional characteristics. The photothermal performance of individual nanofluids and binary nanofluids has been investigated under laboratory and outdoor conditions. Many studies on solar absorption of nanofluids has been proved that individual nanofluids are less attractive for solar absorption as compared to binary nanofluids [12]. Previous literature has reported that binary nanofluids consisting of carbon-based composites and metal-based nanoparticles absorb more solar radiation and prove to be suitable materials for solar absorption [13]. For example, binary composites of copper oxide and multiwall carbon nanotubes have shown excellent photothermal performance because of increased absorption capacity into the visible solar spectrum using direct or volumetric solar thermal collector [14]. Many similar research studies provide suggestion that binary nanofluids has enough potential to absorbs the solar energy for water desalination applications as compared to individual nanofluids due to excellent absorption [15].

Solar desalination is the cheapest technique for the purification of fresh water using solar energy as renewable energy resource [16]. Due to industrialization, population, and urbanization, the requirement of fresh water is the need of time. Therefore, provision of clean drinking water is essential. For this purpose, it is necessary to integrate solar energy for production of cleaned water from sea water, waste water and brackish water [17]. There were many conventional or traditional water purification methods like reverse osmosis, forward osmosis, nanofiltration and electrodialysis. But these traditional techniques are expensive and energy intensive [18]. Solar energy is a widely available and inexpensive mean which can be used for direct absorption energy collection in water treatment applications. Additionally, the solar powered cleaning process does not pose any health risk or carbon footprint issues as compared to conventional desalination techniques. Therefore, solar energy-based water purification is an effective, reliable, less expensive and alternative technique as compared to conventional desalination methods [19]. Nanoparticles are superior to millimeter and micrometer particles due to large area to volume ratio and higher photothermal efficiency under solar radiation. Many researches work reported for evaluation of photothermal efficiency of nanofluids such as Amjad et al. [20] examined the photothermal efficiency of several nanofluids including aluminum oxides (Al_2O_3), zinc (Zn), copper (Cu), iron (Fe) and silver (Ag) under concentrated solar flux and observed that small amounts of nanoparticles in the base flux increased solar absorption, resulting in mass loss. The mass loss was considered for the calculation of the evaporation performance to estimate vapor production. Abdul et al. [21] found that solar systems based on nanotechnology are efficient and effective for removing fluoride, arsenic and other metals at different scales or levels. The study also found that the efficiency of desalination systems based on nanotechnology was much better than conventional systems previously used for these applications. Many similar studies on solar desalination have been reported such as Zhang et al. [11], Bekhir et al. [22], Al-Sayed et al. [23], Syednazada et al. [24], You et al. [25], Wang et al. [26], Liu et al. [27], Thibault et al. [28], Rufus et al.

[29]. In all these studies, various nanofluids including water-based TiN-nanofluids, multi-wall carbon nanotubes, gold, titanium oxide, wood-based graphene oxide composites, binary combinations of metal oxides, and reduced graphene oxide nanofluids were used respectively to evaluate the photothermal performance for efficient use of water purification while considering steam generation. Several research studies had also conducted using nanofluid-based solar thermal collectors to generate steam to estimate the thermal concert considering sensible heating and evaporation efficiency of desalination systems based on solar nanotechnology which were significantly higher than conventional solar thermal collectors [30]. Many researchers such as Li et al. [31], Jin et al. [32], Wang et al. [33], Fu et al. [34], Wang et al. [35], Shi et al. [36], Wang et al. [37], Liu et al. [38], and Wang et al. [39] used water-based nanofluids for photo-induced evaporation, including graphene oxide (GO) and carbon-based black nanofluids, graphene and graphene-Au nanocomposite, silver titanium oxide (Ag–TiO_2), gold (Au), single and multi-walled carbon nanotubes. , carboxyl group, titanium trioxide (Ti_2O_3), reduced graphene oxide (RGO) to test the suitability of nanofluids for water purification applications for improved photothermal performance. Subsequently, total photothermal efficiencies of 80.3 % [32], 95 % [40], and 59.2 % [34] were described for gold nanoparticles at different light powers of 220, 280, and 16.77 Suns, respectively. But, evaporation efficiency of 46.8 % [33], 60.3 % [36], 60 % [41], 66.9 % [31], and 48 % [39] found for other nanofluids at different intensities of light. This evaporation performance indicated the suitability of various nanofluids using volumetric solar thermal collectors for water purification applications.

Current research works reported that despite excellent optical absorption of nanoparticles and the proven improved photothermal performance for water purification applications, water purification applications using nanofluidic systems are still lacking. It depends on many factors like size of nanoparticles, concentrations of nanoparticles, types of nanoparticles, economy and cost of nanoparticles [42]. This show that water purification using nanofluids as solar absorbers have to overwhelmed optimization problems with the usage of appropriate and suitable nanofluids in the system, e.g. Alternatively, inappropriate concentrations of nanoparticles in base fluids may not yield optimal results. This has also been proven that many of existing research works were performed using sun simulators with very low nanofluid's concentrations, which may not reflect the actual application environment [43]. Furthermore, many nanofluids were investigated under different conditions making the evaluation of nanofluids for water desalination applications difficult. Therefore, there is a great need to test nanofluids for water treatment applications under realistic conditions to understand the influence of nanofluid type and concentration. However, lower thermal performance of conventional or traditional solar thermal collectors is big challenge due to large thermal losses and have also shown several problems with nanofluids such as high cost, lower solar absorption and lower dispersion stability [44]. How solar absorption efficiency can be significantly improved by suspending nanoparticles of different materials in the base fluid for water desalination applications is the research question to be answered in this experimental work. Now, a present requirement for effective solar desalination application is to select those nanofluids having high heat transfer capability, low cost and type of solar collector to enhance solar absorption. To achieve this goal, this research work has proposed direct or volumetric solar thermal collectors and carbon based nanofluids (GO), metal oxides (ZnO, FeO) and their binary composites consisting of carbon and metal oxides (GO-ZnO and GO-FeO) to maximize solar absorption to determine their suitability for water desalination applications. Nanoparticles are a promising technology for future solar thermal energy systems based on direct solar absorption. Therefore, with many research studies on different nanofluids and nanomaterials for solar energy harvesting applications, a comprehensive comparison of the photothermal conversion properties of different nanofluids under the same experimental conditions is very important, especially for water desalination applications.

This research work deals with photothermal applications in solar energy area. The attention is on a comprehensive study of various nanofluids, from their synthesis to practical applications. These nanofluids look promising for existing solar thermal collectors and provide a sustainable solution using renewable energy to achieve higher photothermal efficiency than currently available. This study serves the following three objectives that contribute to the novelty of this work which are as follows: i) This research investigation provides a platform to test the suitability of various individual nanofluids and their binary combinations for water treatment applications under realistic rather than controlled conditions, which can reflect the real application environment. ii) This research study experimentally investigates the effect of selecting suitable nanofluids on bases of their thermophysical properties under realistic solar exposure conditions, which led to large-scale water purification on a commercial basis. iii) The results of this study provide sustainable solutions for improving solar energy scavenging methods to enhance absorption using a variety of nanofluids with increased photothermal efficiency. The experimental results of this research work are useful for practical applications with nanofluids for water purification using solar energy under local environmental and climatic conditions. Future recommendation for effective solar desalination application requires choosing nanofluids with high heat transfer capacity, low cost and advanced solar collector design to enhance solar absorption. Low cost, high heat transfer nanofluids and minimal thermal losses are useful in solar thermal collectors to explore the potential of nanoparticles for water purification.

To accomplish these research objectives, and to determine the potential for water desalination applications the photothermal performance of three different water-based nanofluids GO, ZnO, and FeO with binary composites (GO-ZnO and GO-FeO) at 0.01 wt% concentration under natural solar flux was investigated. Nanofluid samples were exposed to natural solar radiation for approximately 5 h. Temperature rise was measured using three K-type thermocouples. Mass loss due to evaporation was measured using a digital weighing scale, which is an important factor for evaporation-based applications. The sensible heating efficiency, evaporation efficiency and total photothermal efficiency of nanofluids (GO, ZnO, FeO) and their binary nanofluids (GO-ZnO and GO-FeO) were used to compare their performance for water desalination applications. This allows to answer the suggested research question and to advance photothermal applications through direct absorption collectors for solar -driven water desalinations using different types of nanofluids.

2. Materials and methods

2.1. Nanofluids' preparation

A two-step method [45]was used to prepare nanofluids containing GO, ZnO, FeO, and their composites (GO-ZnO and GO-FeO). First, these particles are produced using various synthesis methods then they are dispersed in deionized water which is base fluid. For example, for synthesize GO nanoparticles by modified Hummer's method, graphite powder and sodium nitrate ($NaNO_3$) were mixed in a 9:1 wt ratio in a beaker. Then slowly add sulfuric acid (H_2SO_4) and stir continuously for 24 h to obtain a homogeneous mixture. To control the temperature, place the mixture in an ice bath. Then slowly add the strong oxidizing agent potassium permanganate ($KMnO_4$) to the solution mixture with stirring. Due to the exothermic reaction, a large amount of heat is generated in this step, so the beaker was put inside ice bath for cool down to 0–5 °C. Then, remove the ice bath and incubate the solution for the next 24 h at room temperature, approximately 35–40 °C. Then, deionized water mixed into the solution with process of stirring to initiate oxidation process. After the oxidation process, a brown solution mixture was obtained. Set up a 2-necked flask apparatus. Pour the brown solution into a two-necked flask and heat the solution to 65–70 °C. After heating, H_2O_2 was added to stop the reaction and HCl was added to separate the graphite oxide layers. Then, solution washed many times by deionized water to maintain pH at 6–7 and filtration was also performed to remove excess acid and salt. When solution pH reached at 6–7. Then, it dried in oven at 50–60 °C. Then grinding has been done using a pestle and mortar. Finally, graphene oxide (GO) nanoparticles were obtained. Other nanoparticles ZnO, FeO were synthesized using co-precipitation method. The binary nanocomposite containing (GO-ZnO and GO-FeO) were produced by the hydrothermal method. In this study, a concentration of 0.01 % by weight of nanofluids is used to test the potential of nanofluids for water purification applications. Various nanopowders of GO, ZnO, FeO and their binary combinations (GO-ZnO, GO-FeO) have been employed for the preparation of nanofluids using two-step method. By applying this method, nominated nanopowders are mixed into

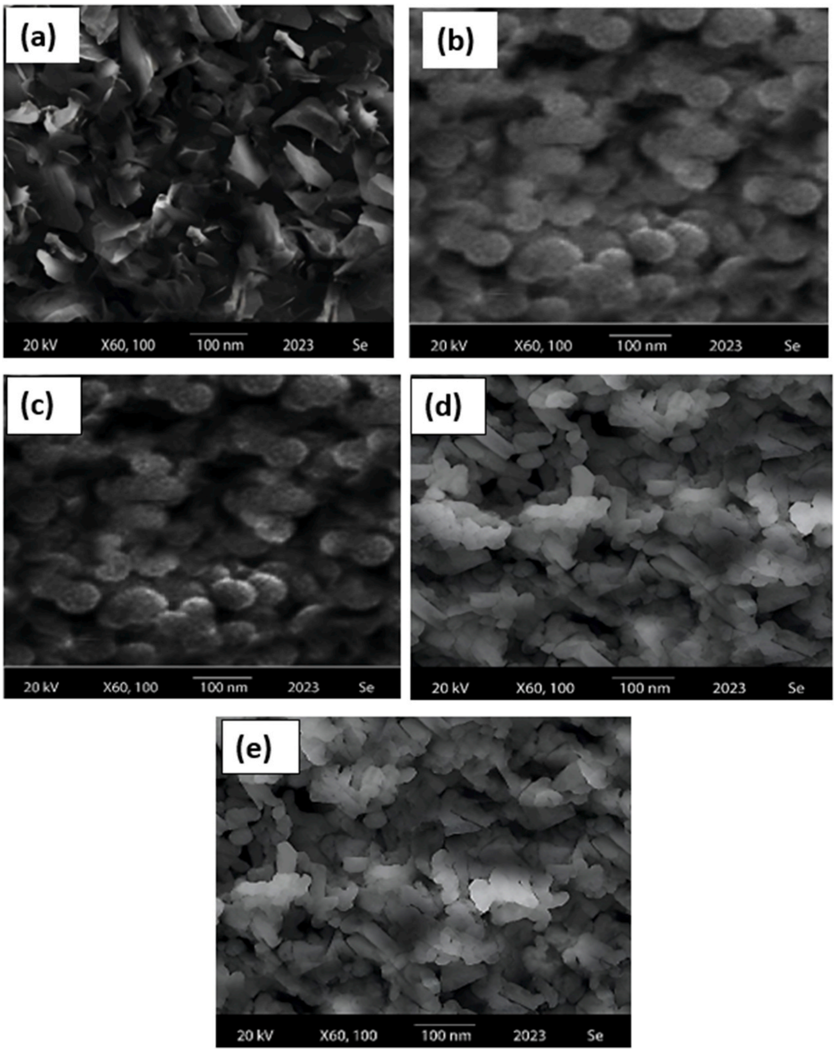

Fig. 1. The SEM images of (a) GO, (b) ZnO, (c) FeO, (d) GO – ZnO, (e) GO – FeO.

deionized water directly. To prepare a concentration of 0.01 % by weight, 0.01 g of nanopowders were mixed with 100 g deionized water under vigorous stirring. Then mixture was sonicated for about 1 h with the help of ultrasonication bath before starting the photothermal experiment.

According to equations (1)–(3) given in section 3.4 which describes the evaporation efficiency, sensible heating efficiency and photothermal efficiency, m_{loss} is the mass loss of the nanofluid due to evaporation in the time t given in Equation (1) and m_w is the initial mass of water used as the base fluid in this study given in Equation (2). Both these masses were measured directly with a digital weighing scale. Therefore, the mass flow rate was not calculated from the volume flow rate and it also did not account for density of the nanofluids.

2.2. SEM characterizations

In this study, nanoparticles consisting of GO, ZnO, and FeO as well as their binary composites (GO-ZnO and GO-FeO) have been synthesized and their sizes, and shapes were confirmed with scanning electron microscope (SEM) images. Particle sizes were measured using ImageJ software. SEM images given in Fig. 1(b) and (c) show that ZnO and FeO particles are spherical with average diameters of 52.53 nm and 56.82 nm, respectively, while the GO nanoparticles consist of nanosheet, with the average length 88.15 nm respectively which is shown in Fig. 1(a). The GO-ZnO and GO-FeO SEM images show the shape of nanorods with average diameters of 50.16 nm, 53.82 nm and average lengths of about 96.17 nm and 98.02 nm respectively given in Fig. 1(d–e). Table 1 describes the properties of nanoparticles containing size and shape. SEM analysis showed that all nanoparticles in this study showed size of particle a lesser than 100 nm. This minimum size makes nanoparticles a potential candidate to prepare the nanofluids with good dispersion stability which enhances their solar absorption for water desalination applications [46].

2.3. Experimental procedure

Fig. 2 represents the schematic diagram of the experimental setup. This setup contains a Petri dish, digital weighing balance, pyranometer, thermocouples and data logger. A Petri dish of 4 cm has been used to contain the samples of nanofluids. Deionized water was used as a base fluid for preparation of nanofluid samples under 1-h ultrasonication's. Before the start of each experiment, this Petri dish was filled with 100 g of water for 0.01 wt % weight concentration of nanoparticles and expose the solar radiation under natural sun for direct absorption collections. To measure the temperature of the nanofluid samples, three K-type thermocouples were mounted at three different heights into Petri dish. One thermocouple (TC1) was held with upper surface, the second (TC2) in the middle, and the third (TC3) near the bottom of the Petri dish. TC4 measured environmental temperature. All K-type thermocouples (OEM WRR2-130) were used for measurement of the nanofluid samples temperature with an uncertainty of ± 0.01 °C. The nanofluid samples were exposed to natural solar radiation for 5 h, and a pyranometer, with an uncertainty of ± 10 W/m^2, was used to record the irradiance data during the experiment. The Petri dish was positioned above the digital weighing balance (Cornell, Germany) with an uncertainty of ± 0.0001 g to measure the mass loss of the nanofluids samples due to evaporation. The dispersion stability which assess the sedimentation of the nanoparticles in base fluid have been carried out using visual and absorption spectra methods. No sedimentation was observed during the photothermal experiment. Dispersion stability is an important factor for Improved performance of nanofluids. In this research work, the role of nanofluids composed of GO, ZnO, FeO and GO-ZnO, GO-FeO at 0.01 wt% concentration was explored. The dispersion stability was noted with UV–visible spectroscopy. A higher absorbance value represents better suspension of nanoparticles in the base fluid which is deionized water in this study. UV–visible spectroscopy shows quantitative results regarding the concentration of nanofluids. In this study, surfactants were not used in the preparation of nanofluids samples to increase dispersion stability because surfactants increase stability but reduce collector efficiency due to formation of air bubbles and foam [47]. Therefore, ultrasonication technique was used to prevent aggregation of nanoparticles or to break large nanoparticles clusters into smaller particles in base fluid. It was observed that increasing the ultrasonication time resulted in more dispersed and stable nanofluids. Stability is not a monotonic function of sonication time, especially in binary nanofluids (GO-ZnO, GO-FeO). On the other hand, nanofluids do not have enough energy to ensure continuous dispersion of nanoparticles at low sonication level. This also leads to a decrease in the absorption of nanofluids. In this study, after 30 min of sonication time, absorbance (because of increase in Brownian motion) was observed to be continuously improved with additional sonication i.e. splitting of nanoparticles increases with increasing sonication time. After sonication for 30 min, the UV–Visible spectrum of all nanoparticles was examined and the results are given in Fig. 5(a–c).

The maximum absorption value for pure GO was found to be 2.2 a. u, while that of pure ZnO and pure FeO was found to be 1.4 a. u and 1.2 a. u, respectively, as shown in Fig. 5. Among all the nanofluids, pure GO showed maximum absorption indicating that it is well dispersed in the base fluid and exhibits the highest stability. Binary nanofluids (GO-ZnO) and (GO-FeO) showed higher absorption values than individual nanofluids (ZnO and FeO) as shown in Fig. 5. This indicates that they are more dispersed and more stable than

Table 1
Properties of nanoparticles.

S. No.	Nanoparticle	Diameter (nm)	Length (nm)	Shape
1	GO	–	83.15	nanosheet
2	ZnO	52.53	–	spherical
3	FeO	56.82	–	spherical
4	GO – ZnO	50.16	90.17	nanorod
5	GO – FeO	53.82	93.02	nanorod

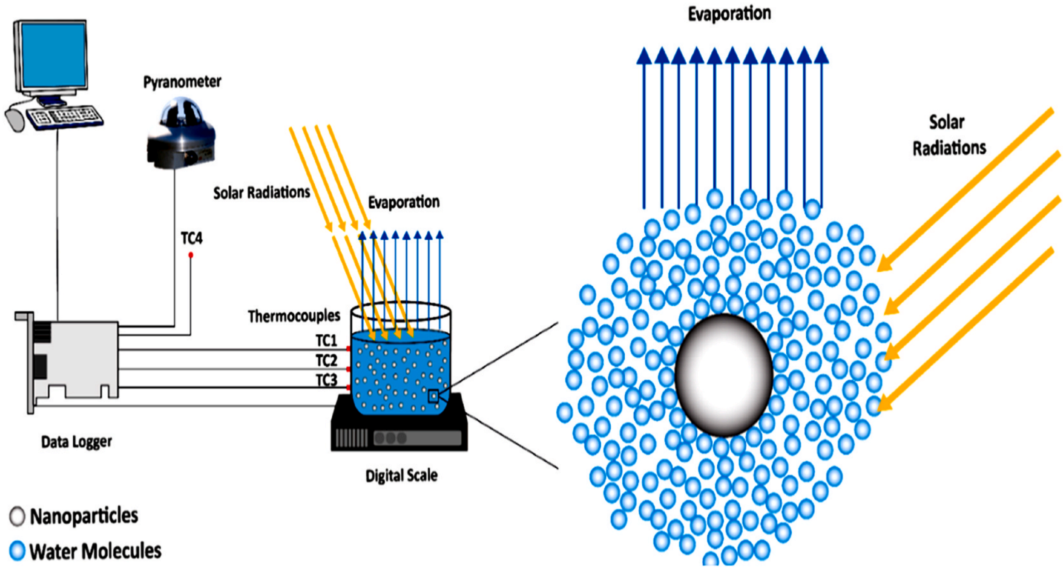

Fig. 2. Schematic diagram of experiment presenting the location of thermocouples and digital scale setup under natural sun.

individual nanofluids (ZnO and FeO). After sonication for about 3 h, the nanofluids were observed to be stable for up to 1 day.

In Fig. 3(a–e), the system design and dimensions are provided. The diameter and depth of the Petri dish that was used to hold nanofluid samples for conducting the experiments are shown in Fig. 3(a). The length and thickness of the thermocouple is given in Fig. 3(b) which was used to measure the temperature. The length and width of the digital scale is also given in Fig. 3(c) which was used for measuring the evaporation rate. Fig. 3(d) represents design and dimensions of a pyranometer for natural solar flux measurement consisting of three disks. The dimensions of each disk are carefully noted. Fig. 3(e) shows the width, height, and thickness dimensions of data logger that was used to record all data for analysis of photothermal experiments.

In this photothermal experiment three processes were performed to heat the liquid until it achieved a steady state for their evaluation of nanofluids for water desalination applications.

- A thermal insulation material was used in the face opposite to solar radiation.
- To obtain high accurate temperature measurements for achieving steady-state conditions, thermocouple holders were used to ensure that the sensor position was correctly positioned at the top, middle and bottom in the petri dish to avoid leakage.
- Additionally, the experiment was conducted under clear sky conditions. The experiment was conducted at a constant concentration of 0.01 % by weight for each type of nanofluids four days to obtain accurate photothermal data. The solar irradiance values shown in Fig. 4 below indicate the potential magnitude of apparent solar flux under which the experiment was conducted and steady state conditions were obtained. The maximum average temperature was recorded at 43 °C.

Methods for achieving test conditions are described as follows. In this work, experiments were performed for the comparison of the photothermal efficiency of GO, ZnO, FeO and their binary combinations GO-ZnO, GO-FeO for their potential application in water purification under natural solar flux. The location of the experiment was Lahore, Punjab Pakistan (32.692° North Latitude and 75.254° East Longitude). Experiments were performed with predetermined conditions. The sample concentration was kept at 0.01 wt % concentration, and thermocouple positions were determined for the top, middle, and bottom of the Petri dish in the tested fluids. Three equally spaced K-type thermocouples were used for temperature measurement. These thermocouples were calibrated at three points before being used in this experiment and the mass loss due to evaporation was also recorded using a digital balance. Irradiance data was recorded using a pyranometer.

Temperature, mass loss and irradiance data were recorded after 10 s through a data acquisition system. Experiments were repeated for four days at the same 0.01 wt% concentration for each type of nanofluids to obtain accurate and precise photothermal data including temperature data, mass loss data, and irradiance data. Experiments were conducted under clear sky conditions to evaluate the photothermal performance of nanofluids under natural solar flux under realistic conditions. Further, uncertainty analysis is described in Section 3.5.

Nanofluids are an important area of research used in heat transfer applications due to their exceptional heat transfer capabilities. The choice of nanoparticles depends on their stability in the base fluid. GO, ZnO, FeO and their binary combination (GO-ZnO, GO-FeO) were used in this research study due to their high stability, high thermal conductivity, high absorption, high specific heat value and low density. The physiochemical properties of these nanoparticles are given in Table 2. Based on these properties, these nanoparticles have been selected for the preparation of nanofluids that are used as working fluids in the system.

Photothermal experiments were performed on various water-based nanofluids including GO, ZnO, FeO and binary nanofluids (GO -ZnO and GO-FeO) at a concentration of 0.01 wt% under natural solar flux. Binary nanofluids (GO-ZnO and GO-FeO) containing

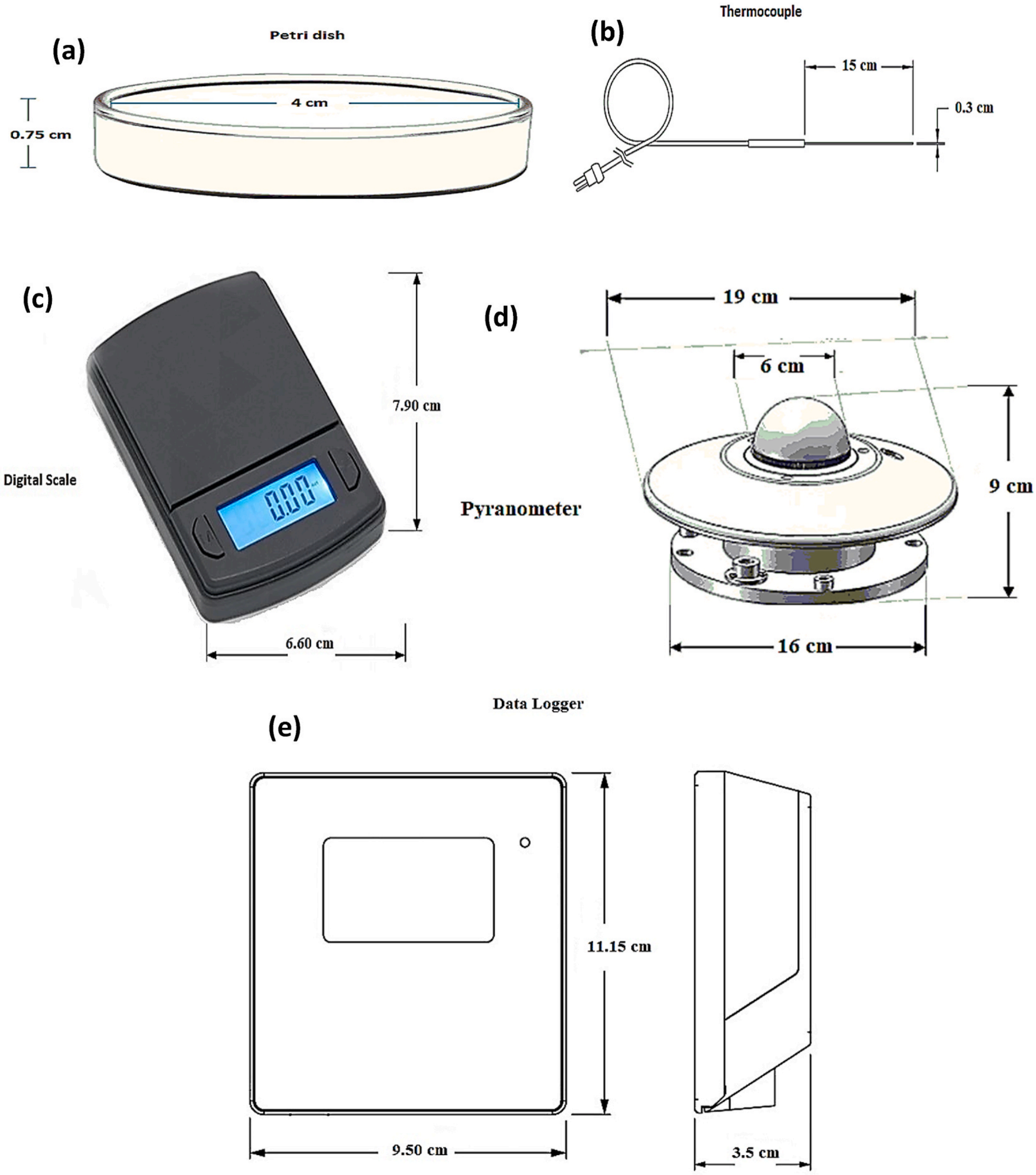

Fig. 3. The System design and dimensions of (a) Petri dish, (b) thermocouple, (c) digital scale, (d) data logger, (e) pyranometer.

different mixing ratios are analyzed. Table 3 shows the photothermal experiments for water based nanofluids of GO, ZnO, and FeO, and binary combinations of GO-ZnO and GO-FeO at 0.01 wt%. Were done. The amount GO varies in each sample, but the total weights of the binary nanofluids is still the same by varying the amount of other nanoparticles used in this work. During the experiments, it was revealed that a small addition of nanoparticles to the base fluid (DI water) increased the thermophysical properties of the water which is used as a base fluid in this study. It was also observed that photothermal performance of binary nanofluids (GO-ZnO and GO-FeO) is strongly dependent and sensitive to the ratio of the optimum concentration of nanoparticles and the large ratio of individual nanoparticles containing ZnO and FeO reduced overall performance.

3. Results and analysis

3.1. Optical absorbance

It is very important to assess the effectiveness of nanofluids for absorbing light in the visible range of the solar spectrum using UV–visible spectroscopy techniques. This technique measures optical absorption in which a nanofluid sample absorbs light and converts it to heat. Optical absorption analysis to assess dispersion stability and light absorption is important in determining the suitability of nanofluid samples for use in solar energy applications such as water desalinations. Highly absorbent materials with the

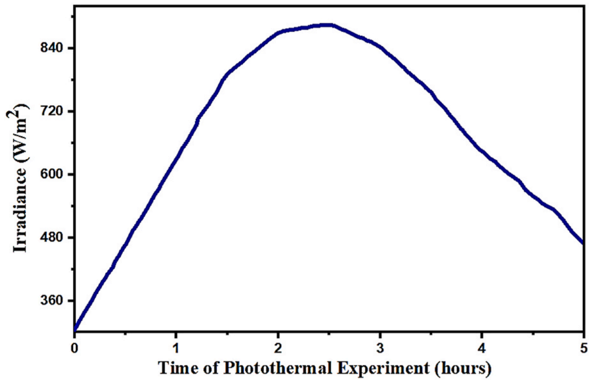

Fig. 4. Average solar flux observed in a photothermal experiment.

highest dispersion stability are considered good candidates for solar energy harvesting. For this purpose, UV–Vis spectrometer was used to test the optical absorption of different nanofluids at 0.01 % by weight of nanoparticles. In the UV–visible region, various nanofluids, given in Fig. 5(a–c), have different absorption peaks at a concentration of 0.01 % by weight. Experimental results show that different types of nanofluids have shown different optical absorption peaks in the UV to visible light spectrum. Water based nanofluids composed of GO, ZnO, and FeO nanoparticles at 0.01 % by weight exhibit broad shoulders at wavelengths of 281 nm, 362 nm, and 395 nm, respectively is given in Fig. 5(a). The maximum absorption value was obtained in the case of pure GO. This high absorption of GO nanofluids sample can be related to its dark color, good dispersion stability, high absorption and high thermal conductivity. While the least absorption was found in FeO nanofluids because FeO is not a good absorber of solar energy in the visible light spectrum as compared to other nanofluids used in this study. Compared to GO, the optical absorption of all other nanofluids in this study has most of their absorption peaks in the UV to visible region. In Fig. 5(b–c), the optical absorbance of the binary nanofluids (GO-ZnO and GO-FeO) is presented. The absorption spectrum shows absorption in the visible and infrared but significant absorption region in the UV region. In both binary (hybrid) combinations, the intensity of the absorption peaks decreases with decreasing GO concentration. Therefore, pure graphene oxide (100%GO) nanofluids exhibited the highest absorption peak among all water based nanofluids (GO, ZnO and FeO) and their composites (GO-ZnO and GO-FeO) due to maximum absorptivity.

As the amount of GO decreases and the amount of ZnO and FeO increases in both (GO-ZnO and GO-FeO) binary combinations, the contribution of GO to the absorption spectrum decreases because of the different electronic structure of ZnO and FeO compared to GO. The difference in optical absorption of GO-ZnO and GO-FeO binary nanofluids is a result of changing the amount of GO, ZnO and FeO in the overall absorption spectrum. The electronic structure of GO, ZnO and FeO describe their interaction with light, which changes the absorption properties when the mixing ratio is varied. Maximum absorption is observed in 100 % GO nanofluids samples compared to other samples which indicates that GO is a carbon-based nanomaterial that exhibits strong absorption peak due to its conjugated electronic structure. In the binary composite of (GO-ZnO and GO-FeO) materials, reducing the amount of GO decreases the optical absorption due to the presence of other nanoparticles (ZnO) and (FeO).

A comparison of the results obtained with previous work on optical absorption is reported in Table 4 in terms of maximum absorption value and wavelength at the maximum absorption peak. The optical absorbances given in Table 4 for this study have been increased compared to previous work due to the increased concentration of samples. The published work in the table was performed at a concentration of 0.0004 wt%. And the present work of this paper is carried out at 0.01 wt% concentration.

3.2. Bulk fluid temperature

In the photothermal experiment, minute amounts of nanoparticles in deionized water (DI water) are used to prepare nanofluid samples, which are used to treat the nanoparticle temperature as the bulk fluid temperature of the nanofluid sample. To observe the solar absorption of nanofluids consisting of GO, ZnO, FeO and their composites (GO-ZnO and GO-FeO) in a direct or volumetric solar thermal collector, all these types of nanofluids including deionized water (base fluid) were heated under natural sunlight for 5 h. Three equally spaced thermocouples were used for measuring the average temperature of each type of nanofluid used in this work. At the beginning of the experiment, a linear increase in average temperature has been observed in all temperature measuring thermocouples. But, this trend was not observed later. The temperature rise is given in Fig. 6(a–c), referred as the average temperature change between the initial temperature of the nanofluids at the beginning of the experiment and the final temperature during exposure to sunlight. At the beginning of the experiment, most of the solar thermal energy was transferred into the solution of the nanofluids samples resulting in a linear increase in temperature. Some heat is lost to the atmosphere. As the temperature of the nanofluid samples increases, the average temperature difference between the sample and the environment also increases. As a result, the heat loss increases so that later the linear trend is not observed as at the beginning of the experiment. Furthermore, thermocouple TC1 showed higher temperature rise than the other two thermocouples TC2 and TC3 as shown in Fig. 2. This was observed due to the tendency of solar radiation to decrease with required optical length. A maximum temperature rise of 17.75 °C was observed as measured by three equally spaced K-type thermocouples. The temperature rise was calculated using the formula $\Delta T = (\Delta TC1 + \Delta TC2 + \Delta TC3)/3$. Average temperature rise versus time was plotted for all types of nanofluids at a particle concentration of 0.01 % under natural solar flux. The average increase in

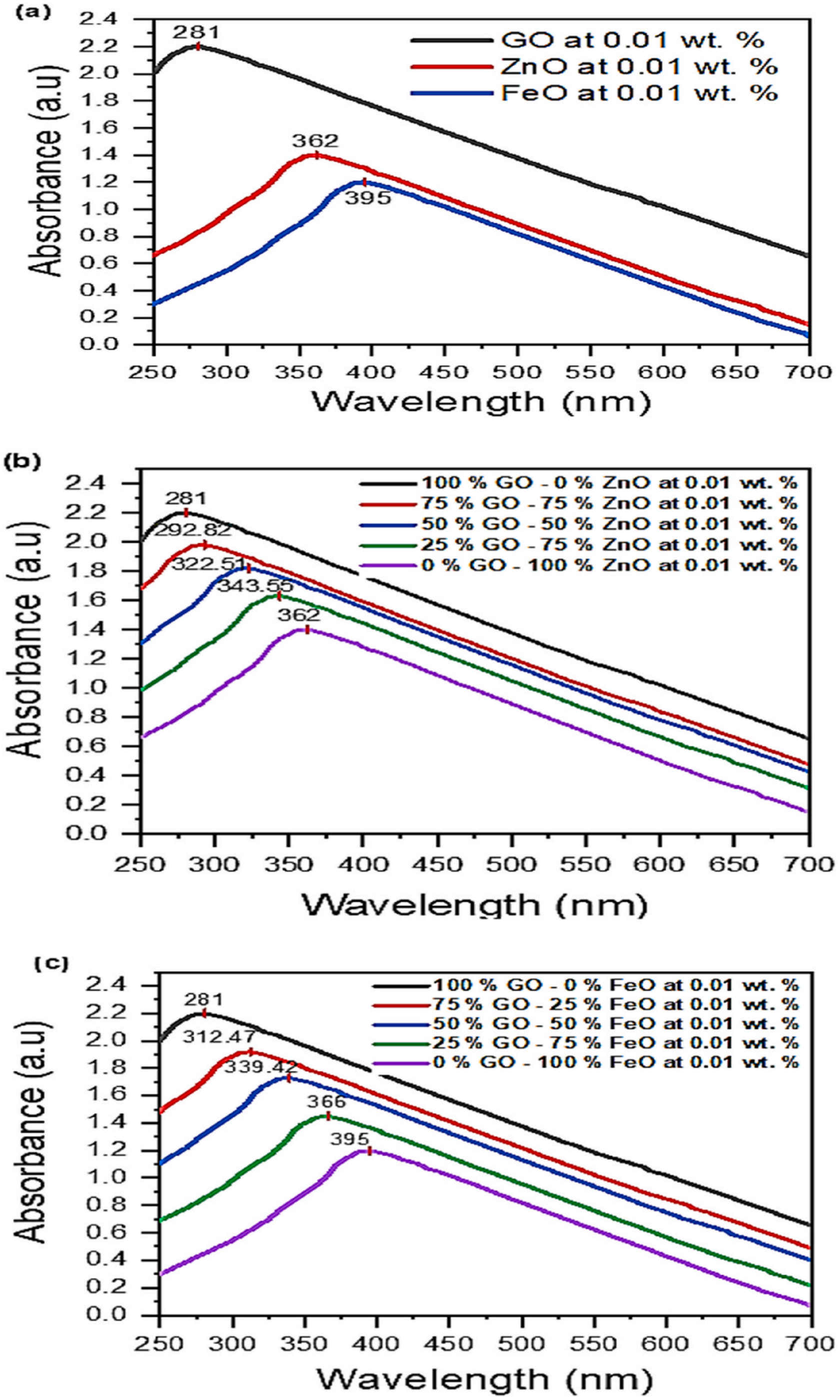

Fig. 5. Optical absorbance spectra at a concentration of 0.01 wt %. (a) Nanofluids of GO, ZnO, and FeO, (b) binary nanofluids with GO-ZnO, (c) binary nanofluids with GO-FeO.

temperature profile of GO, ZnO, FeO and their binary composite ((GO-ZnO and GO-FeO) is revealed in Fig. 6(a–c). It has been experimental observed that all types of nanofluids show a higher temperature gradient than DI water. At 0.01 wt% concentration, the average temperature rise of GO, ZnO, and FeO nanofluids was 17.75 °C, 10.88 °C, and 8.31 °C, respectively, for a period of 5 h under natural solar flux. Photothermal experiments were also conducted to evaluate the thermal performance of binary nanofluids containing GO-ZnO and GO-FeO. This experiment compared the performance of GO-ZnO and GO-FeO binary nanofluids with single component ZnO and FeO nanofluids as well as DI water. The experimental outcomes presented that the average temperature change for binary nanofluids initially increased and then lessened by increasing concentrations of ZnO and FeO. However, the binary

Table 2
Properties of nanoparticles and base fluid.

Substance	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat value (kJ/kg-K)	References
GO	2267	2000–5000	0.710	[48]
ZnO	5601	50	0.494	[49]
FeO	5740	2.2	0.449	[50]
DI water	998	0.6	4.19	[51]

Table 3
Different nanofluids with different nanoparticles mixing ratio.

S.No.	Nanofluid (%)	GO amount(g)	Nanofluid Concentration (wt. %)
1	100 % GO	0.01	0.01
2	75%GO +25 % ZnO	0.0075	0.01
3	50%GO +50 % ZnO	0.0050	0.01
4	25%GO+ 75 % ZnO	0.0025	0.01
5	100 % ZnO	0.0000	0.01
6	75%GO +25 % FeO	0.0075	0.01
7	50%GO +50 % FeO	0.0050	0.01
8	25%GO+ 75 % FeO	0.0075	0.01
9	100 % FeO	0.0000	0.01

Table 4
Comparison of optical properties of different nanofluids at different mixing ratios with previous results.

Current work			Published work			
Name of sample	Maximum Absorbance (a.u)	*Wavelength at maximum absorbance (nm)*	Name of sample	Maximum Absorbance (a.u)	*Wavelength at maximum absorbance (nm)*	References
100 % GO	2.2	281	100 % GO	~1.62	275	[52]
75%GO +25 % ZnO	1.98	293	80%GO +20 % ZnO	~1.27	250–400	
50%GO +50 % ZnO	1.82	323	60%GO +40 % ZnO	~1.09	250–400	
25%GO+ 75 % ZnO	1.63	344	20%GO+ 80 % ZnO	~0.98	250–400	
100 % ZnO	1.4	362	100 % ZnO	~0.93	300–400	
75%GO +25 % FeO	1.92	312.4	NA			
50%GO +50 % FeO	1.73	339.42				
25%GO+ 75 % FeO	1.45	366				
100 % FeO	1.2	395	100 % FeO	1.22	388	[53]

nanofluids performed better than the single component ZnO and FeO nanofluids, as given in Fig. 6(b–c). At higher concentrations of GO, the addition of ZnO and FeO nanoparticles decreased the performance of the composites, even at lower mass concentrations of ZnO and FeO. However, the mixture still performed better than DI water. It was also noted that temperature rise is directly related to sensible efficiency calculated from Equation (2) and revealed in Fig. 8(a–c). Highest temperature rising and sensible heating efficiency were obtained in pure GO nanofluid amongst all the nanofluids because of its maximum solar energy absorption at 0.01 wt% concentration. Pure graphene oxide (GO) has exceptional properties with strong radiation absorption due to its unique atomic and electronic structure. Graphene oxide (GO) has efficient electron delocalization and dark color, making it an excellent absorber of solar radiation. The increase at high temperature was due to the carbon-based structure of GO with black color. This dark-colored GO absorbs more radiation than all other nanofluids used in this study.

3.3. Evaporation rate (mass loss)

To calculate the evaporation efficiency, which is an essential factor in the field of water desalination, a digital weighing scale was used for measuring the mass loss of the nanofluids samples due to evaporation. For this purpose, the experiment was conducted under natural sunlight for 5 h, which initially heated the bulk fluid. The sensible heat contributions for water-based nanofluids GO, ZnO, FeO, and their composites (GO-ZnO and GO-FeO) were confirmed in Fig. 8(a–c). As experimentation progressed, the absorbed energy was utilized to vaporize the nanofluid sample, resulting in enhanced loss of heat loss towards environment as overall average temperature of sample volume increased. Experimental outcomes showed that mass loss of nanofluid samples was proportionate to rise in the bulk fluid temperature of samples, as presented in Section 3.2. Fig. 7(a–c) shows average evaporative mass loss of individual nanofluids (GO, ZnO, FeO) and their binaries (GO-ZnO and GO-FeO). At a particle concentration of 0.01 wt%, the highest mass loss of pure GO

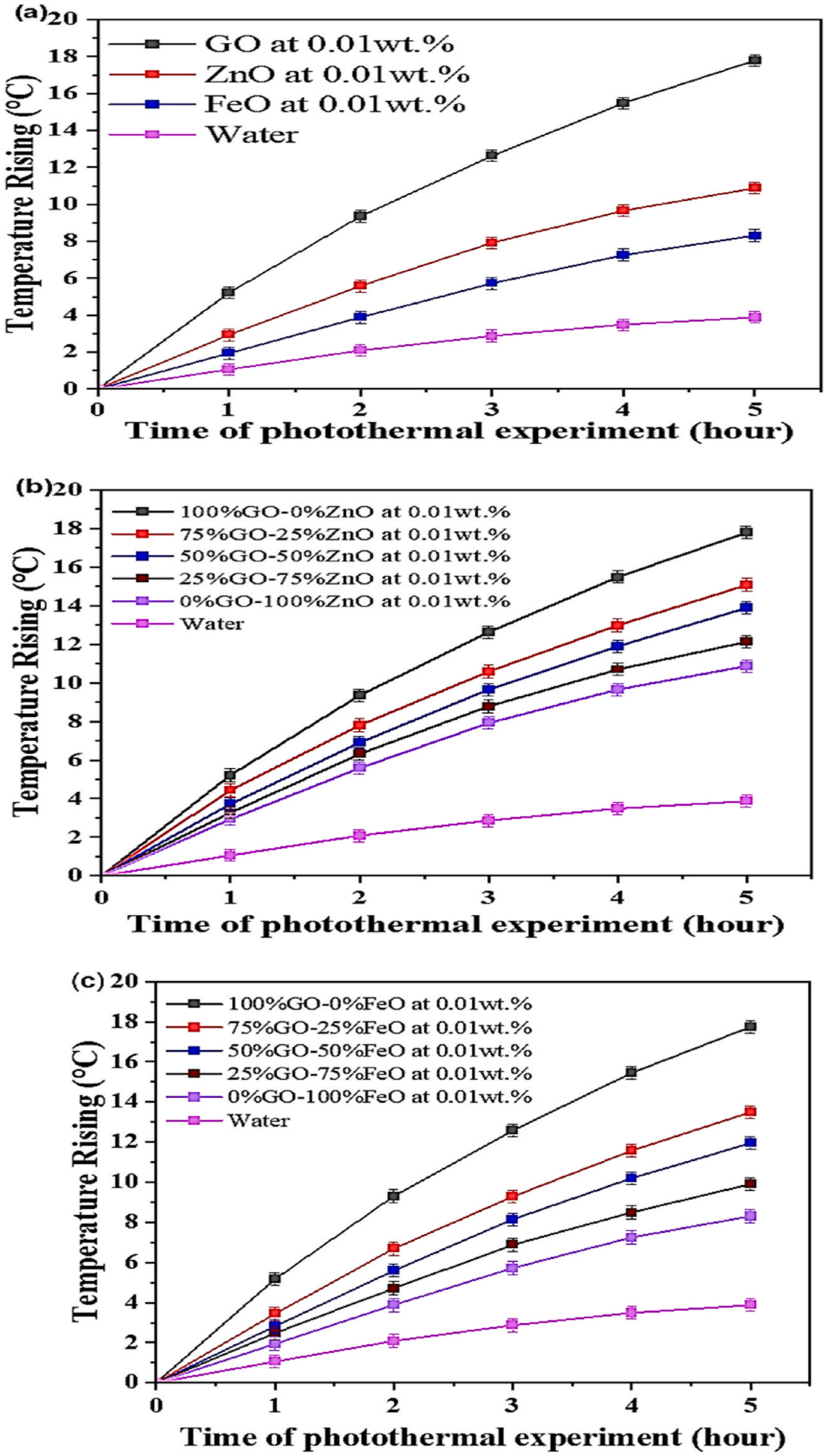

Fig. 6. Average temperature rising at a concentration of 0.01 wt %. (a) Nanofluids of GO, ZnO, and FeO, (b) binary nanofluids with GO-ZnO, (c) binary nanofluids with GO-FeO.

nanofluid was observed, which proved that graphene oxide (GO) absorbed more solar energy than other nanofluid samples in this study. It was found that pure GO was able to absorb more solar flux than other nanofluid samples in this investigation and the maximum mass loss was observed due to higher absorption in GO nanofluid, and less low absorbance was observed in deionized water. This is also in align with the results of other research studies [54]. For the binary nanofluids (GO-ZnO and GO-FeO) with 0.01 wt%

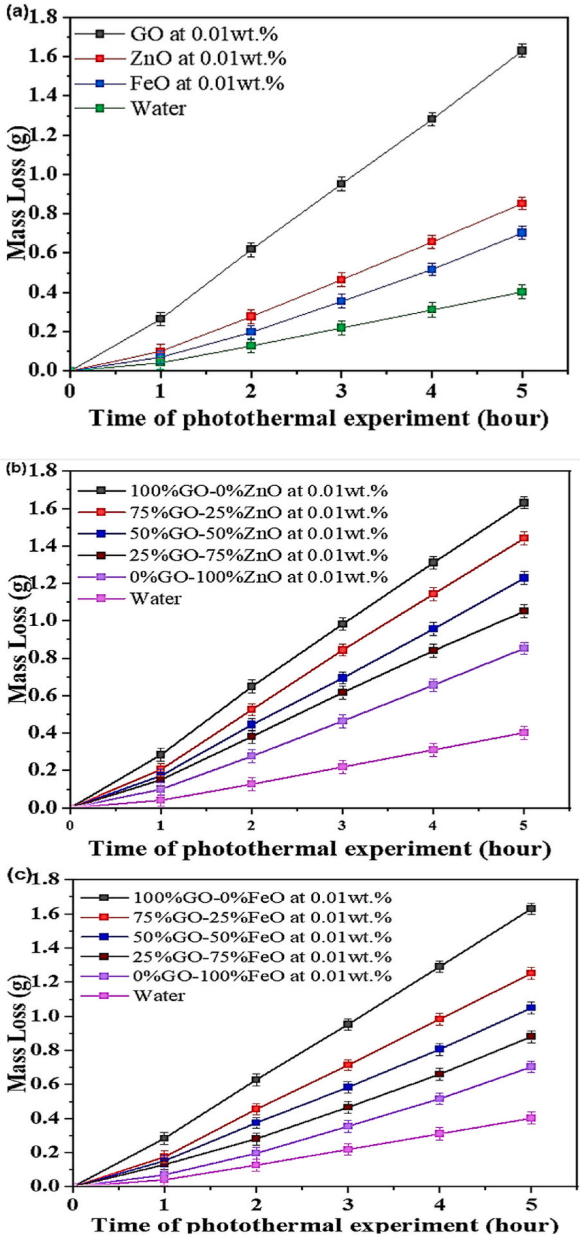

Fig. 7. Average mass loss at a concentration of 0.01 wt %. (a) Nanofluids of GO, ZnO, and FeO, (b) binary nanofluids with GO-ZnO, (c) binary nanofluids with GO-FeO.

particle concentration, the average mass loss augmented at first and then reduced with increasing concentrations of FeO, and ZnO which is displayed in Fig. 7(b–c).

In case of pure GO, the highest mass loss was observed compared to pure ZnO, pure FeO and their binary combination which is described in form of different solar absorption of nanoparticles in base fluid (DI water). As GO is a carbon-based nanofluid with an unusual arrangement of carbon atoms with oxygen-containing functional groups that allows greater interaction with solar radiation resulting in greater absorption and greater evaporation. The decrease in mass loss also depends on the concentration of GO in (GO-ZnO and GO-FeO) which decreases with decreasing GO concentration. Each GO nanoparticle in binary mixture (GO-ZnO and GO-FeO) serves as a potential candidate for absorbing solar radiation from the natural sun. A higher concentration of GO means that a larger number of particles allow more solar radiation to be absorbed, which increases the overall solar nanoparticle's absorption capacity in base fluid leading to a higher evaporation rate.

3.4. *Photothermal efficiency*

Solar energy harvesting is evaluated by analysing evaporation efficiency, sensible heating efficiency, and total photothermal ef-

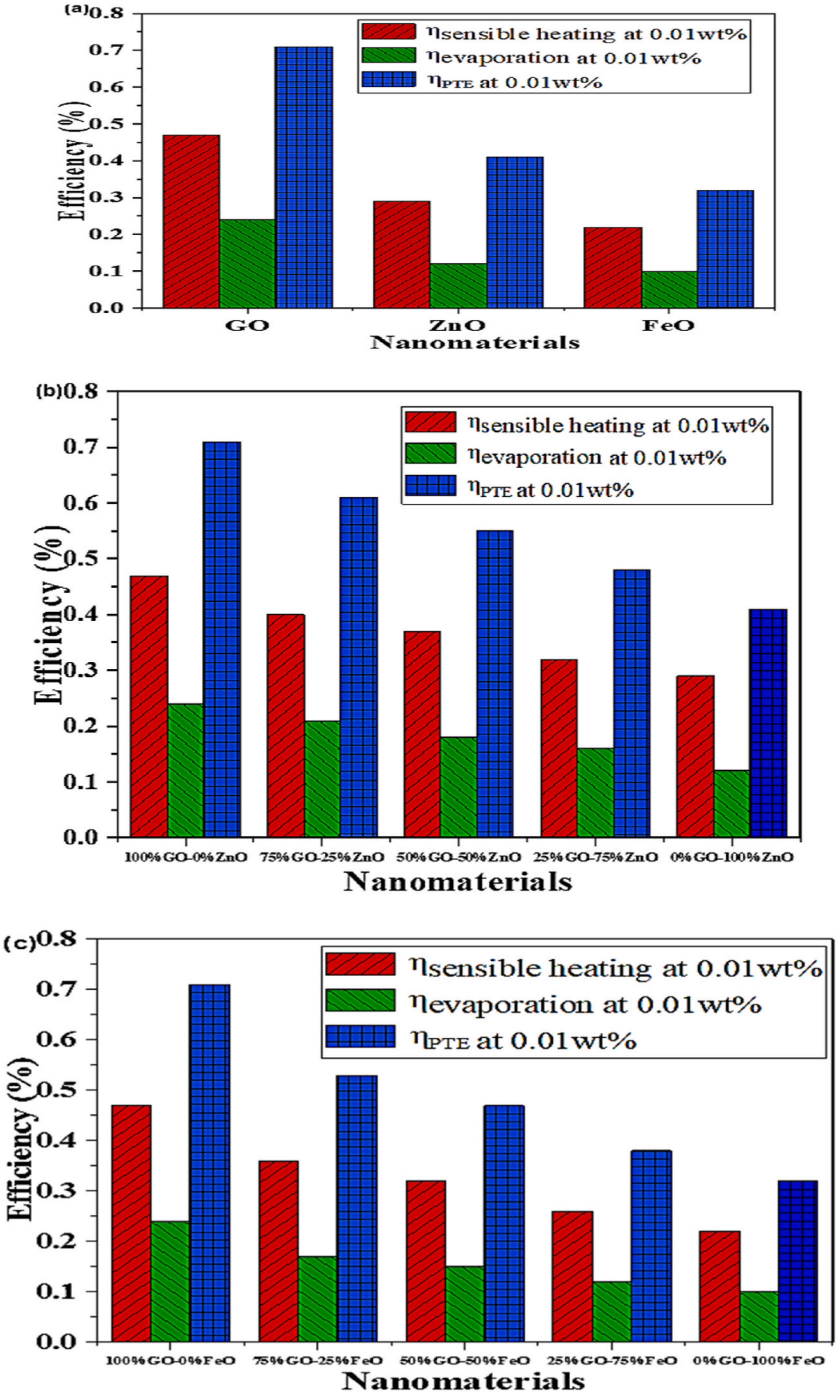

Fig. 8. Sensible heating efficiency, evaporation efficiency and photothermal efficiency at a concentration of 0.01 wt %. (a) Nanofluids of GO, ZnO, and FeO, (b) binary nanofluids with GO-ZnO, (c) binary nanofluids with GO-FeO.

ficiency which are used to determine the suitability of nanofluids for water desalination applications under natural sunlight. Evaporation efficiency $\eta_{(\text{evaporation})}$ is stated as the ratio of latent energy of evaporation to input energy of incident radiations [55].

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

where L_v is latent heat of vaporization for a nanofluid supposed to be equal to that of water at pressure of 1 atm m_{loss} is the mass loss of the nanofluid samples. A is illumination area of the nanofluid sample exposed to light. I represent solar flux. t is the illumination time, when sample is exposed to light.

Sensible heating efficiency ($\eta_{(\text{sensible heating})}$) is also an important parameter for solar energy harvesting e to evaluate the performance of nanofluids under natural solar flux. It measures the effectiveness of a heating system that transfers heat to a fluid. It can describe as the ratio of the amount of heat used in heating the nanofluid samples to the input energy of the radiation [55].

$$\eta_{(sensible\ heating)} = \frac{(C_w m_w).\ \Delta T}{I.A.t} \quad (2)$$

In equation (2), C_w represents specific heat capacity of the base fluid water having value of 4.19 kJ/kg.K. m_w is the initial mass of water. ΔT represents the average change in temperature rise of the nanofluid sample in time (t).

Photothermal efficiency (η_{PTE}) is the sum of sensible heating efficiency and evaporative efficiency calculated by equation 03 [55].

$$\eta_{\text{PTE}} = \eta_{(\text{evaporation})} + \eta_{(sensible\ heating)} \quad (3)$$

Fig. 8(a–c) contains the main experimental results of this study at 0.01 wt% under natural sunlight. Experimental results are expressed in terms of sensible heat efficiency, vaporization efficiency and photothermal efficiency depending on temperature change and mass loss. Higher temperature change and mass loss mean result in higher sensible and evaporation efficiencies, respectively. As a result of this higher Photothermal efficiency is achieved.

Fig. 8(a–c) shows the sensible heating efficiency, evaporation efficiency, and photothermal efficiency of GO, ZnO, FeO and binary combinations (GO-ZnO and GO-ZnO) for 0.01 wt% particle concentration. This also shows that the photothermal efficiency depends on sensible heating efficiency and evaporation efficiency. More sensible heating and evaporation Efficiency, more will be photothermal efficiency.

Equations (1) and (2) correspond to the energy harvesting s system in which sensible heating efficiency depends on the temperature rise and the evaporation efficiency depends on the mass loss of the nanofluids. So, maximum temperature increases and mass loss which is given in Sections 3.2 and 3.3 were found maximum in the case of pure GO. Therefore, the most sensible heating efficiency, evaporation efficiency, and photothermal efficiency were found in case of pure GO due to the maximum absorption amongst all the nanofluids used in this research study.

Fig. 8(b–c) shows the photothermal performance of binary nanofluids (GO-ZnO and GO-FeO) which strongly depends on the mixing ratio of nanoparticles and a larger proportion of single nanoparticles containing ZnO and FeO reduced the overall efficiency. As the amount of GO decreases in both binary combinations (GO-ZnO and GO-FeO), resulting in decreased photothermal efficiency. According to the results of these experimental investigations are shown in Fig. 8(a–c), pure GO and its binary composites are proven as a potential candidate for direct absorption solar collection which can be used in water purification applications compared to single ZnO and FeO nanofluids. The higher sensible, evaporation and photothermal efficiencies of GO nanofluids are directly related to the maximum solar energy absorption.

Table 5 contains the experimental results of this study at 0.01 wt% concentration under natural sunlight. Temperature change, mass loss, sensible heating efficiency and evaporation efficiency are considered as important factors in the calculation of photothermal efficiency to evaluate the solar scavenging potential of individual, and binary nanofluids. It was observed that pure GO, pure ZnO and pure FeO show photothermal efficiencies of 71 %, 41 % and 32 %, respectively.

The photothermal performance of binary nanofluids (ZnO–GO and GO–FeO) strongly depends on the concentration of GO. As the amount of GO decreases, the photothermal efficiency decreases. The interaction between GO, ZnO and GO, FeO enhances the effect of nanofluid samples resulting from solar absorption from natural sunlight. (GO-ZnO, GO-FeO) synergistic effect, enhanced solar absorption. The electronic structure of GO, ZnO and FeO also significantly affects the solar absorption as discussed in Sections 3.1 to 3.3. Table 5 shows that comparing all the nanofluids used in this study, the pure Go nanofluids have the highest photothermal efficiency at 0.01 wt% under the sun and proved to be a potential candidate for energy utilization for water desalination applications. Graphene oxide (GO) has a carbon-based atomic structure, high thermal conductivity, high stability and dark color nature, which makes GO an excellent absorber of solar energy, which increased its photothermal efficiency level.

Table 6 includes a comparison of photothermal efficiency based on previous and current results. The photothermal efficiency given in Table 6 for this study have been increased compared to previous work due to the increased concentration of the samples. Previous results of photothermal efficiency are at 0.0004 wt% concentration and in the present work the photothermal efficiency was calculated

Table 5
Sensible heating, evaporation and photothermal efficiencies of different nanofluids with different mixing ratios of different nanoparticles.

S. No.	Nanofluid (%)	ΔT(°C)	$\eta_{(\text{sensibleheating})}$	$\eta_{(\text{evaporation})}$	$m_{\text{loss}}(g)$	$\eta_{(\text{PTE})}$
1	100 % GO	17.75	47 %	24 %	1.63	71 %
2	75%GO +25 % ZnO	15.05	40 %	21 %	1.44	61 %
3	50%GO +50 % ZnO	13.85	37 %	18 %	1.23	55 %
4	25%GO+ 75 % ZnO	12.10	32 %	16 %	1.05	48 %
5	100 % ZnO	10.88	29 %	12 %	0.85	41 %
6	75%GO +25 % FeO	13.49	36 %	17 %	1.25	53 %
7	50%GO +50 % FeO	11.95	32 %	15 %	1.04	47 %
8	25%GO+ 75 % FeO	9.91	26 %	12 %	0.88	38 %
9	100 % FeO	8.31	22 %	10 %	0.70	32 %

Table 6
Comparison of photothermal performance of nanofluids at different mixing ratios with published results.

Current work		Published work		
Nanofluids samples	η_{PTE}	Nanofluids samples	η_{PTE}	Reference
100 % GO	71 %	100 % GO	~41 %	[52]
75%GO +25 % ZnO	61 %	80%GO +20 % ZnO	~38 %	
50%GO +50 % ZnO	55 %	60%GO +40 % ZnO	~33 %	
25%GO+ 75 % ZnO	48 %	20%GO+ 80 % ZnO	~26 %	
100 % ZnO	41 %	100 % ZnO	~22 %	
75%GO +25 % FeO	53 %	NA		
50%GO +50 % FeO	47 %			
25%GO+ 75 % FeO	38 %			
100 % FeO	32 %			

at 0.01 wt% concentration.

3.5. Uncertainty analysis

Measurement uncertainty is the uncertainty in the results of any measurement. Well-designed instruments provide accurate answers. But for every measurement, there is always a margin of doubt or error. Equation (3) represents the photothermal conversion efficiency. According to this equation the photothermal efficiency is summation of sensible heating and evaporation efficiencies which are functions of m_w, ΔT, m_{loss}, and I. Therefore, uncertainty in photothermal efficiency U(η) is calculated using equation (4).

$$(U_\eta)^2 = \left(\frac{\partial \eta}{\partial m_w} Um_w\right)^2 + \left(\frac{\partial \eta}{\partial \Delta T} U\Delta T\right)^2 + \left(\frac{\partial \eta}{\partial m_{loss}} Um_{loss}\right)^2 + \left(\frac{\partial \eta}{\partial I} UI\right)^2 \tag{4}$$

Uncertainties in measurements are given in Table 8.

Table 7 describes the accuracy of the instruments used in this experimental work. In this work, different instruments are used to calculate different parameters for measuring the photothermal efficiency of nanofluids. A thermocouple, weight balance, and pyranometer were used to measure average temperature, evaporative mass loss, and solar flux, respectively, during the experiments.

Further, the uncertainty in parameter measurements is given in Table 8.

Three methods were used in this study to validate the results.

- All instruments used in experimental testing were calibrated, for example, calibration was performed on the thermocouples using a National Institute of Standards and Technology traceable precision glass thermometer with an accuracy of ±0.01 °C. The digital scale and pyranometer were also calibrated with instrument accuracy of ±10 W/m^2 and ±0.0001 g, respectively.
- Experiments were repeated for four days at the same 0.01 wt% concentration for the same type of nanofluids to obtain accurate and precise photothermal data.
- Error bars were used graphically to signal the variability in experimental data known as uncertainty.

Error bars indicate graphical presentations of data variability and are displayed in graphical figures to indicate error or uncertainty in reported measurements of experimental data of any experimental study. In this study, Error bars were calculated using the standard deviation, which is the mean difference between the data points and their mean. Figs. 6 and 7 show the error bars for temperature rise and mass loss used to calculate both sensible and evaporative efficiencies, respectively, and their sums define the photothermal efficiency.

3.6. Comparison with existing technologies

Solar energy is of great attention worldwide as a renewable energy source, resulting in many applications and research works on it. It has applications in both thermal and power generation. Approximately 30 % of sun radiation reaches the earth after every 20 min, enough to end the global energy crisis. As a renewable energy source, solar energy is widely accessible in power generation systems around the world [56]. The use of heat transfer fluids containing nanoparticles to capture solar radiation has great potential for water purification. Nevertheless, harnessing solar energy effectively is a challenging endeavor. The low solar absorption of nanofluids can be a significant challenge when considering their use in solar thermal systems in a solar-powered water purification application. Solar absorptivity is an important parameter that determines how efficiently a fluid absorbs sun rays and alter it in heat, which is essential for numerous solar energy applications. Solar thermal collectors capture the energy that is produced by the sun. In solar thermal systems, efficient absorption and retention of maximum solar energy is critical for optimal heat transfer and energy conversion.

Table 7
Accuracy in measuring devices.

Devices	accuracy
thermocouples	±0.01 °C
pyranometer	±10 W/m^2
digital weighing balance	±0.0001 g

Table 8
Uncertainty in measuring parameters.

Parameter	Uncertainty (%)
Temperature	±1.3 %.
Mass loss	±2.24 %.
Irradiance	±5 %.
Sensible heating efficiency	±2.16 %.
Evaporation efficiency	±1.35 %.
Photothermal efficiency	±3.51 %.

Previous studies have shown that conventional solar thermal collectors which is the existing technology for capturing solar radiation, work through the process of radiative absorption on a black surface, which then transfers the absorbed heat to the working fluids. The first radiation is absorbed in the black coating plate, transported in the tube using conduction mode, and then transferred from tube to working fluids via convective mode of heat transfer. As radiation passes through the three mediums in the form of heat, it causes thermal loss in each medium. Therefore, this conventional solar thermal technology is not effective for capturing radiation due to thermal resistance between solar rays and working fluids which ultimately reduce solar absorption. Fig. 9(a) shows the absorption phenomena of a surface-based or conventional solar thermal collector and Fig. 9(b) illustrates the working principle of a conventional or surface-based solar thermal collector, which is an ancient art technique for heating the working fluids by capturing solar energy.

In this research work, to reduce these thermal losses, a new technology called volumetric was developed for direct absorption solar collection. In a volumetric collector, solar radiation falls directly on the working fluids. Therefore, there is no thermal resistance to solar radiation reaching the working fluids.

The solar absorption phenomena using a volumetric collector is shown in Fig. 10. It clearly shows that the solar radiation falls directly on the nanofluid samples and does not encounter any resistance. Fig. 10 (b) explain the working principle step by step. On the bases of the principle of operation, volumetric collector has proved to be one of the best technologies used in this research as compared to existing technology which is surface-based absorption solar collectors. The newly proposed volumetric solar thermal collection technology reduces thermal losses due to direct absorption without any resistance between solar radiation and working fluids. It enhances the solar absorption of nanofluids to test their potential for water purification applications.

Various losses including reflection loss, absorption loss, radiation loss, heat conduction loss, and heat convection loss in the case of conventional or surface-based solar thermal collectors which are a previous technology for capturing solar radiation is given in Fig. 11 (a).

$$\eta_{absorption} = 1 - \frac{Q_{loss}}{Q_{solar\ incident}} \tag{5}$$

Thermal losses reduce the absorption efficiency of collector which is described with Equation (5). According to Fig. 11(a) below, the total thermal loss in surface or conventional base solar thermal collection was 40 % using surface-based technology. Fig. 11(b) represents the thermal losses using a volumetric or direct solar thermal collector, which is novel. This technology showed only minimal thermal losses and 80 % absorption could be achieved compared to existing solar technology. If a comparison is made between conventional (existing technology) and volumetric solar thermal collectors (new technology), it can be easily seen that the least thermal losses occur in volumetric type of the collector as shown in Fig. 11. According to Equation (6), higher absorption can be achieved using the volumetric-based technology due to the minimal thermal losses compared to the surface-based technology that is

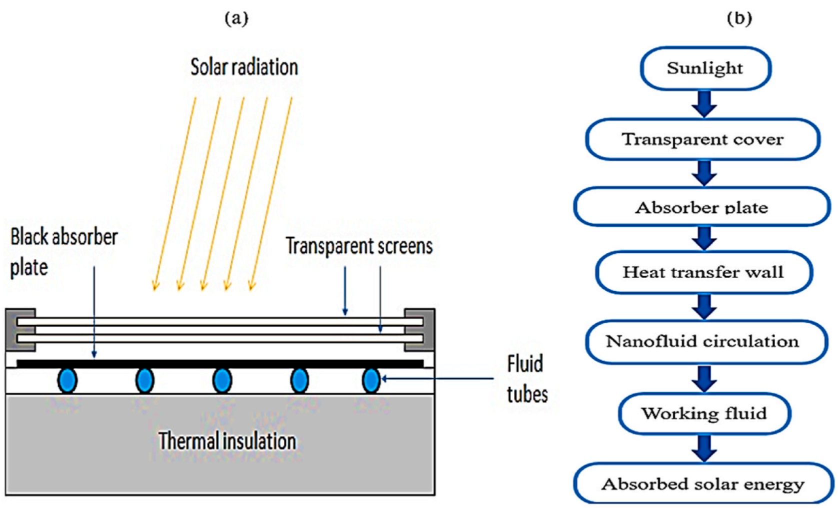

Fig. 9. Surface base or conventional solar thermal collector (a) Solar absorption phenomena [57] (b) Working principle.

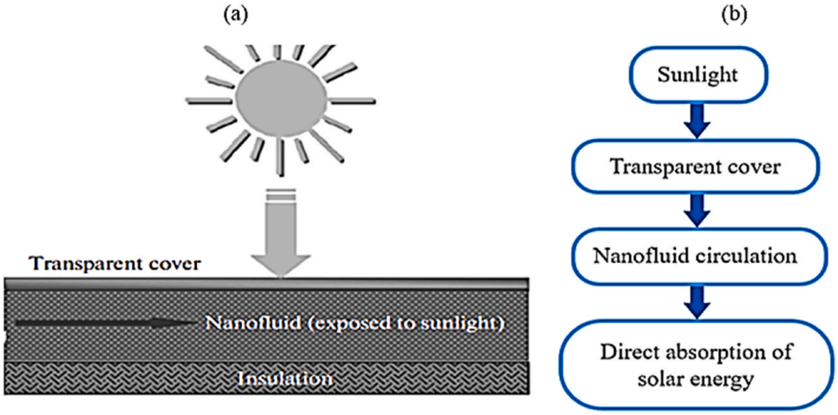

Fig. 10. Volumetric or direct absorption solar thermal collector (a) Solar absorption phenomena [58], (b) Working principle.

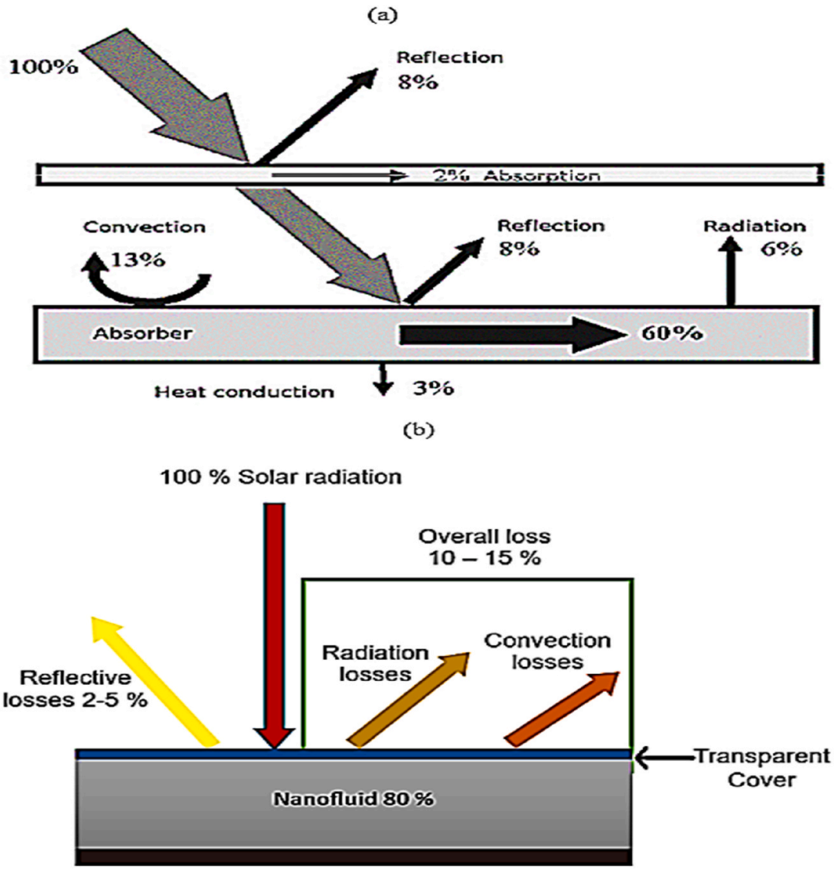

Fig. 11. Heat losses in (a) Surface base or conventional solar thermal collector [59], (b) Volumetric or direct absorption solar thermal collector [60].

existing available. For this reason, volumetric solar thermal collectors were used instead of conventional or surface ones. It is considered to be an efficient solar thermal collector. Fig. 11 illustrates the comparison between existing technology called conventional or surface solar thermal collection systems and volumetric or direct absorption solar collection in terms of thermal loss and solar absorption. Minimum losses and high absorption were achieved in volumetric base solar capturing technology.

This current research study deals with photothermal applications in solar energy sector. The focus is on the comprehensive study of various nanofluids, from their synthesis to actual applications. These nanofluids look promising for existing solar thermal collectors and provide a sustainable solution using renewable energy to achieve higher photothermal efficiency than currently available.

This work consists of four main points: synthesis, SEM characterization, optical characterization and solar energy conversion of different types of nanofluids using a volumetric collector for water purification applications.

A photothermal performance of nanofluids containing GO, ZnO, FeO, and their composites (GO-ZnO and GO-FeO) have been studied under the natural sun to determine the potential for water desalination applications at particle concentrations of 0.01 wt%.

A summary of this research work is given below which describes the new about this research.

- Various synthesis methods such as co-precipitation method, modified Hummer method and hydrothermal methods have been used to prepare different types of nanoparticles. Regardless of the method used, the key is to prevent particles from agglomerating into larger particles, achieve uniformity, and ensure their long-term stability. In this research work, optimization of different synthesis processes provides useful methods to ensure long-term stability and lowest aggregation potential, especially for binary nanoparticles.
- The lack of comprehensive and standardized characterization methods prevents researchers from fully exploiting the potential of nanoparticles while ensuring their safety and reliability. Addressing this research gap is essential to advance the understanding of nanomaterials in diverse domains. To this end, SEM is a versatile tool for characterizing nanoparticles, providing valuable insight into their size, shape, surface structure, and stability properties. In present research work, SEM images were obtained and analyzed at a magnification of 60100 using a SEM machine. SEM analysis revealed an average nanoparticle size of less than 100 nm as shown in Fig. 1. These results confirmed that the particles do not agglomerate and their minimum size makes them potential candidates to prepare the stable nanofluids with good stability, which is key challenge for better performance of nanofluids in solar absorption applications of nanofluids, especially water desalinations.
- In this work, optical absorption of individual nanofluids and its binary composites were characterized using UV–visible spectroscopy. This technique described the evaluation and capabilities of nanofluids showing that the absorption of solar radiation increased for those nanofluids that showed higher absorption values than others. These results provided a new platform for the analysis of new individual nanoparticles and their binaries with different thermophysical properties for energy harvesting, especially for water purification. Analyzing the results of this study, this study developed stable and highly absorbent nanofluids for solar-based water purification applications, which are new in the field of nanotechnology-based solar energy.
- Experimental photothermal analysis of various individual nanofluids and binary nanofluids has been explored in water desalination applications under natural sunlight. To accomplish this objective, a volumetric base absorption solar collection setup was implemented which contains a petri dish to hold the nanofluid samples to act as a volumetric solar thermal collector for direct absorption solar collection, a pyranometer for measuring the radiation intensity of the natural sun, three k-type thermocouples for measuring the temperature-increasing rate and digital weighing scale for evaporation (mass loss) rate. The excellent photothermal performance of individual nanofluids and its binary mixtures has led to new research and considerations in water purification processes that are largely solar-powered. Moreover, in this research work, to reduce thermal losses, a new technology called volumetric or direct absorption solar collector was developed to collect the absorbed solar energy directly which has been used in solar harvesting applications and provides a new path to explore the role of nanofluids for numerous photothermal applications, especially water purification. This experimental work also investigated the effect of selecting suitable nanofluids on the bases of their thermophysical properties under realistic solar exposure conditions, which led to large-scale water purification on a commercial basis. The results of this study provided sustainable solutions for improving solar energy scavenging methods to enhance absorption using a variety of nanofluids with increased photothermal efficiency. The results of this experimental investigation report will be helpful for the application and promotion of nanofluids under local environmental and climatic conditions. Future recommendation for effective solar desalination application requires choosing nanofluids with high heat transfer capacity, low cost and advanced solar collector design to enhance solar absorption. Low cost, high heat transfer nanofluids and minimal thermal losses are useful in solar thermal collectors to explore the potential of nanofluids for water purification.

3.7. Pressure drop

Pressure drop and heat transfer rate are important factors for thermal management system design. A pressure transmitter is one of the devices used to measure pressure drop. Theoretically, the pressure drop (ΔP) can be determined using equation (6) below [61].

$$\Delta P = \frac{fL\rho\ V^2}{2D_h} \tag{6}$$

In Equation (6) f represents the friction factor, V is average flow velocity, D_h is hydraulic diameter, ρ is density and L represents length of the channel.

A force called cohesive forces usually exists between a surface and the fluid that flows over that surface. Cohesive and frictional forces are responsible for reducing the flow near the surface and causes a pressure drop due to drag. Nanoparticles with a high surface area-to-volume ratio are chosen for excellent heat transfer capabilities but present experimental databanks in this study claim that the photothermal efficiency depends purely on the temperature change of the nanofluids measured using a K-type thermocouple and the mass loss due to evaporation measured using a digital balance. From equations (1)–(3), it can be clear that the photothermal efficiency did not account for the pressure drop. A pressure transmitter is used to measure the pressure drop. Since the photothermal efficiency does not depend on the pressure drop, therefore, the pressure transmitter was not used for the pressure drop calculation in the experimental step shown in Fig. 2. So, this study is not associated with pressure drop.

4. Conclusion

To assess the potential for water desalination applications, a photothermal performance of water based nanofluids consisting of GO, ZnO, FeO, and their binary combinations (GO-ZnO and GO-FeO) have been studied under the natural solar flux using volumetric or direct solar absorption collector. Optical absorption, rise in temperature, mass reduction due to evaporation, sensible heating efficiency and evaporation efficiency of the nanofluids samples are considered in the context of photothermal performance and following conclusions have been drawn.

1. It has been experimental observed that all types of nanofluids GO, ZnO, FeO and their composites (GO-ZnO and GO-FeO) show higher photothermal performance than the base fluid due to high solar absorption nature. This is revealed by higher temperature rising, higher mass loss due to evaporation which suggests nanofluids potential for efficient solar absorption in volumetric collector.
2. The photothermal efficiency of the binary composite (GO-ZnO and GO-FeO) nanofluid was higher as compared to the individual nanofluids (ZnO, FeO) except for pure GO, which is a carbon-based nanoparticle, which has higher solar absorption than the other nanofluids used in this study. However, the binary combination of nanofluids depends on the concentration mixing ratio, and the excessive addition of individual component (ZnO, FeO) in the binary combination can reduce the photothermal and absorption efficiency.
3. Comparing photothermal performance for water desalination application, the decreasing order of nanofluids in this study is (pure GO, 75%GO-25%ZnO, 50%GO-50%ZnO, 25%GO-75 % ZnO, 75%GO-25 %FeO, 50%GO-50%FeO, 25%GO-75%FeO, pure ZnO and pure FeO) at 0.01 wt%.This order shows the potential of nanofluids for water desalination applications where solar absorption, temperature gain and mass loss are considered important factors. Pure GO nanofluid shows the maximum enhancement in photothermal conversion efficiency amongst all types of nanofluids used in this research work due to its dark color, good dispersion stability, high absorption and high thermal conductivity.

This study recommends that GO nanofluids and (GO-ZnO, GO-FeO) nanofluids provide a potential alternate in direct solar thermal energy harvesting at appropriate concentration mixing ratios for water desalination applications due to strong solar absorptivity nature. This research work only deals with the photothermal properties of nanofluidsto assess their potential for water desalination applications. The excellent photothermal performance of pure GO and its binary composites (GO-ZnO, GO-FeO) propose further research and consideration in the application of water desalination which is driven by solar energy on large scale. Further, this study underscores the significance of nanofluids which is the promising technology for water desalination application. By analyzing the results of this study, researchers can develop the sustainable solution for water desalination application based on solar energy prompting critical upgrades in energy reserve funds and asset use.

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CRediT authorship contribution statement

Abdul Sattar: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bai Bofeng:** Writing – review & editing, Visualization, Supervision, Resources. **Faraz Fazal:** Writing – review & editing, Validation, Data curation, Visualization, Investigation. **Muhammad Farooq:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Fahid Riaz:** Writing – review & editing, Project administration, Funding acquisition, Data curation. **Ijaz Hussain:** Data curation, Validation, Writing – review & editing. **Muhammad Imran Khan:** Writing – review & editing, Visualization, Validation, Investigation.

Declaration of Competing interest

I on the behalf of the all authors, declare that there is no conflict of interest and all the elements of the submission are also in compliance with the journal publishing ethics. By submitting this manuscript, the authors agreed that the copyright for their article should be transferred to this journal if the article is accepted for publication. The work contained within the research paper is our original contribution and has not been published anywhere.

Data availability

Data will be made available on request.

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