Broadband absorbing mono, blended and hybrid nanofluids for direct absorption solar collector: a comprehensive review

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Abstract
The evolution of nanofluids over the years has opened new research opportunities in the field of renewable energy. Research on the optical properties of nanofluids for application in direct absorption solar collectors (DASCs) is progressing at a burgeoning speed. In a DASC system, nanofluid with high optical absorptivity can convert the incident solar energy into the thermal energy of the fluid. The dispersed nanoparticles in the fluid act in the process through the phenomenon of absorption and scattering. Studies conducted on the optical property characterization of monocomponent nanofluids have become saturated. Moreover, the photothermal efficiency (PTE) of the nanofluid can be enhanced by using multicomponent nanofluids. Nanofluids prepared using varying materials, shapes and sizes of nanoparticles can tune the absorption spectra of the bulk fluid to improve the PTE. A hybrid nanocomposite can similarly enhance the absorptivity due to the synergy of materials present in the nanocomposite particle. In this review, a comprehensive survey on the synthesis and optical characterization of different monocomponent, blended and hybrid nanocomposite nanofluids has been performed.
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Nomenclature

A aperture area (m²)

$C_{p,nf}$ specific heat (J kg⁻¹ K⁻¹)

I solar intensity (W m⁻²)

$I_\lambda$ solar spectral intensity (W m⁻² nm⁻¹)

$K_e$ extinction coefficient

$S_m$ solar weighted absorption fraction

$\Delta T$ instantaneous temperature difference

$Q_{sol}$ solar radiation intensity (W)

$\gamma$ penetration depth (m)

$Q_{nf}$ thermal energy of the nanofluid (KJ)

Greek parameters

$\alpha$ absorptance

$\lambda$ wavelength (nm)

$\tau$ transmittance

$\eta_{th}$ thermal efficiency

Abbreviations

AM air mass

ASTM American Society for Testing and Materials

ATO antimony-doped tin oxide

CNT carbon nanotube

CNH carbon nanohorn

CTAB cetyltrimethylammonium bromide

DASC direct absorption solar collector

DI deionized water

EG ethylene glycol

GCOOH carboxylated graphene

GO graphene oxide

GOH hydroxylated graphene

LSPR localized surface plasmon resonance

MWCNT multi-walled carbon nanotube

NIR near-infrared

NP nanoparticle

NR nanorod

PTE photothermal efficiency

PUMWNT partially unzipped multiwalled carbon nanotube

PVP polyvinyl pyrolidone

RGO reduced graphene oxide

SDS sodium dodecyl sulfate

SWAF solar weighted absorption fraction

SWCNH single-walled carbon nanohorn

SHMP sodium hexa meta phosphate

SDBS sodium dodecyl benzene sulfonate

UV ultraviolet

ZNG nitrogen-doped graphitic carbon

1. Introduction

Increasing population density and rising energy demand have urged the world to focus on the efficient utilization of energy. Fossil fuels contribute around 80% of the total energy production in the world [1]. Solar energy with a magnitude of $1.2 \times 10^5$ TW is an imperative energy resource. Due to its tremendous potential, the world is leaning towards solar energy [2]. The energy from solar radiation is utilized using three different energy conversion methods, namely, photothermal, photovoltaic and photochemical conversion methods [3]. Silicon-based PV modules assist in photovoltaic conversion [4], while photochemical energy conversion takes place via the photosynthesis method [5]. In a photothermal conversion system, the energy of incident solar radiation is converted into thermal energy for different applications. Solar thermal collectors form a major portion of photothermal systems.

Conventional solar collectors employ surface-based absorption of solar radiation for water heating applications. Most commonly, a spectral-selective coating or matte black [6] will be applied to the solid
absorption surface material that receives the incident solar radiation. After photothermal energy conversion at the absorber surface, heat transfer by conduction and convection takes place from the absorber surface to the working fluid. As the absorber surface has the highest temperature, the rate of heat loss to the remaining parts of the system through conduction, and the surroundings by convection and radiation, is high [7]. To minimize the thermal resistance in the solar thermal energy conversion process, an innovative idea of absorbing the incident radiation using the working fluid itself was proposed. In this type of volumetric absorption system, thermal resistance, as well as heat loss, are remarkably reduced. Thus, the challenge is to develop a better performing working fluid that can harness solar energy through the photothermal conversion process. Nanoparticle dispersed suspensions termed ‘nanofluid’ were found to increase the thermal properties of the base fluids [8]. Higher surface-to-volume ratio of nanomaterials would enhance the baseline thermophysical and optical properties of the host fluid [9, 10]. Brownian motion [11], thermophoresis effect [12], absorption and scattering [13] of light by nanoparticles are some of the phenomena that govern the optical properties of nanofluids. In this nanofluid-based direct absorption system, the solar energy from incident radiation is converted to the thermal energy of the fluid through photothermal conversion. This energy conversion takes place due to the phenomenon of scattering and absorption of incident radiation by suspended nanomaterials in the medium.

Minardi and Chuang were the first to propose the idea of direct absorption solar collectors (DASCs) by developing a system containing fluid passing through transparent tubes that absorb solar radiation [14]. This volumetric phenomenon was later investigated by Huang et al [15] by experimenting with a black liquid, with high absorptivity running in transparent tubes in a concentrating parabolic trough collector (PTC). The investigation of volumetric absorption of fluid containing microparticle additives (graphite, carborundum and silicon dioxide) was performed by Arai et al [16]. The results from their study state that the absorption coefficient of semitransparent suspensions is promising for further research. Bohn et al [17] conducted an experimental study on the performance of a molten salt–based direct absorption system for application in a central receiver system. Later, Tyagi et al [18] proposed a theoretical model of the DASC, which paved the way for further research in nanofluid-based solar thermal energy conversion.

With the recent rise in the popularity of DASCs, investigation into improving the optical properties of the fluid medium through the addition of better solar radiation absorbing nanomaterials is increasing. The conventional working fluids (oil, water, ionic liquids, glycol, etc) alone have very poor absorptivity along with the UV, visible and NIR ranges of the radiation spectrum [19]. Based on many recent findings, it is inferred that the optical properties of base fluids can be enhanced by the addition of nanomaterials at low concentrations. Numerous methods are available for tuning the optical absorptivity of nanofluids for potential applications in DASCs. Within the past few years, numerous studies have been performed to arrive at a better nanofluid-based volumetric absorber by analyzing the optical properties of different nanomaterial suspensions. Absorption spectra of nanofluids can be modified to the solar spectral region with maximum energy density by augmenting the nanoparticle concentration, material, shape and size. By analyzing the studies on the optical properties of nanofluids for DASC, it can be inferred that the most of the research is based on monocomponent nanofluids, where the effect of altering the nanoparticle volume ratio, shape and size is mostly investigated. Meanwhile the studies on hybrid and blended nanofluids for DASC are very rarely explored.

In a DASC, the optical properties of nanomaterials used for dispersion determine the solar spectral absorption ability of the fluid. Each material has absorption peaks in a different electromagnetic spectral range. Since the energy from solar radiation is distributed across the visible to near-infrared (NIR) spectrum, the use of monocomponent nanofluid would put a limit on the highest possible optical efficiency of the nanofluid. This limitation is addressed by the intervention of hybrid nanofluids. Hybrid nanofluids and multicomponent nanofluids used for DASCs are either a nanocomposite dispersion in the base fluid or the dispersion of two or more nanoparticles with different materials or geometry. Nanomaterials with absorption peaks in different spectral regions (ultraviolet, visible and near-infrared regions) can be used to make a nanocomposite-based hybrid nanofluid using an appropriate chemical or physical process so that broadband absorption of solar radiation is possible. Hybrid nanofluids of two or more different nanomaterial dispersions with absorptivity across the spectrum (UV, visible and NIR regions) are also a viable method to develop broadband absorbing nanofluids. Based on a comprehensive literature survey on optical nanofluids, it is inferred that hybrid nanofluids for DASCs are far less explored. Even though previous studies have reviewed the optical properties of nanofluids [10, 20], nanofluid-based DASCs [21, 22], and hybrid nanofluids [23, 24], a detailed review of broadband absorbing hybrid nanocomposite nanofluids, blended nanofluids and monodisperse nanofluids for direct absorption applications was conducted for the first time.

Hybridizing suitable spectral-selective nanoparticles with different absorption peaks in the electromagnetic spectrum can produce nanofluids with superior thermo-optical properties even at lower volume fractions. With hybrid nanofluids being the next-generation fluids and DASC being a newly
emerging field, reviews on the synthesis and optical absorptivity properties characterization of hybrid nanofluids in direct absorption applications are very rare. The present state-of-the-art review provides a clear review of the various nanofluids used for DASCs. The types of monocomponent and blended nanofluids used to date are discussed and tabulated. Numerous synthesis techniques adopted by researchers in preparing hybrid nanocomposite are discussed in detail along with their thermo-optical characterization. Photothermal efficiency (PTE) and solar-weighted absorption fraction (SWAF) of the nanofluids are tabulated to shed light on the optical absorption efficiency.

2. Previous reviews on photothermal applications of nanofluids

Numerous reviews have been conducted in the past to provide a broad understanding of the nanofluid characteristics [25], synthesis methods, application [26], enviro-economic impact, and their drawbacks. Most of the research was focused on analyzing the thermal and heat transfer performance of nanofluids in various systems, while only a few researchers have reviewed the optical properties of nanofluids [10, 27–29] and their application in DASCs [22, 30–33]. Although most of the existing review covers the studies conducted on the spectral absorptivity of nanofluids, there have been no extensive and focused reviews of broadband absorbing nanofluids (monocomponent, blended and hybrid nanofluids) to date. Hence, the present review on full-spectrum absorbing nanofluids imparts knowledge on broadband absorbing nanomaterials and nanofluids.

3. Review methodology

In this work, research papers from different reputable publishing houses, namely, Elsevier, Royal Society of Chemistry, and Springer Nature were selected for review. This review was focused on the synthesis and optical characterization of broadband absorbing nanofluids in volumetric absorption systems. In this critical review, research works on optical nanofluids (monocomponent, blended and hybrid nanocomposite nanofluids) have been consolidated to guide future research on advanced nanoparticle synthesis and solar photothermal conversion applications. This review tries to showcase nanofluids with broad spectral absorptivity, and the data gathered during the process is summarized to provide comprehensive knowledge on the optical properties of nanofluids. An attempt has been made to analyze a number of research articles published with the keywords ‘nanofluid’ and ‘photothermal’. As observed in figure 1, the number of publications on nanofluids was found to increase within a span of ten years. The number of research papers with the keywords ‘photothermal’ and ‘nanofluid’, was considerably smaller. Hence, the scope and need for further study of optical properties of nanofluids can be inferred.

4. Grounded theory

Research in the field of nanofluids started due to its enhanced thermal properties and wider scope of application in heat transfer equipment. Monodispersed nanofluids with enhanced thermo-physical properties were initially attracting attention. Later, binary nanofluids and hybrid nanofluids started to become research focused. With the advancement of DASCs, the research thrust has shifted to the enhancement of optical properties of nanofluids. In this category, numerous monodispersed nanofluids with exceptional solar radiation absorption capability were synthesized. Some of the initial studies on using multicomponent nanomaterials with spectral absorption in different wavelength ranges paved the way for broadband absorbing hybrid nanofluids. Hybrid nanofluids (nanocomposite and multicomponent dispersed nanofluids) have the advantage of spectral absorption tuning by augmenting their material, shape, size and volume fraction. Nanofluids can be categorized based on the nanomaterial used for dispersion or on the base fluid used for synthesis, as shown in figure 2. Most commonly, deionized water (DI) [34–36], ethylene glycol (EG) [37–39], engine oil [40, 41], thermal oil [42], molten salt [43–45] and paraffin wax-based nanofluids [46] are developed. Ionic liquids consist of inorganic or organic anions and organic cations [47]. Monocomponent nanofluids are the dispersion of a single nanomaterial with uniform shape and size. A hybrid nanofluid is a nanoparticle dispersion in a base fluid having more than one nanomaterial or a combination of more than one nanoparticle shape and size. Blended nanofluids and hybrid nanocomposite nanofluids form the category hybrid nanofluid.

5. Optical property characterization of nanofluid

Thermophysical and optical properties of nanofluids affect the performance of solar thermal systems. Thermal conductivity, specific heat, density and viscosity are the properties that affect heat transfer
efficiency, while the optical absorption properties (absorption and transmittance) of nanofluids directly influence the efficient performance of DASCs. These properties have been measured experimentally, and their correlations [48, 49] have been generated by researchers to predict them, based on nanoparticle shape, size, concentration and base fluid. The theoretical models can be extended to hybrid nanofluids to accurately predict the characteristics [35]. The absorption and transmittance of the nanofluid are measured using a spectrophotometer, in which the fluid is placed in a cuvette and a beam of known spectrum and intensity is allowed to pass through it. The same procedure is taken for the reference fluid (base fluid) that is used to compare the absorbance enhancement of the nanofluid. Changes in the beam intensity are measured after the beam crosses the fluid volume. Numerous precise instruments (e.g. UV–vis spectrophotometer and UV–vis–NIR spectrophotometer) are widely available to characterize the properties of optical nanofluids. Based on the literature survey, it was found that the spectrophotometric analysis was mostly done in the wavelength range from 200–2500 nm. A fixed optical path length of 10 mm is normally taken for the beam to pass through the cuvette. The extinction coefficient of the nanofluids is calculated using Beer–Lambert’s law, as shown in equation (1). Using the transmittance coefficient \( \tau(\lambda) \), and neglecting the reflection and scattering losses, the extinction coefficient is obtained. The optical properties of nanofluids can also be determined using three common optical theories, namely, Rayleigh scattering, Mie scattering and Maxwell Garnett theories:

\[
\tau_\lambda = e^{-yK_e} = 1 - \alpha_\lambda.
\] (1)

5.1. Solar-weighted absorption fraction

Drotning [50] introduced a term called solar-weighted absorption fraction (Sm), as shown in equation (2), which is used to measure the percentage of solar energy absorbed by the fluid volume in the cuvette. The ASTM standard at AM 1.5 was used as the reference spectra for the calculations. Complete absorption of incident radiation occurs when the solar-weighted absorptivity plot coincides with the reference spectra:

\[
Sm = \frac{\int_0^\lambda I_\lambda \alpha_\lambda d\lambda}{\int_0^\lambda I_\lambda d\lambda}.
\] (2)
5.2. Photothermal conversion efficiency

Photothermal conversion tests are conducted to analyze the energy conversion efficiency of nanofluids. Nanofluids placed inside a transparent cuvette [51] or test tube [52] will be illuminated by solar simulators. Thermocouples inserted inside the fluid volume will measure the temperature of the nanofluid during illumination, and the incident solar radiation will be measured using a pyranometer [53]. The PTE of the nanofluid is the percentage of energy absorbed by the nanofluid to the total incident solar energy [54]. Most commonly, xenon [55] and halogen lamps [56] are used for photothermal conversion tests, as observed in figure 3(a). The solar spectrum almost coincides with that of the xenon lamp. Consequently, halogen lamps are usually used with shortwave optical filter lenses to match the solar spectral irradiation [57]. Since the test setup is illuminated by solar radiation in only one direction, non-uniform volumetric heating takes place inside the fluid. To counteract this drawback, Guo et al [58] used an optical fiber as an internal light source, which is inserted into the fluid medium and illuminated on its other end by a solar simulator. This mechanism facilitates uniform volumetric absorption inside the fluid volume. A photothermal conversion test is also performed under direct solar irradiation [53, 59], as shown in figure 3(b). The photothermal energy conversion efficiency of nanofluids is calculated using equation (3):

$$\eta_{th} = \frac{Q_{nf}}{Q_{sol}}$$

$$\eta_{th} = \frac{m_{nf}C_{p,nf} \Delta T}{IA}.$$  \hspace{1cm} (3)

6. Solar thermal applications of optical nanofluids

Nanofluids with specific optical properties are used as working fluids in DASCs, and spectral filters for solar energy systems. In a DASC, the nanofluids absorb the incident solar radiation instead of absorber material. Hence, this reduces the heat loss from the absorber surface and improves the heat transfer efficiency. Different types of DASCs have been developed by researchers over the years. Research on a direct absorption-based flat plate collector [60], PTC [61], compound PTC, etc, has shown good results. Spectral
splitting PV/T collectors are another system that utilizes the solar spectrum by using a filter to separate the solar radiation for different applications (photovoltaic, photothermal and photochemical conversions) [62]. Fluid and solid filters are used in these systems. This review facilitates the selection of appropriate materials for future works on spectral splitting systems.

7. Monocomponent nanofluids for DASCs

Most of the previous research on the synthesis and characterization of working fluids for direct absorption applications was limited to monocomponent nanofluids. The nanoparticle dispersion consists of only one type of nanomaterial. Over the years, numerous researchers have investigated the optical absorption and photothermal conversion properties of these nanofluids. Studies on metallic [63, 64], metal oxide [65, 66], carbides, nitrides, graphene, graphite and carbon nanotube nanoparticle-based monocomponent nanofluids have been identified and discussed. Significant findings from studies on the optical property characterization of nanofluids are summarized in table 1.

7.1. Metallic nanoparticle-based nanofluid

He et al [67] studied the PTE of Cu nanofluids and observed that the maximum achievable temperature was enhanced by 25.3% compared to the base fluid. The study also reported a considerable decrease in transmittance with an increase in particle size, volume fraction and optical depth. Zang et al [68] performed an experimental investigation into the photothermal characteristics of gold (Au) nanoparticles at different wavelengths using a solar simulator. The results show that the highest energy conversion efficiency was reported for the nanofluid in the NIR spectrum (710–1064 nm). Filho et al [69] conducted a study on the photothermal conversion efficiency of plasmonic silver (Ag) nanoparticles. The study concluded that enhancement as high as 144% was observed for the nanofluid at a lower volume concentration of 6.5 ppm. The PTE of metallic nanoparticles (Cu, Ag, Fe and Zn) was studied by Amjad et al [70]. The study confirmed that Ag nanoparticles achieved the highest enhancement with a photothermal conversion efficiency of 99.7% compared to the base fluid. Amjad et al [71] analyzed the volumetric solar absorption in Au nanoparticle dispersions with a focus on steam generation. Enhancement in PTE (95% over base fluid) was observed at 0.04 wt%. Sharaf et al [72] investigated the optical characteristics of broadband absorbing polyethylene glycol (PEG) and trisodium citrate (CIT)-based Au nanofluids with a focus on improving thermodynamic stability. The results show that PEG-based Au nanofluids exhibit higher thermal stability and require less particle loading for better direct absorption. Sharaf et al [73] synthesized Au nanofluids using the citrate reduction technique. Nanoparticles were coated with PEG, polyvinyl pyrrolidone, or bovine serum albumin, and the photostability of these nanofluids was investigated. The polymeric-coated nano-dispersions were observed to be highly stable during cyclic solar radiation exposure. Li et al [74] used Au nanofluids to selectively absorb solar radiation to be applied to the spectral splitting PV/T. The nanofluid exhibited higher radiation extinction in the visible spectrum, and the system achieved about 75% solar energy conversion efficiency. Ham et al [13] developed an Fe₃O₄ nanofluid-based volumetric absorption and surface absorption collector. The results reveal that the volumetric absorption solar collector performs better than the surface absorption collector.
| Nanoparticle type | Reference          | Nanoparticle/base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|--------------------|-------------------------|--------------------|-----|------------|------------------------------|-----------------|-------------------|
| Metallic          | He et al [67]      | Cu/water                | 250–2500 nm        | —   | SDBS       | Near spherical/outer diameter 25–50 nm | 0.01–0.2 wt% | • Higher solar radiation absorbance in the wavelength range of 250–1370 nm.  
|                   |                    |                         |                    |     |            |                              |                 | • Enhanced photothermal conversion capability.  
|                   |                    |                         |                    |     |            |                              |                 | • Nanofluids exhibit improved photothermal conversion efficiency at 710–1064 nm waveband.  
|                   | Zhang et al [68]   | Au/water                | 300–700 nm         | 8%–29% | —          | Ball shape/outer diameter 15–30 nm | 1.5 ppm | • Based on the different waveband filters used for the photothermal experiment, the Vis–IR spectrum showed the maximum temperature rise in the fluid.  
|                   | Filho et al [69]   | Ag/water                | —                  | —   | —          | Irregular 10 nm               | 0.000 1625%–0.065% | • The addition of Ag nanoparticles even at low concentrations showed an increase in absorption efficiency.  
|                   |                   | Cu, Ag, Zn, Si, Al₂O₃ and Fe/water | 250–900 nm | Ag: 35% | Trisodium citrate (TSC) | Cu: 35–45 nm  
Ag: 50–60 nm  
Zn: 40–60 nm  
Fe: 50–80 nm  
Si: 30–50 nm  
Al₂O₃: 40–80 nm | 0.01 wt% | • Higher enhancement of stored energy was obtained at peak temperature.  
|                   | Amjad et al [70]   |                          |                    |     |            |                              |                 | • Ag nanofluids exhibited the highest photothermal conversion efficiency.  
|                   |                    |                         |                    |     |            |                              |                 | • The highest enhancement of 99.7% was obtained.  

(Continued.)
Table 1. (Continued.)

| Nanoparticle type | Reference | Nanoparticle/base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|-----------|-------------------------|--------------------|-----|------------|-----------------------------|-----------------|------------------|
| Amjad et al [71]  | Au/water  | 200–1000 nm             | 27%                | —   | —          | Spherical/20–30 nm          | 0.08–0.040 wt% | • Even under vigorous boiling, the nanoparticle does not enter the condensate.  
• PTE linearly increases with weight percentage during boiling by volumetric heating. |
| Sharaf et al [72] | CIT-Au nanoparticles, PEG-Au nanoparticles | 300–800 nm         | —                  | —   | Au: 10 nm  | Spherical 13 nm             | 0.001 vol%     | • PEG-Au nanofluids have higher solar absorptivity and thermal stability relative to CIT-Au nanofluids. |
| Sharaf et al [73] | CIT-Au/water PEG-Au/water BSA-Au/water PVP-Au/water | 300–1100 nm        | CIT-Au: 71.2%      | —   | Spherical 13 nm | 0.1611 mg ml⁻¹  | —   | • The photostability of polymer-coated nanoparticle dispersions was found to have the highest photostability compared to other nanofluids during cyclic solar radiation exposure. |
| Li et al [74]     | Au/water  | 240–2400 nm             | 51%–84%            | —   | Spherical 6–20 nm | 10–75 ppm  | —   | • Fluid temperatures as high as 49.9 °C was produced with a nanofluid spectrum filter with a fluid thickness of 18 mm. |
| Ham et al [13]    | Fe₃O₄/water | —                      | 50%                | —   | Spherical 6–15 nm | 0.01–0.1 wt%  | —   | • Nanofluid-based volumetric absorption collector was found to perform better compared to surface absorption collector. |

(Continued.)
| Nanoparticle type | Reference | Nanoparticle/base fluid | Measured bandwidth | PTE  | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|-----------|-------------------------|-------------------|------|------------|-----------------------------|----------------|-------------------|
| Metal Oxide       | Zhang et al [75] | Mesoporous CuO/water    | 200–1500 nm       | 83.66% | —          | Leaf-shaped Nanosheet/      | 10–100 ppm.     | • Mesoporous CuO has reported higher optical efficiency compared to non-porous CuO due to a smaller bandgap.  
• Mesoporous metal oxides are a better option due to the retainability of the optical properties after heating cycles. |
|                   | Karami et al [76] | CuO/water-EG mixture (ratio of 70:30) | 200–1500 nm | — | PVP | Irregular geometry/(<40 nm) | 12.5–100 ppm | • The study reported that the volume fraction has a linear dependence on solar absorption efficiency.  
• Observed an increase in thermal conductivity with volume fraction and the fluid temperature.  
• Compared to the surface absorber and base fluid, the magnetic nanofluid exhibited excellent PTE. |
|                   | Liu et al [77] | Fe$_3$O$_4$/water | — | 41% | SDS | p) Spherical 10 nm | 0.05 vol% | • For all the nanofluids studied, CuO showed the highest solar absorption and lowest transmittance, followed by Fe$_2$O$_3$ nanofluids. |
|                   | Milanese et al [78] | Al$_2$O$_3$, CuO, TiO$_2$, ZnO, CeO$_2$, and Fe$_3$O$_4$/water | 200–1400 nm | — | — | — | 0.05–1 vol% | • The study reported that increasing the operating temperatures has less effect on the optical properties of gas-based nanofluids.  
• The results show that the addition of these nanoparticles increases the photothermal conversion efficiency.  
• Magnetite nanofluids produced the highest enhancement in collector efficiency compared to the other two nanofluids. |
|                   | Milanese et al [79] | ZnO, CeO$_2$ and Fe$_3$O$_4$/chloroform | 200–800 nm | — | — | Fe$_3$O$_4$: Spherical/Dia: 4.3 nm CeO$_2$: Spherical/Dia: 3.0 nm | 3 mg l$^{-1}$, 5 mg l$^{-1}$ |  |
|                   | Gorji et al [80] | Fe$_3$O$_4$/water (graphite/water, Ag/water) | 200–1100 nm | 81% | TPABr | Spherical | 5–40 ppm |  |

(Continued.)
| Nanoparticle type | Reference | Nanoparticle/base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|-----------|------------------------|-------------------|-----|------------|-----------------------------|----------------|------------------|
| Zaid et al [100]  | Al₂O₃, TiO₂/water | 200–1100 nm | — | SDS, PVP, PEG, and HTAB | Spherical | 0.1–0.3 vol% | • For a range of wavelengths, TiO₂ has a higher extinction coefficient than Al₂O₃ nanofluids.<br>• PEG and PVP were observed to be the better dispersants for TiO₂ and Al₂O₃ nanofluids, respectively. |
| Nitrides, Zhu et al [81] | TiN/water, AlN/water (ZnO/water, ZrC/water) | 300–2000 nm | — | E80, SHMP | — | ZnO, ZrC, TiN: 0.02 wt % AlN: 0.02–0.1 wt % | • ZrC and TiN nanofluids reported the highest solar thermal conversion efficiency compared to ZnO and AlN nanofluids. |
| Zyla et al [82]   | Si₃N₄/EG | 200–1100 nm | — | — | 20 m | 0.01–0.1 wt% | • High absorbance in the UV region was observed for the nanofluid.<br>• The optical absorptivity of the base fluid showed exceptional improvement even with a lower mass fraction of nanoparticles. |
| Wang et al [83]   | TiN/L-QB320 (oil) | 300–1500 nm | 50% | — | Irregular/30–40 nm | 0.001–0.01 wt% | • The optical absorption of nanofluids was observed to increase with volume fraction to 0.003%.<br>• The steady-state temperature of nanofluids increase with solar intensity. |
| Carbides, Meng et al [84] | ZrC/water | 300–1400 nm | 95.5% | PVP | Spherical/10–20 nm | 0.002–0.02 wt% | • At lower weight fractions of nanoparticles, the fluid showed almost complete solar beam absorption.<br>• Broadband absorption was observed for the nanofluid. |
| Nanoparticle type | Reference | Nanoparticle/ base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|-----------|---------------------------|-------------------|-----|------------|-----------------------------|----------------|-------------------|
| CNTs/CNHs         | Qu et al [85] | MWCNT/water               | 200–2000 nm       | 55%–96% | TNWDIS | Fibre/Inner dia: 5–15 nm Outer dia: 20–50 nm | 0.0015–0.025 wt% | • Optimum concentration was found by evaluating PTE and solar absorption after repeated cycles of heating. |
|                   | Lee et al [86] | MWCNT/water               | —                 | —    | CTAB      | Dia: 30 nm                  | 0.0005–0.005 vol% | • This study reported an increase in the extinction coefficient of MWCNT nanofluids with volume fraction. |
|                   | Karami et al [87] | f-CNT/water               | 200–1500 nm       | —    | —         | Fibre/Dia: 10 nm Length: 5–10 μm | 5.6–53 mg l−1 | • Enhancements in optical efficiency and thermal conductivity were reported even at lower concentrations. |
|                   | Hordi et al [88] | f-MWCNT/water, EG, PG, Therminol VP-1 | 200–1500 nm       | —    | Surface functionalized (carboxyl groups) | Dia: 30 nm Length: 4 μm | 5.6–53 mg l−1 | • This study produces the first report on the long-term, stability (up to 8 months) of MWCNT nanofluids. |
|                   | Shende et al [89] | PUMWNT/EG, water          | 200–900 nm        | —    | —         | Outer Dia: 40 nm Inner Dia: 8 nm | 5–75 ppm | • Glycol-based MWCNTs demonstrated higher solar absorptivity and thermal stability compared to water-based nanofluids. |
|                   | Meng et al [90] | CNT/glycol                | 200–2500 nm       | 18% (enhancement) | HNO₃ (Oxidation Treatment) | — | 0.5–4.0 wt% | • Thermo-optical properties of water-dispersed nanofluids were found to be greater than that of EG dispersed. |
|                   |            |                           |                   |      |           |                             |                | • Significant improvement in the extinction coefficient of the fluid was noted even at low concentrations. |
|                   |            |                           |                   |      |           |                             |                | • CNT/glycol nanofluids reported a significant enhancement in photothermal conversion efficiency. |
|                   |            |                           |                   |      |           |                             |                | • In addition to thermal conductivity improvement, the viscosity is lower than pure glycol, which makes a good working fluid in solar thermal systems. |

(Continued.)
### Table 1. (Continued.)

| Nanoparticle type | Reference | Nanoparticle/base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings |
|-------------------|-----------|-------------------------|--------------------|-----|------------|-----------------------------|----------------|-------------------|
| SWCNH/water       | Mercatelli *et al* [91] | 250–1750 nm | — | SDS | Nanohorn | 0.005–0.06 g l\(^{-1}\) | • Higher thermal and optical stability was shown for EG-based CNH nanofluids at higher temperatures.  
• CNH was found to be a better fluid for solar thermal conversion.  
• The solar thermal conversion properties of SWCNH nanofluids were exceptional even at lower concentrations.  
• SWCNH nanofluids were found to demonstrate better optical properties compared to conventional amorphous carbon black nanofluids. |
| SWCNH/EG          | Sani *et al* [92] | 250–1750 nm | — | — | Nanohorn/100 nm | 0.005–0.06 g l\(^{-1}\). Carbon black: 0.01–0.12 g l\(^{-1}\) | • Considerable enhancement in the extinction coefficient of the base fluid was observed with the addition of even a low concentration of nanoparticles.  
• Higher solar absorption will pave the way for tailored GnP with broad-spectrum absorptivity.  
• Photothermal conversion efficiency was found to increase with volume fraction.  
• Higher absorption was observed in the visible spectrum.  
• Improvements in optical absorptivity and thermal conductivity were observed.  
• PTE increases with an increase in the mass fraction of nanofluids. |
| f-graphene nanoplatelet (f-GnP)/mixture (Havoline-XLC: water (50:50)) | Sani *et al* [93] | 300–2700 nm | — | SDBS | Stacked graphene layers  
Thickets: 2–3 nm  
Main dimension: 200 nm | 0.005 wt%, 0.05 wt% | • Considerable enhancement in the extinction coefficient of the base fluid was observed with the addition of even a low concentration of nanoparticles.  
• Higher solar absorption will pave the way for tailored GnP with broad-spectrum absorptivity. |
| Graphene Nanoplatelet/water | Vakili *et al* [94] | 200–2500 nm | — | — | Dia: <2 μm  
Thickness: 2 nm | 0.00025–0.005 wt%. | • Photothermal conversion efficiency was found to increase with volume fraction.  
• Higher absorption was observed in the visible spectrum. |
| 3D graphene/EG | Bing *et al* [55] | 250–1400 nm | 67.2% | — | Porous Nanosheet  
Thickness: 5 nm  
Pore dia: 100–2000 nm | 0.026 wt%, 0.048 wt% and 0.064 wt% | • Photothermal conversion efficiency was found to increase with volume fraction.  
• Higher absorption was observed in the visible spectrum.  
• Improvements in optical absorptivity and thermal conductivity were observed.  
• PTE increases with an increase in the mass fraction of nanofluids. |

(Continued.)
Table 1. (Continued.)

| Nanoparticle type | Reference   | Nanoparticle/base fluid | Measured bandwidth | PTE | Surfactant | Nanoparticle shape and size | Volume fraction | Important findings                                                                 |
|-------------------|-------------|-------------------------|--------------------|-----|------------|----------------------------|----------------|-----------------------------------------------------------------------------------|
| Sani et al[95]    | Graphite/diamond/EG | 300–2500 nm           | —                  | —   | Spherical  | —                          | 0.0025 wt%, 0.005 wt%, 0.01 wt%          | • A photothermal test proved that nanofluids are a promising candidate for volumetric absorption.  
  • Transmittance was observed to be much less at a lower mass fraction. |
| Shu et al[96]     | RGO/EG      | 250–2500 nm            | —                  | —   | Nanosheet  | —                          | 0.2–1.6 mg ml⁻¹ | • This study reports that in addition to broadband solar absorption, the nanofluid possesses high specific heat and low viscosity, which are desirable for DASC systems. |
| Li et al[97]      | Graphene/water GO/water | 200–1500 nm         | GO:46.26%          | —   | Nanosheet  | 10–100 ppm                 | 15–25 nm       | • Nanofluid exhibited PTE enhancement during reverse solar irradiation mode. |
| Other novel       | Guo et al[98]| LaB₆/water             | 200–1350 nm        | 98% | —          | Irregular 15–25 nm         | 0.002–0.02 wt% | • High solar absorption was observed across 380–1350 nm wavelength.  
  • The highest PTE was observed for 0.02 wt% nanofluid.  
  • The cheaper carbon-based nanofluid absorbs 70% of incident solar radiation. |
| nanofluids        |             | Carbon soot/water     | 280–1200 nm        | —   | —          | Irregular 50 nm            | 0.2 wt%        |                                                                                  |
7.2. Metal oxide nanoparticle-based nanofluid
Zhang et al [75] analyzed the optical absorptivity of a full-spectrum absorbing mesoporous CuO nanofluid. The study revealed that the mesoporous CuO nanofluid exhibited 83.66% efficiency enhancement compared to the nonporous CuO nanofluid, which has 58.86% efficiency. Karami et al [76] investigated EG-water mixture-based CuO nanofluids for application in a low-temperature DASC. At 0.01% volume fraction, the nanofluid absorbed energy equal to four times that of the base fluid. An experimental study of the solar thermal energy conversion properties of water-based Fe3O4 nanofluids on a direct absorption parabolic trough was conducted by Liu et al [77]. The magnetic nanofluid-based collector exhibited 25% and 12% higher efficiency than conventional and selective surface absorber systems, respectively. Milanese et al [78] experimentally measured the optical properties of different metal oxide nanofluids (Al2O3, CuO, TiO2, ZnO, CeO2, and Fe3O4) for low-temperature DASCs. The CuO and Fe3O4 nanofluids exhibited the highest extinction efficiency and least transmittance among the other nanofluids. Milanese et al [79] further analyzed the optical absorptivity of gas-based ZnO, CeO2 and Fe3O4 nanofluids for high-temperature solar applications. Increasing the temperature of nanofluids has a negligible influence on their optical absorptivity. Gorji et al [80] studied magnetite, graphite and Ag nanofluids for low-temperature direct absorption applications. Magnetite nanofluids exhibited the highest photothermal conversion efficiency compared to other nanofluids.

7.3. Nitride/carbide nanoparticles
Zhu et al [81] analyzed the radiative properties of titanium and aluminum nitride nanofluids. The study showed that TiN has better optical absorptivity compared to other nanofluids. Zyla et al [82] performed thermal, electrical and optical property characterization of the EG-based Si3N4 nanofluid. An absorption peak was observed in the UV region and the absorptivity increased with the volume fraction. The experimental analysis conducted by Wang et al [83] on TiN-based DASC showed that a solar-weighted absorption of 99% could be achieved at 0.01 wt%. Meng et al [84] analyzed the potential of ZrC nanofluids for direct absorption applications. High PTE and solar-weighted absorption coefficients of 92% and 0.99% were reported at 0.02 wt%.

7.4. Carbon nanotube nanoparticle-based nanofluid
Qu et al [85] examined the photothermal conversion efficiency of multi-walled carbon nanotube (MWCNT)-based nanofluids. An enhancement of 22.7% in maximum temperature was achieved over the base fluid at an optimal mass fraction (0.01%) of CNT nanofluid. An experimental study on MWCNT nanofluids for DASC-based applications conducted by Lee et al [86] shows that the extinction coefficient increases linearly with volume percentage. Karami et al [87] reported that functionalized CNTs with high dispersion stability and thermo-optical properties are potential candidates for solar nanofluids. Thermal conductivity enhancement of 32.2% was reported in the analysis. An experimental study on nanofluids for DASC, conducted by Hordy et al [88], showed that MWCNT nanofluids possess broadband absorption along the solar spectrum and exceptional stability over a longer period of work time. Shende et al [89] investigated the thermo-optical properties of a partially unzipped multiwalled carbon nanotube (PUMWNT) nanofluid. Water-based nanofluid was found to possess higher thermo-optical properties. Meng et al [90] studied the effect of nanofluid mass fraction and temperature on the photothermal phenomenon and thermal and rheological properties. The study reported a maximum enhancement of 18% in PTE of CNT nanofluids at 0.5 wt%. Experimental investigation into the solar absorption properties of EG and water-based SWCNH nanofluids was conducted by Mercatelli et al [91]. The optical absorption characterization of SWCNH by Sani et al [92] shows that the nanofluid has superior photothermal conversion efficiency.

7.5. Graphene/graphite nanoparticle-based nanofluid
The optical and rheological properties of functionalized graphene nanoplatelet nanofluids were investigated by Sani et al [93]. The addition of nanoparticles produces considerable enhancement of solar absorption even at lower concentrations. Photothermal property characterization of graphene nanoplatelets performed by Vakili et al [94] reported that 0.005 wt% nanofluid showed the highest efficiency. A 20% enhancement of PTE by graphene nanofluids over the base fluid was reported in the study conducted by Bing et al [55]. Sani et al [95] analyzed the optical properties of an EG-based graphite/diamond nanofluid. The results indicate almost complete extinction of solar radiation within a 15 mm path length for a concentration of 0.01 wt%. Shu et al [96] synthesized reduced graphene oxide (RGO) nanofluids with excellent dispersion stability for DASC. In addition to broadband absorption, the nanofluid exhibited improvement in thermal conductivity and decrement in viscosity. Li et al [97] conducted a study on the PTE of single-layered graphene and graphene oxide (GO) nanofluids through direct and reverse irradiation methods. Both graphene and GO nanofluids exhibited the highest PTE enhancement of 189% and 172%, respectively, in the reverse
irradiation mode. A novel lanthanum hexaboride (LaB$_6$) nanofluid was prepared through a solid-state synthesis route by Guo et al [98]. The nanofluid shows a photothermal energy conversion efficiency of 98.65%. The absorption is found to range across the solar spectrum with exceptional absorptivity in the 380–1350 nm wavelength range. Sreekumar et al [99] developed cheaper carbon soot-based nanofluid for application in DASC. The results showed that the nanofluid could absorb about 70% incident solar radiation. The photothermal efficiencies of the above-discussed monocomponent nanofluids are graphically represented in figure 4. The maximum photothermal efficiencies achieved by each nanofluid were selected. However, the graph can only be used to provide information on the photothermal capability and cannot be used for comparing the PTE. This is because each research work was performed under different experimental conditions and with different nanofluid concentrations. In the present review, it was observed that the novel LaB$_6$ nanofluid displayed a PTE as high as 98% at a low concentration (0.02 wt%) [98]. Other nanofluids including MWCNT, ZrC and Au-based nanofluids also display promising energy conversion efficiency.

8. Broadband absorbing hybrid nanocomposite-based nanofluids

Various methods adopted by researchers for synthesizing broad spectral absorbing hybrid nanocomposite-based nanofluids are depicted in this section. The photothermal and optical absorption efficiencies of each nanocomposite along with important findings from each study are explained in detail and provided as shown in table 2.

8.1. ATO/Ag nanocomposite

Sreehari et al [101] synthesized hybrid antimony-doped tin oxide (ATO)/Ag nanofluids using a facile one-step reduction reaction. Ag nanoparticle is attached to ATO nanoparticle, as observed from the TEM image of nanocomposite in figure 6(a). A two-step method was followed to produce DI water-based nanofluids. In this study, the mass fraction of broadband absorbing hybrid nanoparticles and surfactants was
Table 2. Summary of studies on the optical properties of hybrid nanocomposite nanofluids.

| Reference        | Nanofluid         | Base fluid | PTE/SWAF (maximum) | Concentration | Measured bandwidth | Method of synthesis | Results                                                                 |
|------------------|-------------------|------------|--------------------|---------------|--------------------|---------------------|-------------------------------------------------------------------------|
| Li *et al* [29]  | SiC/MWCNT         | EG         | 97.3%/99.9%        | 0.5 wt%       | 200–1100 nm        | Sand milling        | • The study shows that the hybrid nanofluid possesses broadband absorption properties in the visible and NIR regions (200–1100 nm).  
  • Higher PTE and solar radiation extinction were observed. |
| Lee *et al* [56] | Au@SiO$_2$, Ag@SiO$_2$ | Therminol  | 87%/—              | 0.009–0.012 vol% | 350–1800 nm       | Sol–gel method      | • Au@SiO$_2$ hybrid nanofluid was observed to absorb the incident light with negligible scattering.  
  • Broadband absorbing nanofluids with high photothermal conversion efficiency were developed and optimized for DASC.  
  • High thermal efficiency was reported for hybrid nanofluids applied to parabolic troughs. |
| Sreehari *et al* [101] | ATO/Ag          | Water      | —/98.9%            | 0.2 wt%       | 280–1200 nm        | One-step reduction reaction | • Compared to Fe$_3$O$_4$ and TiN nanofluids, the Fe$_3$O$_4$/TiN hybrid nanofluid has enhanced photothermal conversion ability and thermal conductivity.  
  • Tuning solar absorption by using full-spectrum absorbing magnetic nanofluids has greater research potential. |
| Zeng *et al* [102] | Fe$_3$O$_4$/TiN  | Water      | —/100%             | 0.04 vol%     | 280–1400 nm        | Condensation polymerization | • PTE is not linearly dependent on nanoparticle concentration.  
  • The use of kerosene with nanofluid enhances PTE.  
  • Nanofluids have high stability even at 150$^\circ$ C of heating.  
  • High-temperature stability makes it applicable to different solar thermal systems. |
| Khashan *et al* [105] | Fe$_3$O$_4$@SiO$_2$ | Water      | 98.5%/—             | 1 mg ml$^{-1}$ | —                  | Modified Stöber method | • PTE is not linearly dependent on nanoparticle concentration.  
  • The use of kerosene with nanofluid enhances PTE.  
  • Nanofluids have high stability even at 150$^\circ$ C of heating.  
  • High-temperature stability makes it applicable to different solar thermal systems. |
| Tao *et al* [109] | Fe$_3$O$_4$@graphene | Silicone oil | —/—               | 0.025–0.1 mg ml$^{-1}$ | 300–800 nm | Modified Hummer’s Method |

(Continued.)
Table 2. (Continued.)

| Reference | Nanofluid | Base fluid | PTE/SWAF (maximum) | Concentration | Measured bandwidth | Method of synthesis | Results |
|-----------|-----------|------------|--------------------|---------------|--------------------|---------------------|---------|
| Shi et al [110] | Fe$_3$O$_4$@CNT | Water | 88.7%/>— | 0.5 g l$^{-1}$ | — | Condensation polymerization | • The Fe$_3$O$_4$@CNT nanofluid exhibits broadband solar absorption in the visible region and has higher vapor generation efficiency. |
| Wang et al [111] | Au/Bi$_2$WO$_6$ | Water | 44%/95% | 10–100 ppm | 200–1400 nm | Hydrothermal method | • Loading Au nanoparticles on Bi$_2$WO$_6$ significantly improves PTE. • Higher stability is also reported, which makes it applicable to solar thermal systems. |
| Wang et al [113] | Au/TiN | EG | 98%/90% | 2, 5 and 10 wt% | 280–2500 nm | Impregnation–reduction method | • Enhancement in PTE by the dual plasmonic effect of Au and TiN nanoparticles was observed. • Compared to monocomponent nanofluids, the hybrid has broad absorption in the visible and NIR spectrum. |
| Li et al [114] | Ag@TiO$_2$ | Ethanol | — | — | 300–800 nm | One-pot synthesis | • At optimum conditions, the SPR peak of nanoparticles is around 474 nm, which causes higher absorption in the visible region. • The dual plasmonic effect of Au and ZNG enhanced the PTE of individual nanofluids. |
| Wang et al [116] | Au/ZNG | Water | 100%/96% | 100 ppm | 280–1500 nm | Impregnation–reduction method | • The dual plasmonic effect of Au and ZNG enhanced the PTE of individual nanofluids. |
| Mehrali et al [118] | Ag/RGO | Water | 78%/99% | 100 ppm | 200–2500 nm | Wet chemical reaction method | • Ag nanoparticle decoration s RGO nanosheets reported enhancement in the absorption of solar radiation. • Highly efficient hybrid nanofluids can reduce the penetration depth of solar thermal systems. • Au loading on TiO$_2$ broadens the spectral absorption with the highest efficiency of 49.1%. • The energy conversion efficiency of nanofluid reaches 87.3% with an increase in light intensity. • Hybrid nanofluids shows full-spectrum absorption ranging from the visible to the NIR region. • The PTE increased with volume fraction and maximum reported at 35 °C. |
| Wang et al [120] | Au/oxygen-deficient TiO$_2$ | Silicone oil | 49.1%/>— | 100 ppm | 200–2000 nm | Immersion reduction reaction method | • Hybrid nanofluids shows full-spectrum absorption ranging from the visible to the NIR region. • The PTE increased with volume fraction and maximum reported at 35 °C. |
| Yu et al [123] | CuO/Ag | Water | 96.11%/>— | 0.025 vol% | 250–1300 nm | Reduction method | • Hybrid nanofluids shows full-spectrum absorption ranging from the visible to the NIR region. • The PTE increased with volume fraction and maximum reported at 35 °C. |
Table 2. (Continued.)

| Reference         | Nanofluid                  | Base fluid | PTE/SWAF (maximum) | Concentration | Measured bandwidth | Method of synthesis                                                                 | Results                                                                                                                                                                                                 |
|-------------------|----------------------------|------------|--------------------|---------------|--------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Xuan et al [126]  | TiO$_2$/Ag                 | Water      | 20.9%/             | 0.005 vol%    | 200–2400 nm        | Photochemical impregnation method                                                   • The PTE of plasmonic hybrid nanofluids is higher than that of individual nanofluids at the same incident light intensity.                             |
|                   |                            |            |                    |               |                    |                                                                                   | • TiO$_2$/Ag composite has a cost advantage.                                                                                                                                                             |
|                   |                            |            |                    |               |                    |                                                                                   | • ZnO-Au nanofluid has better stability after multiple heating-cooling cycles.                                                                                                                             |
|                   |                            |            |                    |               |                    |                                                                                   | • Sn/SiO$_2$/Ag composite nanofluid has a synergy of optical absorption and solar thermal energy storage.                                                                                                 |
| Wang et al [127]  | ZnO-Au hierarchical        | Silicone Oil| 58%/—              | 1.0 mg ml$^{-1}$| 300–800 nm        | Electrostatic adherence                                                            • ZnO-Au composite has a cost advantage.                                                                                                                                                                 |
| Zeng et al [130]  | Sn/SiO$_2$/Ag core/shell/shell | Water       | 98.4%/—            | 0.05 vol%     | 200–800 nm         | Hydrolysis and polycondensation reduction and silver mirror reaction             • ZnO-Au composite has a cost advantage.                                                                                                                                                                 |
| Shende et al [133]| N-(RGO–MWNTs)              | Mixture (W: EG of 2:1) | —                  | 0.05 vol%     | 200–850 nm         | Two-step method                                                                    • Water-based hybrid nanofluids exhibited the highest efficiency improvement of about 17.7%.                                                                                  |
|                   |                            |            |                    |               |                    |                                                                                   | • Improvements in thermal conductivity and dispersion stability are also observed.                                                                                                                        |
| Zhu et al [136]   | Ag–Au/ZNGs                 | Water      | 74.3%/97.1%        | 100 ppm       | 200–1400 nm        | Impregnation–reduction method                                                       • Ag–Au/ZNG hybrid nanofluid exhibited 36% higher PTE than the base fluid.                                                                                                                                  |
|                   |                            |            |                    |               |                    |                                                                                   | • The high PTE was due to the LSPR effect of components (Au and Ag) and the presence of carbon material.                                                                                                    |
| Wang et al [137]  | Fe$_3$O$_4$@C              | Oil        | 60.9%/—            | 500 ppm       | 300–1800 nm        | Two-step method                                                                    • The solar thermal efficiency improved from 42.2% to 60.9% with an increase in the volume fraction.                                                                                               |
|                   |                            |            |                    |               |                    |                                                                                   | • The external magnetic field enhances PTE by 12.8%.                                                                                                                                                     |
Table 2. (Continued.)

| Reference   | Nanofluid         | Base fluid | PTE/SWAF (maximum) | Concentration | Measured bandwidth | Method of synthesis     | Results                                                                 |
|-------------|-------------------|------------|--------------------|---------------|---------------------|------------------------|------------------------------------------------------------------------|
| Fu et al [139] | GO–Au             | Water      | —/—                | Au: 2.6–15 wt% | —                   | Citrate reduction method | ● The synergistic effect of GO nanosheets and Au nanoparticles improves the solar absorption and thermal transport in the fluid. |
| Duan et al [143] | SiO₂/Ag         | Water      | —/—                | Small particle: 21%—43% | 200–2500 nm | —                      | ● For nanofluids having a majority of particles with a medium and large size, the absorption is improved at wavelengths around 1.0 μm and from 1.1 to 2.5 μm, respectively. |
|             |                   |            |                    | Medium particle: 23%–47% |          |                        | ● Absorption spectra are broadened with an increase in the proportion of larger particles. |
|             |                   |            |                    | Large particles: 25%–38% |          |                        | ● The CuO/ZnO nanocomposite was observed to have higher PTE than CuO. |
| Fang et al [144] | CuO/ZnO         | Water      | 97.35%/99.47%      | 0.01 vol%     | 200–1800 nm         | Co-precipitation method | ● For the same weight fraction of nanoparticles, the hybrid nanofluids exhibit higher absorption efficiency. |
|             |                   |            |                    |               |                     |                        | ● Hybrid nanofluids possess the highest SWAF at all component mixing ratios. |
|             |                   |            |                    |               |                     |                        | ● Ag@Ag₂S octopus-like structure exhibited multiband absorption. |
|             |                   |            |                    |               |                     |                        | ● The maximum efficiency and extinction coefficient reported was 73.3% and 1.01 cm⁻¹. |

(Continued.)
| Reference      | Nanofluid       | Base fluid | PTE/SWAF (maximum) | Concentration | Measured bandwidth | Method of synthesis | Results                                                                 |
|---------------|----------------|------------|-------------------|---------------|--------------------|---------------------|------------------------------------------------------------------------|
| Luo et al     | TiN@RGO        | Water      | 66.74%/99.4%      | 10–100 ppm    | 190–1100 nm        | Two-step method      | • The optimum concentration for achieving the highest PTE was found to be 40 ppm.  
• The nanocomposite-based nanofluid (40 ppm) generated PTE enhancement of 23% over base fluid. |
| Zhu et al     | RGO@TiO$_2$    | Water      | 91.8%/100%        | 0–500 mg ml$^{-1}$ | 200–1400 nm       | Two-step method      | • Hybrid nanofluids generate higher solar conversion efficiency and capability to degrade tetracycline. |
| Huang et al   | Ag@SiO$_2$/CoSO$_4$ | PG        | —/—               | 5.1–50.8 mg ml$^{-1}$ | 200–2400 nm       | Modified Stober method | • The hybrid nanofluid shows complete absorption in a wavelength range of 200–585 nm. |
| Zhao et al    | Ag@SiO$_2$     | Water      | —/—               | 5.1–50.8 mg ml$^{-1}$ | 200–2400 nm       | Modified Stober method | • The hybrid nanofluid exhibited exceptional absorbance between the spectral range of 330–700 nm. |
optimized based on the solar-weighted absorption percentage. The optimized nanofluid was used for experiments in a PTC. The highest SWAF of the nanofluid was reported to be 98.9% for 0.2 wt% of the nanoparticle concentration. The energy efficiency of the hybrid nanofluid-based collector was observed to be 63.5%.

8.2. Fe$_3$O$_4$/TiN nanocomposite
Zeng et al [102] synthesized the full-spectrum absorbing hybrid Fe$_3$O$_4$/TiN nanocomposite using condensation polymerization. In this process, the carboxyl group present on the surface of Fe$_3$O$_4$ and amino groups present on the surface of TiN will be coupled [103] to generate hierarchical Fe$_3$O$_4$/TiN nanocomposite. A one-pot hydrothermal method [104] was used to prepare highly water-dispersed iron oxide nanoparticles. The nanofluid was prepared according to the two-step method. The nanomaterials have absorptivity at different spectral ranges, hence the hybrid reported the highest absorption efficiency compared to individual nanofluids. Almost 100% solar-weighted absorption percentage was observed at a 0.04 vol%.

8.3. Fe$_3$O$_4$@SiO$_2$ nanocomposite
The full-spectrum absorption properties of hybrid Fe$_3$O$_4$ nanoparticles were investigated by Khashan et al [105]. As a first step in hybrid synthesis, the chemical co-precipitation method [106] was employed to synthesize Fe$_3$O$_4$ nanoparticles. The researcher has employed the modified Stöber method [107, 108] for synthesizing hybrid Fe$_3$O$_4$@SiO$_2$ nanoparticles. At a mass fraction of 1 mg ml$^{-1}$, the hybrid nanofluid is reported to have the highest PTE of 98.5%. The author reported a rise in the temperature of nanofluids with the addition of kerosene.

8.4. Fe$_3$O$_4$@graphene nanocomposite
Broadband absorbing Fe$_3$O$_4$@graphene hybrid nanofluids were prepared, and their optical properties were investigated by Tao et al [109]. For the preparation, the modified Hummer's method was used for GO sheet synthesis. Oleylamine (OLA) was used for surface modification of the as-prepared GO nanosheets to generate GO-OLA. Finally, a one-step method was employed to allow the growth of Fe$_3$O$_4$ nanoparticles and the production of graphene. The synthesized Fe$_3$O$_4$@graphene nanofluids were collected by centrifugation and washing. The authors reported a stable colloidal solution even at higher temperatures up to 150 °C.

8.5. Fe$_3$O$_4$@CNT nanocomposite
Shi et al [110] were successful in synthesizing hybrid Fe$_3$O$_4$@CNT composite nanofluids. As the first step in the procedure, Fe$_3$O$_4$ was synthesized by the reduction process. CNTs (0.08 g) were then mixed with Fe$_3$O$_4$ (0.32 g) in DI water by ultrasonication. Functional groups (carboxyl groups and hydroxyl groups) on the surfaces of Fe$_3$O$_4$ and CNT nanoparticles induce adhesion of particles to create Fe$_3$O$_4$@CNT nanocomposite. The Fe$_3$O$_4$@CNT nanofluid was then prepared by dispersing the particles in the base fluid. A photothermal conversion test showed that the nanofluid could achieve a collector efficiency of 88.7% at a low concentration of 0.5 g l$^{-1}$. The highest evaporation efficiency reported by the nanofluid was 60.3% at the same nanocomposite concentration. The hybrid nanofluid was found to be a suitable candidate for different solar thermal applications.

8.6. Au/Bi$_2$WO$_6$ nanocomposite
A DI water-based Au/Bi$_2$WO$_6$ hybrid nanoparticle with broadband absorption capability was synthesized by Wang et al [111]. In this experiment, the author used the hydrothermal method [112] for the preparation of Bi$_2$WO$_6$ nanosheets. The nanofluid achieved an efficiency of 44% in the photothermal conversion test. Solar-weighted absorptivity analysis shows that 95% of the incident beams were absorbed by the hybrid at 3 cm penetration depth, while the percentage absorption by monocomponent nanofluids was comparatively less.

8.7. SiC/MWCNT nanocomposite
Ethylene glycol-based SiC/MWCNT nanofluids were synthesized by Li et al [29]. The SiC and MWCNT mixture in hexane was stirred using a magnetic stirrer, followed by ultrasonication and centrifugation. The collected SiC-MWCNT nanoparticles, after being ground, were mixed with PVP-K30 dispersant and stirred thoroughly. The nanofluid was then made to flow through a sand milling unit. The study reported that the 0.5 wt% hybrid nanofluid absorbs about 99.9% of solar radiation at a small penetration depth of 1 cm. The photothermal conversion efficiency of the nanofluid was 97.3% for 1 wt% of SiC/MWCNT nanofluid.
8.8. Au/TiN nanoparticle
Wang et al [113] successfully prepared Au/TiN plasmonic nanofluids with varying Au concentrations using an impregnation-reduction method. The solar-weighted absorption percentage was found to be higher than 90% for both 70 and 100 ppm nanofluids at 1 cm penetration depth. The solar absorption spectra of both hybrid nanofluid and TiN nanofluid coincided at higher concentration. The photothermal conversion efficiency of hybrid nanofluids is attributed to the dual plasmonic effect of Au and TiN nanoparticles. A photothermal conversion test was conducted by heating at intervals of 5 s using a xenon lamp. The highest PTE of 98% was observed after 60 s for Au/TiN nanofluids.

8.9. Ag@TiO$_2$ core–shell nanocomposite
Li et al [114] prepared Ag@TiO$_2$ core–shell nanoparticles for direct absorption applications using a one-pot synthesis method. For the core–shell structure preparation, Ag nanoparticles were initially synthesized [115]. The two-step method was employed for ethanol-based nanofluid preparation. The morphology of Ag@TiO$_2$, as observed from the SEM image in figure 6(b), is round. The nanocomposite has a Ag core and TiO$_2$ shell. Nanocomposite dispersed solution exhibited a peak in the spectral absorption along the visible region.

8.10. Au/nitrogen-doped graphitic carbon (Au/ZNG) nanocomposite
Broad-spectrum absorbing Au/ZNG nanofluid was prepared by Lingling et al [116] using the impregnation–reduction method. In the preparation procedure, the template method was employed to synthesize ZNG [117]. In this work, ZNG was produced at 900 °C. With the impregnation–reduction method, hybrid Au/ZNG nanocomposite with varying Au loadings was prepared. The nanoparticles were then dispersed according to the two-step method, at different concentrations to obtain the required nanofluid concentrations. An optimum Au loading of 5 wt% Au/ZNG nanofluid was arrived at according to the photothermal conversion test. The synergistic effect of Au and ZNG in Au/ZNG nanofluid produced higher solar energy conversion efficiency compared to ZNG nanofluid.

8.11. Graphene/Ag nanocomposite
Mehrali et al [118] synthesized a full-spectrum absorbing hybrid nanofluid for solar thermal applications. The hybrid nanocomposite synthesized by the wet-chemical reaction method has Ag nanoparticles decorated on the RGO. For the hybrid synthesis, the component GO was synthesized using the modified Hummer’s method [119]. At a volume fraction of 40 ppm, the nanofluid-based DASCs reported an energy efficiency of 77%. The Ag-RGO hybrid nanofluid absorbs the solar beam almost completely at lower penetration depths than that of the RGO nanofluid.

8.12. Au/oxygen-deficient TiO$_2$ nanocomposite
Wang et al [120] analyzed the optical properties of hybrid Au/oxygen-deficient TiO$_2$ nanofluids and reported broadband absorptivity. Oxygen-deficient TiO$_2$ nanoparticles were initially synthesized using the facile reduction method [121]. The immersion reduction reaction method [122] was adopted for the synthesis of hybrid Au/TiO$_{2-x}$ nanocomposite. Nanofluids of various volume fractions were prepared by a two-step method. By analyzing the maximum temperature achieved by the fluids, an enhancement of 26.6 °C was obtained by the nanofluid over the base fluid. A PTE of 49.10% was obtained for the hybrid nanofluid.

8.13. CuO/Ag nanocomposite
Yu et al [123] analyzed the solar thermal conversion capability of CuO/Ag hybrid nanofluids. The hybrid nanocomposite was synthesized using a reduction method [124]. Fusiform-shaped CuO nanoparticles, as observed in figure 7(a), were developed by wet-chemical reactions followed by the thermal decomposition method [125]. The PTE depicted in figure 7(b), shows that an instantaneous PTE of 96.11% was achieved at a temperature of 35 °C. A broadband absorption extending from the visible to the NIR region was observed.

8.14. TiO$_2$/Ag nanocomposite
Xuan et al [126] synthesized a plasmonic TiO$_2$/Ag hybrid nanofluid with a broadened absorption spectrum. In this procedure, TiO$_2$/Ag composite nanoparticles were initially prepared. The author used the photochemical impregnation method for synthesizing TiO$_2$/Ag nanoparticles. Hybrid TiO$_2$/Ag plasmonic nanofluids were prepared according to the two-step method. The photothermal characteristics of TiO$_2$/Ag nanofluids were found to be better than TiO$_2$ nanofluid. Even though Ag nanofluids reported the same temperature rise as that of hybrids, the cost of hybrid preparation for the same concentration is comparatively cheaper.
8.15. ZnO-Au hierarchical nanocomposite
Wang et al [127] synthesized ZnO-Au hybrid nanocomposite for low-temperature DASCs. The author synthesized ZnO nanoparticles using hydrothermal reaction, while the Au nanoparticles were prepared using a reduction process [128, 129]. The electrostatic force between the components generates hedgehog particles decorated with Au nanoparticles as observed from figure 5(b). As a final step, ZnO-Au nanocomposites were obtained in powder form by lyophilization. The morphology of the prepared nanoparticle is shown in figure 5(b). The nanofluid concentration of 1 mg ml$^{-1}$ has achieved a PTE of 58% and an enhancement of 240% over the base fluid.

8.16. Sn/SiO$_2$/Ag core/shell/shell nanocomposite
Zeng et al [130] studied the optical property of tin–silica–Ag hybrid nanocomposite for DASC applications. During the synthesis process, Sn was first prepared, followed by SiO$_2$ and Ag nanoshells on the surfaces. A modified polyol wet-chemical reduction process [131] was employed to synthesize Sn nanoparticles. Hydrolysis and polycondensation of tetraethyl orthosilicate facilitates the growth of SiO$_2$ nanoshells on the tin nanoparticle surface. Ag shells were developed on the surface of the Sn/SiO$_2$ nanoparticles using reduction and Ag mirror reactions [132]. The localized surface plasmon resonance (LSPR) effect of Ag nanoparticles produced an enhancement of solar absorptivity of Sn/SiO$_2$/Ag nanocomposite compared to Sn/SiO$_2$ nanoparticles.

8.17. N-(RGO-MWNT) nanocomposite
Shende et al [133] synthesized hybrid N-(RGO-MWNT) nanofluids for DASCs using the two-step process. As a first step, the constituents (RGO and MWNTs) were synthesized, followed by nanocomposite
preparation and nitrogen doping of the prepared nanocomposite. GO was reduced to RGO by the hydrogen exfoliation technique [134]. Hummer’s method [135] was employed for GO preparation. In addition to the optical properties of the nanofluid, a thermal conductivity enhancement of 17.7% was observed for 0.02 vol% nanofluid. Water-based nanofluids were found to have a higher extinction coefficient compared to EG-based nanofluids.

8.18. Ag–Au/ZNGs nanocomposite
Zhu et al [136] synthesized broadband absorbing Ag–Au/ZNG hybrid nanofluid using the impregnation–reduction method. The photothermal conversion test established that hybrid nanofluids have the highest efficiency of 74.35% compared to Ag/ZNG and Au/ZNG nanofluids. Ethylene glycol-based nanofluids exhibited broadband absorption in the visible and NIR spectral range. The solar energy absorption fraction calculated from figure 8(b) shows that an efficiency of 97.1% was achieved by the hybrid at 10 mm penetration depth for 100 ppm.

8.19. Fe$_3$O$_4$@C nanocomposite
The optical property of the magnetic hybrid Fe$_3$O$_4$@C nanofluid was investigated by Wang et al [137]. The nanocomposite was synthesized by in situ partial reduction of spindle-like Fe$_3$O$_4$ with a carbon coating [138]. The hybrid nanofluid attains a maximum PTE of 60.9% at 500 ppm. The thermal energy conversion efficiency was found to increase with volume fraction and applied external magnetic field.

8.20. GO–Au nanocomposite
Fu et al [139] studied the photothermal conversion efficiency of GO–Au nanocomposite-based nanofluid. The component GO was prepared using the Hummer's and Marcano methods [135, 140]. The Au nanoparticles were prepared using the citrate reduction method [141]. The hybrid nanofluid was prepared by simple mechanical mixing of the components. The synergistic effect of GO and Au improves the solar radiation absorbptivity of the nanofluid. Compared to monocomponent nanofluids, the vapor generation efficiency improves by 10.8% for the hybrid with 15.6 wt% of Au.

8.21. Au@SiO$_2$ and Ag@SiO$_2$ nanocomposite
Lee et al [56] developed thermoel-based core–shell plasmonic nanoparticles for DASC. The Turkevich method [142] was adopted for Au nanoparticle synthesis. The Au@SiO$_2$ nanofluid exhibited an absorption peak at 540 nm and enhanced absorption in the waveband range of 360–700 nm. Ag@SiO$_2$ nanofluid produces an absorption peak at 440 nm. The Ag@SiO$_2$ nanofluid demonstrated a high dispersion stability of 100%.

8.22. SiO$_2$/Ag core–shell nanoparticle
Duan et al [143] conducted a simulation of core–shell SiO$_2$/Ag nanoparticles using a finite-difference time-domain model to study the optical absorption of nanofluids. The absorption band was observed to have broadened with increasing nanoparticle size. At wavelengths closer to 1000 nm, the absorption is enhanced.
for hybrid nanofluid with a majority of medium-sized particles. In the case of nanofluids with the majority of large-sized particles, the absorption is significantly enhanced in the 1100–2500 nm wavelength range.

8.23. CuO/ZnO nanocomposite
Fang et al [144] studied the photothermal conversion properties of CuO/ZnO nanocomposite-based nanofluids. The binary nanocomposite was prepared using the co-precipitation method. Water was selected as the base fluid. The CuO/ZnO nanocomposite with a component ratio of 0.7:0.3 attains the highest photothermal conversion efficiency of 97.35%. As observed in figure 8(a), the optical absorptivity of nanofluids, as measured using the solar-weighted absorption percentage, shows that pure CuO nanofluids have the highest value of 99.47% at 1 cm penetration depth, compared to binary nanofluids of 70% and 50% CuO content.

8.24. MWCNT/Fe₃O₄ nanocomposite
The photothermal conversion characteristics of MWCNT/Fe₃O₄ hybrid nanofluids were analyzed by Tong et al [145]. The EG/water mixture with a weight ratio of 20:80 was chosen as the base fluid. The two-step method was employed for the hybrid preparation. An instantaneous photothermal energy conversion efficiency of 61% was obtained for the hybrid nanofluid at 0.01 wt%. From the SWAF study on nanofluids, MWCNT/Fe₃O₄ nanofluids with a particle mixing ratio of 1:4 completely absorbed the incident solar energy at a penetration depth of 2 cm.

8.25. Ag@Ag₂S nanocomposite
Jiang et al [146] developed an octopod-shaped Ag@Ag₂S nanostructure with an enhanced absorption range. The Ag nanocube dispersion in water generates Ag@Ag₂S core–shell nanoparticles by in situ sulphidation. Photothermal conversion tests performed using laser illumination at three different wavelengths indicated a maximum efficiency of 79.3%.

8.26. TiN/RGO nanocomposite
Luo et al [147] developed the TiN/RGO hybrid nanocomposite by the two-step method. The optimal concentration for achieving higher PTE was observed to be 40 ppm. The hybrid nanofluid showed a solar energy conversion efficiency of 66.74% at 40 ppm. The nanofluids generated an efficiency enhancement of about 23% over water.

8.27. RGO/TiO₂ nanocomposite
The hybrid RGO/TiO₂ nanofluid developed by the two-step method shows significant solar absorption in the wavelength range of 200–1400 nm. Results indicate that the fluid achieved a photothermal conversion efficiency of about 91% [148]. About 94.7% degradation of tetracycline was also observed. Hence, hybrid RGO/TiO₂ nanofluids are considered to be potential candidates for photocatalytic applications.

8.28. Ag@SiO₂ nanocomposite
Huang et al [149] studied the spectral-specific absorptivity of Ag@SiO₂/CoSO₄ nanofluids for spectral splitting PV/T collectors. High absorption was observed in the wavelength range outside the PV window. The
Figure 9. Summary of photothermal efficiencies of hybrid nanocomposite-based nanofluids.

nanofluid-based PV/T showed an overall efficiency of 63.3% with an enhancement in economic value of 67.8% over conventional PV-only systems. Zhao et al [150] investigated the performance of Ag@SiO₂ hybrid nanofluid-based spectrum splitting collector with PG, and PG/water mixture as the base fluid. The results indicate that an increase in the economic value of up to 30% was obtained at optimum nanofluid concentration and nanofluid thickness. A composite SiO₂/Ag nanofluid was synthesized by Joseph et al [53]. The morphology of the nanocomposite could be observed from figure 5(a). The figure 9 shows the maximum photothermal energy conversion achieved by each hybrid nanocomposite-based nanofluid that were revived in this study. In comparison to monocomponent nanofluids, hybrid nanofluids were found to achieve better energy conversion efficiency. During this review, it was observed that the majority of hybrid nanocomposite-based nanofluids display photothermal energy conversion efficiency above 65%. Upon analyzing the data, Au/ZnG, Fe₃O₄@SiO₂, Sn/SiO₂/Ag, Au/TiN and CuO/ZnO nanofluids were found to produce higher PTE.

9. Blended nanofluids for full-spectrum absorption

Blended nanofluids are a modified class of nanofluids. The photothermal conversion efficiency of the colloidal solution is governed by different factors including the material, shape and size of nanoparticles used. In this category of nanofluids, the colloidal solution is formed by dispersing nanoparticles of different materials, sizes or shapes. Hence, by using blended nanofluids, the optical absorptivity of the fluid volume can be tuned to enhance the photothermal conversion efficiency. Three major categories of blended nanofluids are explained below.
9.1. Nanofluid with different nanoparticle shapes
Duan et al [151] analyzed the effectiveness of blending Au nanoparticles of different shapes (rod, sphere and star-shaped) at various mass fractions for direct absorption applications. By analyzing the optical properties of blended nanofluids, broadband solar absorption was observed with performance enhancement over monocomponent nanofluids. The experimental and numerical studies conducted by Wang et al [152] on blended nanofluids showed that PTE enhancement is possible even at low volume fractions. The morphologies of the nanoparticles are shown in figure 10. In this work, Au nanorods and Ag nanosheets were blended to improve solar absorptivity. A maximum efficiency of 76.9% was reported for blended nanofluids at 0.0001 volume fractions. Qin et al [153] explored the method of improving absorption efficiency using sharp-edged metallic nanoparticles. The study reported that the usage of sharp-edged Ag and SiO$_2$/Ag core–shell nanoparticles has a higher solar-weighted absorption coefficient compared to smoother particles. Du and Tang [154] conducted a numerical study on blending different-shaped Au nanoparticles to enhance their optical absorption properties. In this study, different proportions of Au nanorods, nanosheets and nanoellipsoids were blended. Summary of the above-mentioned studies is tabulated as observed from table 3. For blended nanofluids, a significant enhancement in solar energy harvesting efficiency (104%) was reported over the spherical Au nanoparticle dispersion even with smaller particle sizes and at lower concentrations. Photothermal efficiencies of blended nanofluids with different nanomaterial shapes are depicted in figure 11. The results of blended nanofluids are plotted along with individual nanofluids for an effective comparison. Blended Ag nanofluid with nanosphere, nanodisk, nanorod, core–shell and nanoprism-shaped nanoparticles reported the highest efficiency of 98.17% [154].

9.2. Nanofluids with different nanoparticle sizes
Jeon et al [156] experimentally analyzed the optical absorptivity of Au nanorods based on blended nanofluids. Results from the study show that at a low volume percentage of 0.0001%, the extinction coefficient in the visible spectrum was 1.77 cm$^{-1}$. Blending AuNRs of varying aspect ratios broadens the spectral absorption across the visible and NIR regions. Jeon et al [157] conducted further studies on photothermal efficiencies of dispersion in Au nanorods of different aspect ratios. Due to the LSPR phenomenon, the blended nanofluid exhibited excellent PTE along the spectrum during direct absorption analysis under a solar simulator. Chen et al [158] analyzed the photothermal conversion properties of nanofluids based on Au nanoparticles. The morphological analysis and size distribution of Au nanoparticles with varying particle size is depicted in figure 12. Flat and cube-shaped direct absorption models were studied, and it was found that the cube-shaped DASC model had the highest efficiency. The photothermal efficiency of the flat-shaped model decreases with an increase in Au nanoparticle size. Saidur et al [159]
Table 3. Summary of studies on blended nanofluids with different nanoparticle shapes.

| Reference | Blended nanofluid/base fluid | PTE/SWAF | Type | Nanoparticle shape/size | Volume fraction | Measured bandwidth | Results |
|-----------|-------------------------------|----------|------|-------------------------|----------------|-------------------|---------|
| Duan *et al* [151] | Au/water | —/96.3% | Experimental | (a) Spherical Dia: 5–10 nm (b) Rod-shaped Dia: 10 nm Length: 50 nm (c) Star Shaped Dia: 40 nm | 0.0025–0.01 wt% | 300–1350 nm | • Blended nanofluid (40% nanosphere, 40% nanostar and 20% nanorod) has shown broad absorption spectra with the highest solar-weighted absorption coefficient of 0.963, followed by rod-shaped nanofluid, which has 0.95. |
| Wang *et al* [152] | Ag–Au/water | 76.9%/— | Experimental and numerical | (a) Triangular nanosheets/45 nm–75 nm (b) Au: Nanorod/55 nm–85 nm | 0.0001 vol% | 300–1300 nm | • Compared to individual nanofluids, the blended nanofluids of nanosheets and nanorods exhibit the highest solar thermal conversion efficiency. |
| Qin *et al* [153] | Ag–SiO$_2$–core/Ag–shell/water | —/84.5% | Numerical | Star-shaped (with sharp edges) | 0.000001 vol% | 300–1100 nm | • Due to the lightning rod effect and LSPR, nanomaterials having sharp edges were found to exhibit more than one absorption peak along the solar spectrum. • The solar-weighted absorption coefficient of sharp-edged nanoparticles is higher than that of smooth nanoparticles. |
| Reference       | Blended nanofluid/base fluid | PTE/SWAF | Type        | Nanoparticle shape/size                      | Volume fraction | Measured bandwidth | Results                                                                 |
|-----------------|-----------------------------|----------|-------------|---------------------------------------------|-----------------|-------------------|------------------------------------------------------------------------|
| Du et al [154]  | Au/water                   | 82.3%/   | Numerical   | (a) Nanosphere                               | 0.0001 vol%     | 250–1300 nm       | • The nanoparticle size has less influence on the extinction coefficient. |
|                 |                             |          |             | (b) Nanorods                                 |                 |                   | • The blended nanofluids having different ratios of nanorods, nanosphere, and nanorods and nanosheets exhibited the highest solar absorption efficiency. |
|                 |                             |          |             | (c) Nanosheets                               |                 |                   |                                                                        |
|                 |                             |          |             |                                             |                 |                   |                                                                        |
| Duan et al [151]| Au/water                   | 96.3%    | Experiment  | (a) Nanosphere                               | 0.01 wt%        | 300–1350 nm       | • The blended nanofluids with nanospheres, nanostars and nanorods (in ratio 40:40:20) generated the highest PTE. |
|                 |                             |          |             | (b) Nanostar                                 |                 |                   |                                                                        |
|                 |                             |          |             | (c) Nanorod                                 |                 |                   |                                                                        |
|                 |                             |          |             |                                             |                 |                   |                                                                        |
| Mallah et al [155]| Ag/water    | 98.17%/   | Numerical   | Nanosphere, Nanodisk, Nanoprisim, Nanorod, Cao–shell | 0.00015 wt%    | 300–1200 nm       | • Blended nanofluids improve the absorption efficiency by 85%. |

Table 3. (Continued.)
performed a numerical study on the effect of nanoparticle size and volume fraction on the extinction coefficient of nanofluids. The study reported that even though the nanoparticle size has less significance, the volume fraction of the nanoparticle was observed to be linearly dependent on the extinction coefficient. As reported by Liu et al. [160], the carbon and graphite-based nanofluids were reported to show energy conversion efficiency as high as 100%. The optical properties of the blended nanofluids with different nanoparticle size is detailed in table 4. A brief graphical representation of the PTE and the extinction coefficient of the above-discussed nanofluids is shown in figures 13 and 14, respectively. It could be inferred from figure 14 that the blended nanofluid with different nanoparticle sizes performed better compared to its counterparts.
Table 4. Summary of studies on blended nanofluids with different nanoparticle sizes.

| Reference       | Blended nanofluid/base fluid | Type            | PTE       | Nanoparticle size/shape                                      | Volume fraction | Measured bandwidth | Results                                                                 |
|-----------------|------------------------------|-----------------|-----------|--------------------------------------------------------------|-----------------|-------------------|------------------------------------------------------------------------|
| Jeon et al [156]| Au nanorods (AuNRs)/CTAB    | Experimental    | —         | Dia: 15–17 nm                                               | 0.0001%         |                   | • Blended plasmonic nanofluids with different Au nanorod aspect ratios exhibited the highest photothermal conversion efficiency. |
|                 |                              |                 |           | Length: 26–72 nm                                            |                 |                   | • Spectral tunability of solar absorption from the visible and NIR spectrum was achieved. |
|                 |                              |                 |           | Aspect ratio: 1.7–4.7 nm/rod-shaped                         |                 |                   | • Broadband absorption was observed along the visible and NIR regions. |
|                 |                              |                 |           |                                                              |                 |                   | • The direct absorption test showed that also for lower concentrations the performance of nanofluids is comparable to existing technology. |
| Jeon et al [157]| Au nanorods/CTAB            | Experimental    | —         | Dia: 16 nm                                                  | 0.0001%         |                   | • The LSPR effect is prominent at lower concentrations of nanofluids. |
|                 |                              |                 |           | Aspect ratio: 1.77, 2.73 and 4.17/rod-shaped                |                 |                   | • The photothermal conversion efficiency decreases with an increase in the particle size. |
|                 |                              |                 |           |                                                              |                 |                   | • Aluminum nanoparticles show a very strong extinction coefficient at shorter wavelengths. |
|                 |                              |                 |           |                                                              |                 |                   | • The effect of particle size on the optical absorptivity of nanofluids is minimal. |
|                 |                              |                 |           |                                                              |                 |                   | • Volume fraction has a linear dependence on the extinction coefficient. |
|                 |                              |                 |           |                                                              |                 |                   | • Carbon and graphite exhibited better PTE compared to CuO nanofluids. |
| Chen et al [158]| Au/water                    | Experimental    | 86.48%    | Dia: 25 nm, 33 nm and 40 nm/round                           | 0.000008 vol%   |                   | • The LSPR effect is prominent at lower concentrations of nanofluids. |
|                 |                              |                 |           |                                                              |                 |                   | • The photothermal conversion efficiency decreases with an increase in the particle size. |
|                 |                              |                 |           |                                                              |                 |                   | • Aluminum nanoparticles show a very strong extinction coefficient at shorter wavelengths. |
|                 |                              |                 |           |                                                              |                 |                   | • The effect of particle size on the optical absorptivity of nanofluids is minimal. |
|                 |                              |                 |           |                                                              |                 |                   | • Volume fraction has a linear dependence on the extinction coefficient. |
|                 |                              |                 |           |                                                              |                 |                   | • Carbon and graphite exhibited better PTE compared to CuO nanofluids. |
| Saidur et al [159]| Al/water                    | Numerical       | 75.55%    | Dia: 1 nm, 5 nm, 10 nm, 15 nm, 20 nm/spherical             | 0.8%            |                   | • The LSPR effect is prominent at lower concentrations of nanofluids. |
|                 |                              |                 |           |                                                              |                 |                   | • The photothermal conversion efficiency decreases with an increase in the particle size. |
|                 |                              |                 |           |                                                              |                 |                   | • Aluminum nanoparticles show a very strong extinction coefficient at shorter wavelengths. |
|                 |                              |                 |           |                                                              |                 |                   | • The effect of particle size on the optical absorptivity of nanofluids is minimal. |
|                 |                              |                 |           |                                                              |                 |                   | • Volume fraction has a linear dependence on the extinction coefficient. |
|                 |                              |                 |           |                                                              |                 |                   | • Carbon and graphite exhibited better PTE compared to CuO nanofluids. |
| Liu et al [160]| CuO/water, Graphite/water, and carbon/water | Numerical       | C: 80%–100% | Dia: 20–200 nm                                             | —               |                   | • The LSPR effect is prominent at lower concentrations of nanofluids. |
|                 |                              |                 | Graphite: 59%–99% |                                                              |                 |                   | • The photothermal conversion efficiency decreases with an increase in the particle size. |
|                 |                              |                 | CuO: 30–98% |                                                              |                 |                   | • Aluminum nanoparticles show a very strong extinction coefficient at shorter wavelengths. |
|                 |                              |                 |           |                                                              |                 |                   | • The effect of particle size on the optical absorptivity of nanofluids is minimal. |
|                 |                              |                 |           |                                                              |                 |                   | • Volume fraction has a linear dependence on the extinction coefficient. |
|                 |                              |                 |           |                                                              |                 |                   | • Carbon and graphite exhibited better PTE compared to CuO nanofluids. |
Figure 13. Summary of studies on the effect of nanomaterial size on PTE.

Figure 14. Extinction coefficient comparison of blended, monocomponent and base fluid.
9.3. Nanofluids with different nanomaterial suspension

Chen et al [54] characterized the optical absorption and photothermal conversion properties of a CuO-ATO binary nanofluid due to its complementary optical absorptivity in the visible and NIR spectra. The SWAF was maximum for binary nanofluids compared to the individual CuO and ATO nanofluids at the same volume fraction. Zeng et al [51] conducted an experimental study on the photothermal properties of MWCNT-SiO\textsubscript{2}/Ag binary nanofluids. Blending SiO\textsubscript{2}/Ag and MWCNT nanoparticles, which have strong absorptivity along with visible and infrared spectra, respectively, broadened the absorption band significantly. Meglynn et al [161] blended CuO quantum dots and Au nanoparticles to synthesize nanofluids with better absorptivity. The CuO quantum dots have strong absorption in the shorter wavelength region of the visible spectrum and UV spectrum, while the Au nanoparticles have an absorption peak in the visible spectrum. Analyzing the absorption coefficient of blended nanofluids, it was observed to outperform both CuO and Au nanofluids. Qu et al [52] experimentally evaluated the optical absorption and solar energy conversion properties of CuO/MWCNT nanofluids at different mixing ratios of constituents. As observed from TEM images of blended nanofluids in figure 15(a), a uniform mixture is produced. The addition of CNT at very low concentration (0.0015 wt%) in CuO nanofluids was observed to show a significant enhancement in photothermal conversion efficiency. Figure 15(b) shows that the lowest transmittance is reported for nanofluids with the highest weight percentage of CuO nanoparticles. Bhalla et al [57] performed a comprehensive study on direct and surface absorption using Al\textsubscript{2}O\textsubscript{3}/Co\textsubscript{3}O\textsubscript{4} blended nanofluid. The study showed that compared to surface absorption, the blended nanofluid-based direct absorption has higher efficiency and the PTE increases linearly with the mass fraction. Zeiny et al [162] conducted a photothermal energy conversion test on Au–Cu blended nanofluid and compared the results with that of individual and carbon black nanofluids. Carbon black nanofluids were found to exhibit the highest efficiency compared to other nanofluids. Even though the blending of Au and Cu broadens the absorption peak, a reduction in peak value is observed. Chen et al [163] synthesized Ag–Au blended nanofluid having solar absorption at different wavebands and performed a photothermal conversion test. The results show that the energy conversion efficiency of Ag–Au blended nanofluid (30.97%) is almost equal to the sum of the efficiencies of Ag and Au nanofluids at the same concentrations. Menbari et al [164] prepared a multicomponent nanofluid by dispersing Al\textsubscript{2}O\textsubscript{3} and CuO nanoparticles in a mixture of water and EG. The extinction coefficient of a binary nanofluid is observed to be higher than or equal to the sum of its monocomponent nanofluids. Shin et al [165] performed photothermal analysis on blended nanofluids based on CNT and magnetic nanoparticles. The results from the study showed that applying an external magnetic field produced an enhancement in PTE and thermal conductivity of the nanofluid. Wang et al [166] experimentally analyzed the PTE enhancement of an EG-based RGO nanofluid by adding a magnetic nanorotor. Forced convection induced by magnetic nanoparticles exhibits an increase in PTE due to the synergy of multicomponent nanomaterials. Yuan et al [167] developed a nanofluid-based spectrum splitter for greenhouse applications in which the unfavorable solar radiation that is not required by the plants would be absorbed by nanofluids (in the range of 800–1500 nm), and the remaining solar radiation (in the range of 300–800 nm) would be allowed to pass through. The photothermal conversion efficiency is 34.4% and the system yields 358.9 kWh m\textsuperscript{-2}. The use of GO and TiN nanoparticle dispersions in thermal oil was found to produce a thermal energy conversion efficiency of 56.5% for DASC [168]. Zn/ZnO nanofluids were reported to produce a photothermal
conversion efficiency of 18.3% at lower concentration (0.001 wt%) [159]. A brief information on the PTE and solar radiation absorption efficiency of the blended nanofluids discussed above is visualised in Figure 16 and detailed in table 5. By analyzing the graph, it can be concluded that nanofluids with MWCNT as one of the constituents generate higher photothermal and solar absorption efficiency.

10. Challenges and future research scope

Since property enhancement and tunability are advantages for nanoparticle dispersion, nanofluids are finding applications in almost all fields by replacing conventional working fluids. Since nanofluids are a promising working fluid for DASC, certain factors need to be addressed in order to improve their efficiency. Long-term dispersion stability of blended and hybrid nanocomposite nanofluids is a major criterion that needs further study [160]. There is significant scope for study, especially in analyzing the thermo-optical property deterioration with many heating cycles for developing efficient nanofluids with better dispersion stability. Most of the photothermal conversion tests conducted are limited to non-concentrated solar radiation through direct irradiation or solar simulation. To analyze the practicality of nanofluids in concentrated solar thermal systems, a photothermal conversion test should also be performed at concentrated incident radiation. The energy conversion efficiency of a nanofluid-based direct absorption system can be studied for flowing nanofluids. Some of the future research aspects concerning optical nanofluids for DASCs are listed below.

- Recent progress on volumetric absorption using molten salts for concentrated solar power technologies [171] can pave the way for research on advanced nanomaterials. The addition of nanoparticles having high solar radiation absorptivity in the molten salt can further improve the solar absorption efficiency. Studies on the performance investigation of molten salt nanofluid-based solar thermal systems report positive results [44].

- In the meantime, broadband spectrum harvesting PV/T technologies are advancing at a rapid pace [172, 173]. Spectral splitting PV/T collectors utilize a part of the solar spectrum using PV cells for photovoltaic conversion, while the remaining photon energy is absorbed by a nanofluid-based volumetric absorber with an absorption band in the specific spectral range [174, 175].

- Modified phase-change materials (PCMs) with nanoparticle additives are gaining attention due to their significant energy storage capability and property tunability. Works on PCM slurries for photothermal energy conversion and storage have recently been addressed [176]. Studies on thermal property enhancement of PCM using nanocomposites are also progressing [177].

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Figure 16. Summary of PTE of blended nanofluids with different nanomaterials.
Table 5. Summary of studies of blended nanofluids with different nanomaterial suspensions.

| Reference       | Blended nanofluid/base fluid       | PTE/SWAF            | Nanoparticle shape/size | Volume fraction | Component ratio | Measured bandwidth | Results                                                                                                                                 |
|-----------------|------------------------------------|---------------------|-------------------------|-----------------|-----------------|--------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Zeng et al [51] | MWCNT-SiO$_2$/Ag/water             | 97.6%/74.5%         | Spherical/150 nm        | 0.1 vol%        | 4:1             | 280–1200 nm        | • Solar radiation absorption by binary nanofluids is higher than that of MWCNT and SiO$_2$/Ag nanofluids.                                     |
|                 |                                    |                     |                         |                 |                 |                    | • A very low concentration of even 0.005 vol% has shown a higher solar-weighted absorption percentage.                                     |
| Qu et al [52]   | CuO–MWCNT/water                    | —/99.2%             | MWCNT: Outer dia: >50 nm Inner dia: 5–10 nm | CuO: 0.15 wt%  | MWCNT: 0.005 wt% | 3:1                | 200–1400 nm                                                                                                                                 |
|                 |                                    |                     |                         |                 |                 |                    | • The hybrid nanofluids absorb solar energy, which is equal to the sum of the energy absorbed by individual nanofluids.                           |
| Chen et al [54] | CuO–ATO/water                      | 92.5%/99.6%         | CuO: Spheroid/10 nm ATO: Irregular/15 nm | 0.1 vol%        | 4:6             | 300–1400 nm        | • The blended nanofluids exhibit broadband absorption due to the high absorptivity of CuO and ATO nanofluids in the visible and NIR regions, respectively. |
| Bhallo et al [57] | Al$_2$O$_3$/Co$_3$O$_4$/water       | —/80%               | Al$_2$O$_3$: Dia 13 nm Co$_3$O$_4$: Dia 10–30 nm | Al$_2$O$_3$: 20–150 mg l$^{-1}$ | Co$_3$O$_4$: 20–80 mg l$^{-1}$ | 300–2500 nm | • 80% of the incident radiation was absorbed using a blended nanofluid at a depth of about 20 mm.                                      |
|                 |                                    |                     |                         |                 |                 |                    | • SWAF increases with the mass fraction of nanofluids.                                                                                     |
| Meqlynn et al [161] | Au NP–CuO QD/EG                   | —/—                 | CuO: Spherical/3.3 nm Au: Varying/27 nm | Au: 0.0051 vol% | CuO: 0.002 vol%  | 5:1.2              | • A major portion of the incident photon is absorbed by nanofluids since the absorption coefficient is considerably higher than the scattering coefficient. |
|                 |                                    |                     |                         |                 |                 |                    | • Au has better photothermal properties compared to CuO.                                                                                   |

(Continued.)
| Reference          | Blended nanofluid/base fluid | PTE/SWAF | Nanoparticle shape/size | Volume fraction | Component ratio | Measured bandwidth | Results                                                                 |
|--------------------|------------------------------|----------|-------------------------|-----------------|----------------|-------------------|--------------------------------------------------------------------------|
| Zeiny *et al* [162]| Au–Cu/water                 | —/—      | Au: 3.5 nm              | Au: 60–150 mg l\(^{-1}\) | 60:750, Cu: 90:1250, and Cu: 150:2000 | 320–1060 nm          | • Photothermal conversion ability is directly proportional to the volume fraction of the nanofluid. • Blending two nanofluids having various absorbance peaks does not increase PTE but it broadens the width of the absorption peak. |
| Chen *et al* [163] | Au–Ag/water                 | 30.97%/— | Ag: Nearly spherical 30 nm | 750–2000 mg l\(^{-1}\) | 300–800 nm |                       | • The photothermal conversion efficiency of the blended nanofluid was found to be greater than the individual nanofluid efficiencies. • Mixing nanoparticles, with different spectral absorptivity, was observed to be effective. |
| Menbari *et al* [164] | Al\(_2\)O\(_3\)-CuO/EG, and Mixture (EG: Water of 50:50) | —/— | Nearly Spherical CuO: <100 nm \(\gamma\)-Al\(_2\)O\(_3\): 40 nm | \(\gamma\)-Al\(_2\)O\(_3\): 0.04–0.08 vol% CuO: 0.001–0.003 vol% | 4:1, 3:1, 8:3 | 200–800 nm | • The extinction efficiency of binary nanofluids was observed to be higher than that of individual nanofluids and water-based binary nanofluids. |

(Continued.)
Table 5. (Continued.)

| Reference | Blended nanofluid/base fluid | PTE/SWAF | Nanoparticle shape/size | Volume fraction | Component ratio | Measured bandwidth | Results |
|-----------|------------------------------|----------|-------------------------|-----------------|-----------------|-------------------|---------|
| Shin et al [165] | MWCNT/Fe$_3$O$_4$/Mixture (EG: Water of 2:8) | 64%/— | MWCNT/Fe$_3$O$_4$ 19.69 nm | 0.005–0.2 wt% | 1:1 | 300–1100 nm | • Adding MWCNT to Fe$_3$O$_4$ increases the SWAF of hybrid nanofluids. |
| Wang et al [166] | α-Fe$_2$O$_3$:RGO/EG, 56.8%/100% |  | α-Fe$_2$O$_3$: Nanorods 60–500 nm Dia: 30–80 nm 0.01 wt% RGO: 0.0005–0.003 wt% | — | — | 200–1800 nm | • The study reported that increasing the receiver height does not contribute to efficiency increase. • Due to the synergy of the optical properties of different materials, the PTE was found to increase. • An optimum ratio of RGO:α-Fe$_2$O$_3$ of three was achieved. |
| Yuan et al [167] | ATO-WO$_3$/water 34.4%/85.4% |  | ATO-WO$_3$: 28.3–43.8 nm 0.0025–0.01 vol% | 2.4:97.6 | 300–1500 nm | • The spectral-selective ATO-WO$_3$ nanofluid for greenhouse applications effectively absorbs the solar radiation outside the spectrum needed for plants (800–1500 nm). |
| Zhang et al [168] | GO-TiN/oil 56.5%/— |  | GO: Width 30 µm Height 70 µm 0.03–0.1 wt% 73, 5:5, and 3:7 | 300–1500 nm | • The photothermal conversion test shows that the efficiency reaches 57% with the highest temperature of 170 °C. |
| Ma et al [169] | Zn-ZnO/paraffin wax 18.3%/— |  | 10 nm 0.001–0.01 wt% 1:9–9:1 | 280–900 nm | • The fluid with 8:2 ratio (ZnZnO) has the highest solar thermal conversion efficiency. |
- Very few works were reported on the efficiency improvement of DASCs using magnetic nanofluids with an externally applied magnetic field [77]. There is huge research potential on the phenomenon of thermomagnetic convection induced by direct absorption of solar radiation [178].
- Performance investigations on metal foams [179] and metal foam/nanofluid [180] combination-based DASCs have recently been conducted. Studies suggest an improvement in the optical absorption efficiency of solar collectors using metal foams and nanofluids.
- The recent development of the application of gas-phase nanofluids in DASCs has opened up research paths in the field of solar-based air heating [181]. Since the research is in the initial stage, there is much scope for improving the system efficiency.
- Almost all applications of nanofluids demand better colloidal stability and less property degradation with an increasing number of heating cycles. Very few researchers have addressed this issue, and there is much scope for further study.

11. Conclusion

In this review, a detailed summary of the optical characteristics and synthesis methods of monocomponent, blended and hybrid nanofluids for DASCs are discussed. There has been little research carried out in the field of optical nanofluids for DASCs, especially the study of hybrid nanofluids. Significant research attention is needed in the field of tuning the nanomaterial characteristics to improve solar absorption efficiency. Some of the major conclusions from this comprehensive review are listed below.

- Compared to monocomponent nanofluids, the usage of hybrid nanofluids was found to exhibit exceptional absorption tunability. Our study confirms that blended nanofluids having nanomaterials with different shapes and sizes show broadband solar absorption.
- The base fluid and volume fraction of nanofluids were found to be dominant factors in determining the optical absorptivity. While optical transmittance decreases with an increase in volume fraction for the majority of nanofluids, the volume fraction of some nanofluids needs to be optimized. In addition, this detailed review suggests that water outperforms other conventional base fluids in terms of absorption efficiency and dispersion stability.
- Hybrid nanocomposites and blended nanofluids having different nanomaterials with absorption peaks in the visible and NIR spectrum exhibited broader solar absorption and higher extinction coefficients.
- Carbon-based monocomponent nanofluids and hybrid plasmonic nanocomposite nanofluids exhibit high photothermal conversion efficiency and optical absorptivity even at very low volume fractions.
- In addition to the optical properties, significant enhancement in thermal conductivity was also exhibited by almost all the nanofluids, which promotes their usage in heat transfer applications.

Data availability statement

No new data were created or analyzed in this study.

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