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Review Article

A review on utilisation of nanofluid in solar energy harnessin

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ABSTRACT

The current global epidemic and population growth, which led to an increase in energy consumption, highlighted the need to maximize solar energy extraction. Because nanofluids have good intrinsic thermal properties, they are employed to improve the effectiveness of solar collectors. One of the primary research themes in solar energy consumption is to boost the effectiveness of the harvesting technologies. Thus, it is essential to examine the performance of solar energy harvesting devices based on nano fluids. Therefore, it is crucial to look at how well nanofluid-based solar energy production systems work. The article includes information on how various properties can be changed to efficiently harvest solar energy, as well as a summary of recent advancements in nanofluid-based solar energy extraction devices. From this review, it is observed that 85.4% enhancement in solar collector utilizing graphite as TES material, 38.4% enhancement in solar water heater using CuO nanofluid, 84.74% enhancement in thermal efficiency of PV/T system using NEPCM and 196% gain in exergy efficiency of solar still using Ag nanofluid.

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INTRODUCTION

In the 21st century, finding sustainable and renewable energy sources has become a top priority. The world is facing two big problems: fossil fuel stocks are running out, and using them continues to harm the environment. Now is the time to switch to cleaner, more sustainable energy sources [1–2]. Solar energy is one of the most promising renewable energy sources since it is plentiful, reliable, and can meet a large part of the world's energy needs. The Sun is a huge fusion reactor that sends a huge amount of energy to Earth. This energy is more than enough to meet the world's energy needs several times over [3]. Even while solar energy systems have a lot of potential, their current efficiency is still a barrier to their widespread use. Because of this inefficiency, a lot of research has been done on novel technologies and materials that can improve the capture and conversion of solar energy [4]. Using nanofluids to collect solar energy is one area of research that looks promising.

Solar energy is one of the best sources of renewable energy because it is almost always available and doesn't directly release greenhouse gases when it is used. Fossil fuels are limited and found in certain areas of the world, but solar

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energy is available almost everywhere on Earth [5]. The International Energy Agency (IEA) says that the quantity of solar energy that hits the Earth's surface in only one hour is enough to power the world's economy for a whole year. This shocking number shows how solar energy might become a major source of energy over the world [6]. Also, using solar energy could help make energy more secure, cut down on the need to import fossil fuels, and lessen the negative effects on the environment that come with traditional energy production [7]. Solar power can control the climate change by controlling the emission of carbon dioxide and hence it is most powerful renewable energy source. This is the reason behind investment in solar energy technology. Engineers and scientist can get maximum from solar energy by enhancing its efficiency and effectiveness of solar energy system [8].

The world energy scene is changing a lot because of the growing need for energy, population increase, economic growth, and the need to cut carbon emissions right away. According to IEA, the consumption of global energy will enhance in the coming years. The electricity demand along is raised approximately 60% by 2040 [6]. Figure 1 shows the world's population, the amount of CO_2 in the air, the GDP per person, and the median temperature anomaly. This rising demand is a big problem because most of the world's energy still comes from fossil fuels, which are not only limited but also release a lot of greenhouse gases into the atmosphere [9]. Now the entire world is focused on solar energy to find a balance between energy security and environmental sustainability [10]. The world energy demand can be fulfilled by solar energy without and harmful effect on the environment. This energy can be harnessed by both medium directly using PV system and indirectly by solar thermal system. Solar power is now more competitive with traditional energy sources since solar technology is improving quickly and prices are going down. But to keep up with the growing demand, solar energy systems need to become even more efficient and useful [11-12].

Nanofluids are made by mixing nanoparticles—very small particles that are around the size of nanometers—into a base fluid like water, oil, or ethylene glycol [13]. You may make these nanoparticles out of metals (like copper and gold), oxides (like aluminium oxide and titanium dioxide), and carbon-based materials (like graphene and carbon nanotube). Nanofluids are very appealing for use in solar energy systems because they have unique qualities, such as a high surface area-to-volume ratio, better thermal conductivity, and the ability to change their optical properties [14-15]. Nanofluids can greatly increase how well solar thermal systems absorb and transport solar energy [16]. Nanoparticles in the fluid make it better at conducting heat, which makes heat transmission more efficient. Also, some nanoparticles can be designed to absorb certain wavelengths of sunlight better, which means the device can capture more energy [17].

This better thermal performance could make solar collectors work better and lessen the cost of making solar thermal energy. Nanofluids can be utilised as a cooling medium in photovoltaic systems to get rid of the heat that PV cells make. Too much heat can make PV cells less effective and shorten their lifespan, therefore cooling them down is quite important. Due to better thermal characteristics of nanofluid, it can assist PV cell properly which make the entire system more effective and efficient [18]. Researchers and people in the business world are very interested in nanofluids

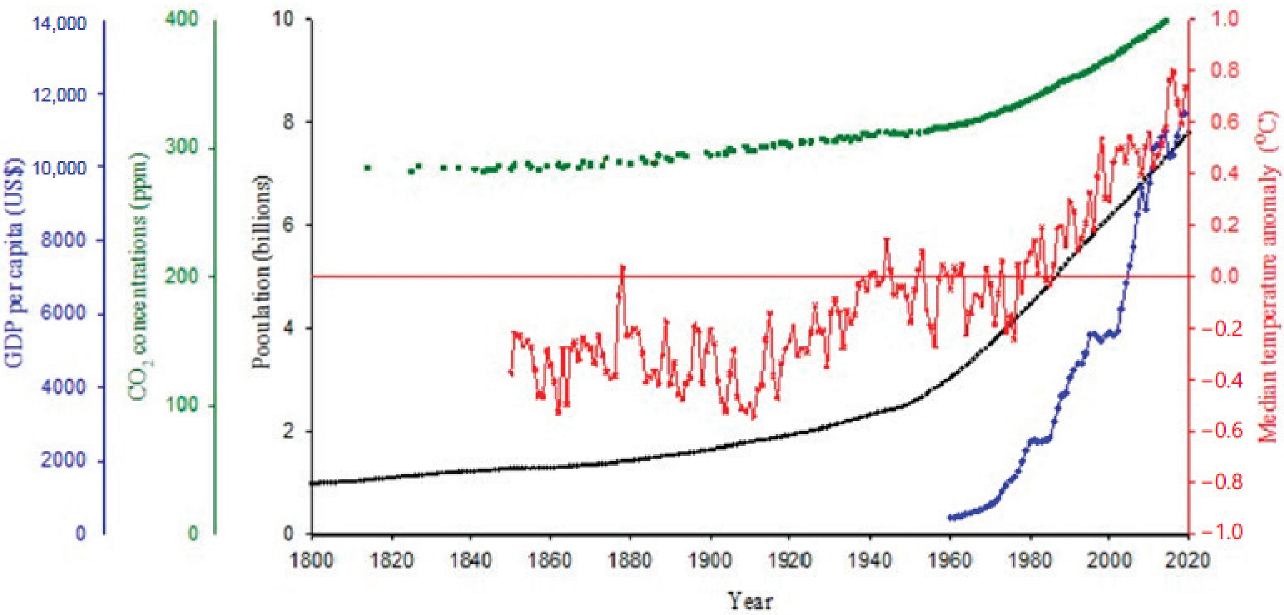

Figure 1. World population, CO_2 concentration, GDP per capita and Median Temperature Anomaly [From Holechek et al. [1], with permission from MDPI].

because they could make solar energy systems work better. Many studies have shown that nanofluids can be used in a variety of solar applications [19–21]. Researchers and scientist are still searching best combination of nanomaterial which can make the system more efficient. Utilization of nanofluid in solar energy harnessing devices can make the solar system more efficient and also fulfill the world energy demand without any harmful impact on the environment.

Already Known

- Nanofluids are colloidal suspension different nanomaterials in a base fluid. Nanofluid offers better thermophysical properties compared to traditional fluid.
- Nanofluid is most widely used in solar harnessing devices because of its better heat transfer ability.
- Energy conversion in solar system has become more effective due to absorption capacity of solar radiation of nanoparticles present in the nanofluid.
- Most of researches are performed on nanoparticles such as Al_2O_3, TiO_2, MWCNT, etc.
- Researchers are focused on efficiency, effectiveness and stability and cost of nanofluid utilization in solar energy harnessing devices.

Gap that Need to be Addressed

- Stability of nanofluid is the major concern when it is used in different environmental condition.
- The utilization of nanoparticles is solar energy devices is very hazardous for health and its long term utilization can also affect the environment.
- Only limited research are available on amount of nanoparticles used in the preparation of nanofluid which can cause problem of higher viscosity and clogging.
- Commercial utilization of nanofluid in solar energy devices to harness solar energy is limited.
- Utilization of nanofluid in solar system is not cost effective.
- Hybrid nanofluid is now used in lab and real life solar system in place of mono nanofluid because of its enhanced thermophysical properties.

Novelty

The novelty of this review article lies in the development of new nanofluid and its utilization in its solar energy harnessing devices. In review article different types of solar system are studies with commercial utilization of nanofluid in the solar system. This review article also focuses on the different way to enhance its long term stability of nanofluid and wide application in solar energy devices.

Objectives and Scope of Study

The primary objective of this review article is to summarize the recent development and utilization of nanofluid in solar energy harnessing systems. In this review article, the development, progress, possible utilization of nanofluid in different solar system is discussed in details along with their commercial usage and limitations. Also this article helps to understand how different nanofluid used in different solar application to optimize system efficiency and effectiveness to use them as an alternate source of renewable energy. The objective covered is as follows:

- Analysis of different types of nanoparticles and base fluid along with their thermophysical properties and characteristics.
- Analysing the behaviour of different types of nanofluid in different solar applications to optimize the system efficiency and effectiveness.
- Exploration of nanofluids in PV/T systems, with a focus on how they can help photovoltaic cells cool down and produce more electrical and thermal energy.
- A summary of computer models, simulations, and experimental studies that look at how nanofluids act in solar energy systems, taking into account things like flow dynamics, heat transfer, and system efficiency.
- There will be a discussion of the real-world problems that come up when using nanofluids, such as stability, cost, scalability, and environmental impact. There will also be a list of possible research directions, technological advances, and new uses that could make nanofluids even better at collecting solar energy.

Table 1 shows how this study's methodology is different from that of previous studies. The authors believe that no other study has looked at these problems in such depth. Hamzat et al. [22] did a similar study; however this one includes the most recent developments, difficulties, and trends in the field since it was published.

Table 1. Description of Earlier Published Review Paper on Similar Topic after 2018

Ref.	Review Detailed
[23], 2018	This study only focused on solar powered membrane distillation for enhancement of energy using nanofluid.
[24], 2019	This is limited to renewable system such as hydrogen production, biofuel and geothermal for energy harnessing using nanofluid
[25], 2020	This review only focused to enhance solar collector efficiency using nanofluid
[26], 2020	This review focused on only harnessing of solar thermal energy using nanofluid
[27], 2021	This research only focused on harnessing solar thermal energy using hybrid nanofluid
[28], 2022	Exclusively solar energy harvesting systems for photovoltaic self-powered applications were reviewed.
[22], 2022	An overview of current developments in nanofluid-based solar energy harvesting systems is provided in this article.

NANOMATERIALS AND NANOFLUID

Nanomaterials are materials with structural components smaller than 100 nanometers, typically consisting of atoms, molecules, or particles at the nanoscale. At this size, materials often have physical, chemical, and biological properties that are very different from those of their bulk equivalents. This is because the surface area is larger, quantum effects are stronger, and surface phenomena are more important [29-30]. Detailed classification of nanomaterials is shown in Fig. 2 and Fig. 3.

There are two main types of nanomaterials: organic and inorganic. Each nanomaterial has its own characteristics. The nanomaterials made by carbon molecules such

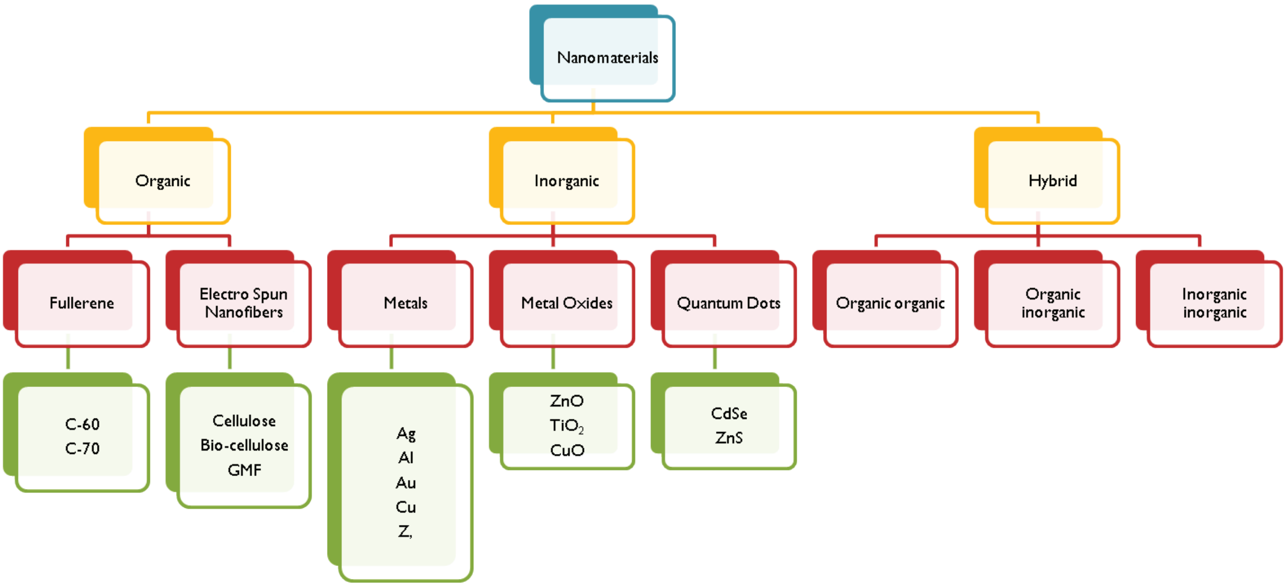

Figure 2. Various Types of Nanomaterials.

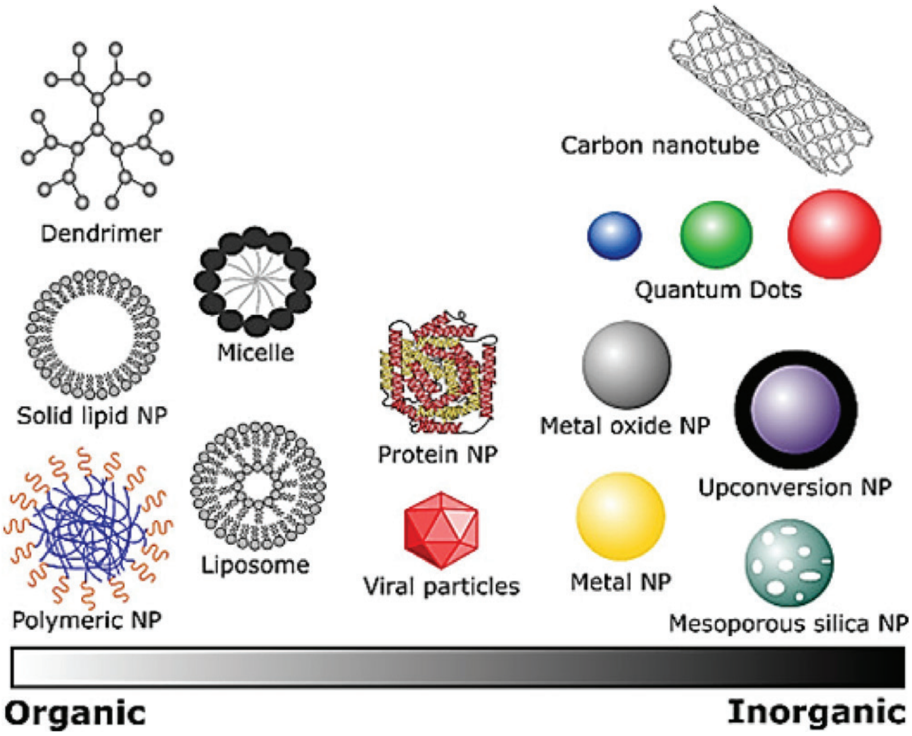

Figure 3. Organic and Inorganic nanoparticles compositions [From Bodunde et al. [31], with permission from Elsevier].

as polymer or organic compound are known as organic nanomaterials. Organic nanomaterials are most widely used in solar cells, optoelectronics, sensors, biomedicines like drug delivery and many more. However, inorganic nanomaterials do not contain any carbon. They are made by metals, metals oxide and ceramics. Such materials possess good strength, electrical conductivity and also stable at very high temperature. These characteristics are very useful for their utilization in electronic industry, solar system and also cleaning the environmental pollution. The materials which contain organic and inorganic material are known as hybrid nanomaterials which have the characteristics of both. So hybrid nanomaterials are versatile and useful in solar applications [31–32].

Nanofluid are the mixture of tiny nanomaterials (1-100 nm) in the base fluid like water, ethylene glycol etc having better heat transfer characteristics. Nanomaterials such as CNT, quantum dots, metal oxides etc. posses high heat transfer and thermophysical properties [33]. Nanofluids were first thought of in the mid-1990s as a new way to improve heat transfer efficiency. After the discovery of nanomaterials, they have got attention of researchers because it makes the system more effective and [34]. The various applications of nanofluid are depicted in Fig. 4.

Nanofluids have better thermal characteristics than regular fluids because the nanoparticles have a large surface area and excellent thermal conductivity, which makes energy transmission more efficient. Nanoparticles make the surface area accessible for heat exchange more effective, which speeds up the processes of heat transmission. Also, the Brownian motion of nanoparticles causes micro-convection in the fluid, which makes thermal conductivity even better [35]. Studies have shown that even a small amount of nanoparticles can make a big difference in how well something conducts heat. This makes nanofluids very useful for things like cooling systems in cars, electronic devices, and renewable energy systems like solar collectors [36].

In renewable energy system, nanofluid has got special attention since it make renewable energy system more effective and reliable. In solar collector, nanofluid absorbs the solar radiation and converts it into thermal energy more prominently [37]. The direct conversion of energy make solar collector more effective compared to other heat transfer fluids. Nanofluids are also used in nuclear reactors for cooling purpose to make reactor more efficient and work better. [38].

Nanofluids offer many advantages and utilizations in various solar energy systems along with possible problems of clogging and stability. Main concern about nanofluid is

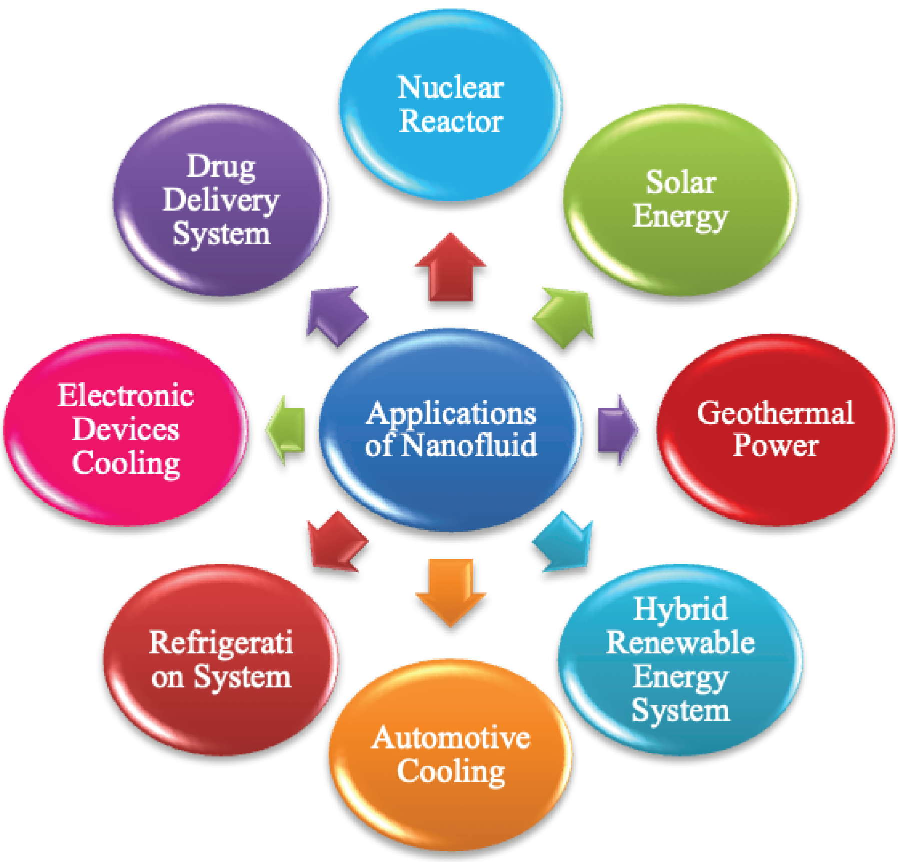

Figure 4. Applications of Nanofluid.

its stability over time since nanoparticles settled together after certain period of time and clogging created and ultimately lose their thermal characteristics [39]. Advance synthesis and characterization techniques are required to make nanofluid stable and its utilization in real life applications. The high cost of nanomaterials also create problem in mass production and its industrial utilization [40].

Researchers are mainly focused on Newtonian base fluid while experimentation on nanofluid since its viscosity does not affected with shear deformation. In case of non-newtonian fluids viscosity affected with shear deformation which cause problem clogging and stability of nanofluid. You can typically find these fluids in more specialized or industrial uses, including in biological fluids, slurries, or some types of lubricants. The behavior of nanofluids in non-Newtonian fluids can be more complicated to predict because the interactions between nanoparticles and the non-linear viscosity of the base fluid can result in complex flow characteristics.

Research on non-Newtonian nanofluids is less common, but it is expanding. This is because learning more about these interactions could lead to new uses for non-Newtonian fluids in areas where they are common. But the difficulty of modeling and testing non-Newtonian nanofluids has probably caused researchers to focus on Newtonian fluids in the beginning phases of nanofluid research.

PROPERTIES OF NANOMATERIALS (NANOFLUID)

The size, shape, concentration, and material composition of the nanoparticles have a big effect on the properties of nanofluids. Figure 5 shows some of the different properties of nanofluid. One of the most interesting things about nanofluids is that they have better thermal conductivity than regular fluids, which makes them very good for transferring heat [41]. Nanofluids also have better viscosity and heat capacity, which can be changed by changing the concentration of nanoparticles. Another important attribute is their stability; well-dispersed nanoparticles stop aggregation and settling, which keeps the thermal performance steady [42]. Nanofluids can also have different optical, magnetic, and electrical properties depending on the nanoparticles utilized. This makes them useful for many different industrial uses, such as solar energy harnessing and cooling systems. Different properties of nanofluids used by different researchers are summarized in Table 2.

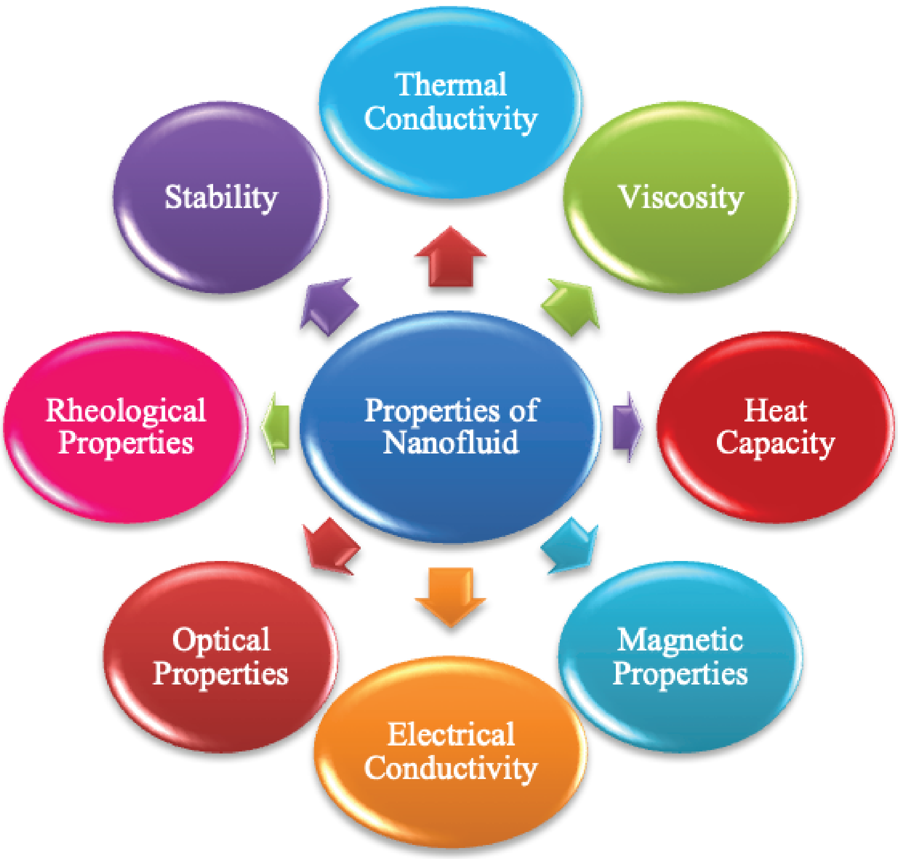

Figure 5. Different Properties of Nanofluid.

Table 2. Earlier Researchers Investigation on Nanofluid Properties

Ref. No.	Nanofluid	Properties of Nanofluid	Remark
[46]	Al_2O_3/H_2O	Thermal conductivity	Maximum boost of 10.1% at the 0.15 weight percent nanoparticle suspension
[47]	Ti_3C_2Tx/water	Thermal conductivity	30.6% increase TC due to Brownian movement
[51]	Al_2O_3/H_2O	Viscosity	2.3 times rise in viscosity was observed at 5% volume concentration
[52]	Ti_3SiC_2/propylene glycol	Viscosity	A 0.2 weight percent inclusion of MXene resulted in a viscosity drop
[55]	Ti_3C_2-soybean oil	Specific heat capacity	The addition of MXene caused a noticeable rise in the heat capacity.
[56]	CuO/ethylene glycol	Specific heat capacity	Maximum 6% increase in SHC
[61]	Cu-Zn/ vegetable oil, paraffin oil, and SAE oil	Stability	All of the samples displayed increased stability for over 72 hours.
[62]	Ti_3C_2-H_2O	Stability	Prolonged storage periods were associated with increased aggregation in the stability of CTAB specimens

Thermal Conductivity

Nanofluids, which are fluids that contain nanoparticles, have a very important property called thermal conductivity that helps solar energy systems work better. Nanofluids have better heat conduction than regular fluids because the nanoparticles have a larger surface area and better heat transfer capabilities [43]. This better thermal conductivity makes solar collectors better at absorbing and transferring heat, which makes the process of turning solar energy into thermal energy more efficient. Researchers want to improve the thermal performance of nanofluids by finding the best kind, concentration, and dispersion of nanoparticles. This makes them good candidates for improved solar energy systems [44,45]. The thermal conductivity of different nanomaterials is shown in Fig. 6.

The impact of pH value fluctuations on the thermal conductivity (TC) of Al_2O_3/H_2O nanofluid was investigated by Zhu et al. [46]. They found that varying SDBS surfactant concentrations in nano-suspensions and pH values had a significant impact on the degree of stability and improvements in TC of Al_2O_3/H_2O nanofluids. By adding optimal SDBS dispersing agent, the TC increased. To increase the TC, it was suggested to combine the pH and chemical surfactant treatments. Ti_3C_2Tx/water TC was studied by Mao et al. [47] at various loading fractions ranging from 0 to 0.5 wt%. It was discovered that at 0.5 weight percent, there was the greatest improvement in TC, measuring 0.8431 W/m.K.

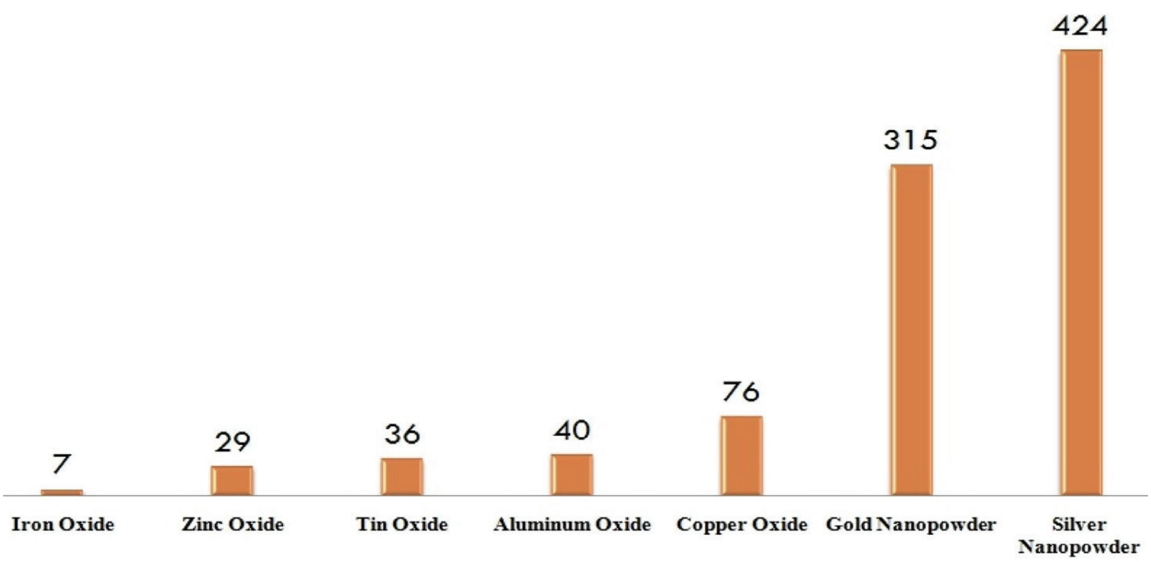

Figure 6. Thermal conductivity of different nanomaterials (W/mK).

The big basal plane of mXene and its Brownian movement in water both contributed to a 30.6% increase.

Viscosity

Nanofluids are fluids that have nanoparticles in them. Their viscosity is an important aspect in deciding if they can be used to collect solar energy. Adding nanoparticles to the fluid can greatly improve its heat conductivity, but it can also change the fluid's viscosity. Higher viscosity can mean that more power is needed to pump the fluid, which could cancel out the advantages in thermal efficiency [48]. To employ nanofluids effectively in solar energy systems, it is important to find the right balance between better thermal conductivity and viscosity that is easy to handle. To get the viscosity just right, researchers are looking at the size, shape, concentration, and composition of nanoparticles. This will make sure that heat is transferred efficiently and that the system doesn't lose too much energy. Figure 7 show that several factors changed the viscosity of the nanofluid.

Nanofluids usually get thicker as there are more nanoparticles in them because the particles interact with each other and with the base fluid more. Smaller nanoparticles usually make the fluid thicker because they have a larger surface area compared to their volume, which makes them interact with the fluid more. Irregularly shaped or long nanoparticles can also make liquids thicker than spherical nanoparticles because they impede flow more [49]. With increase of temperature, viscosity of nanofluid decreases, but this change totally depends upon the type of nanoparticle. At higher temperatures, the thermal motion of particles may overcome the interparticle forces, reducing viscosity [50].

In a laboratory investigation, Chandrasekhar et al. [51] investigated the viscosity of Al_2O_3/H_2O nanofluids. The outcome showed that as the volume fraction of nanoparticles rises, so does the viscosity of nanofluids. At 5% volume fraction, a 2.3-fold increase in viscosity was noted in comparison to the base fluid in this study. Mahesh et al. [52] calculated a reduction in viscosity for Ti_3SiC_2/propylene glycol. A 0.2 weight percent inclusion of MXene resulted in a viscosity drop. Propylene glycol and MXenes demonstrated good surface associations at 0.25 weight percent, as evidenced by a small rise in viscosity. There could be several causes for the MXenes viscosity reduction. One explanation is that there is little interaction between particles at tiny amounts due to charges' tendency to pull away from one another.

Heat Capacity

The heat capacity of nanofluids, which refers to their ability to store thermal energy, is a critical parameter for solar energy harnessing applications. Nanofluids usually have better thermal conductivity; however their heat capacity might change depending on the type and amount

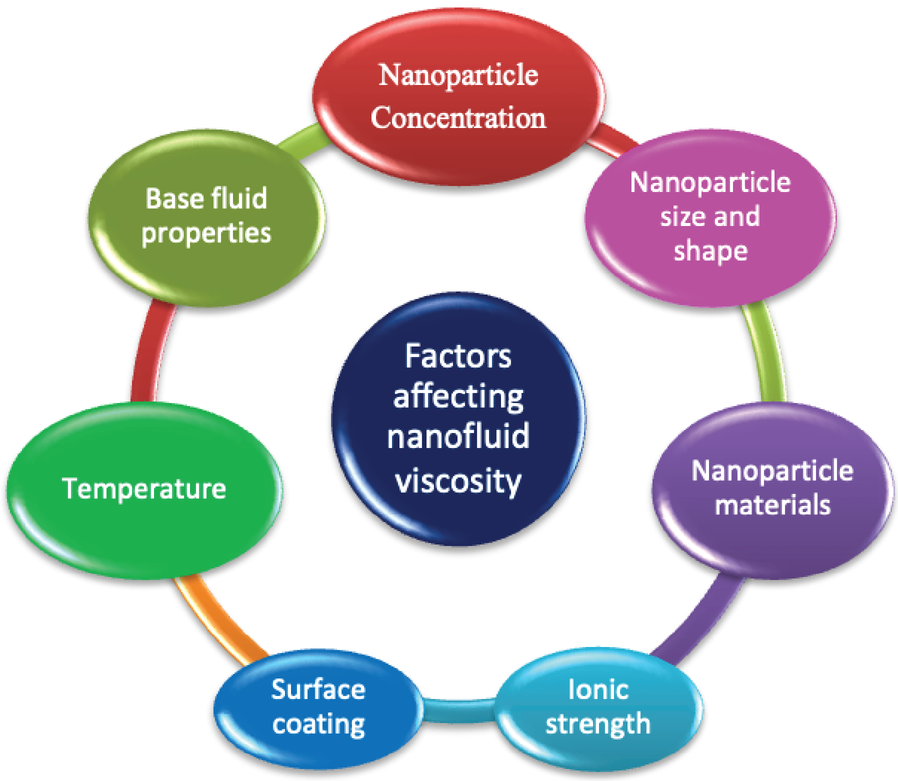

Figure 7. Factors affecting viscosity of nanofluid.

of nanoparticles utilized. A large heat capacity is ideal for solar energy systems because it lets the fluid soak up and store more heat from the solar collector before sending it to a storage unit or directly to where it will be used [53]. However, adding nanoparticles can sometimes lower the fluid's overall heat capacity. A solar thermal system performs much better if its thermal conductivity and specific heat capacity of nanofluid is enhanced [54].

Rubbi et al. [55] examined the SHC of Ti_3C_2-soybean oil at various MXene adding fraction. The heat capacity of nanofluid is enhanced due to inclusion of MXene for temperature range between 25°C to 80°C. Zhou et al. [56] found that their CuO/ethylene glycol nanofluid has an ultimate increase of roughly 6% of its SHC.

Stability of Nanofluid

For nanofluids to work well for collecting solar energy, they need to be stable. The term stability refers to proper distribution of nanoparticles in the base fluid without clogging over time. Solar thermal system works more effectively and efficiently when nanofluid is stable over period of time [57]. Various methods such as magnetic steering, homogenizer, ultrasonication, surfactant addition and many more are used to enhance the stability of nanofluid. Stable nanofluids keep solar energy systems working consistently, requiring less maintenance, and make them last longer and work better overall. As a result, one of the most important areas of research is how to make nanofluids very stable so that they can be used reliably and effectively for solar energy over a long period of time [58]. Various ways to enhance the stability of nanofluid is shown in Fig. 8.

In magnetic stirring, a magnetic stirrer is used to move the nanoparticles regularly and also properly mix them into the base fluid while in ultrasonication a sound wave is used to break the allglomorated particle and distribute them properly. This is possible due to high frequency of sound wave. This method can make the fluid more stable for a short time by making the nanoparticles more evenly spread out [59]. Changing the pH of the nanofluid can make the surface charge of the nanoparticles better, which makes them repel each other more strongly. Stability can be greatly enhanced by getting the pH just right, which is usually where the zeta potential is at its highest. To help nanoparticles spread out better in the base fluid, surfactants and dispersants are added to nanofluids. They work by reducing the surface tension and preventing particle agglomeration through electrostatic or steric stabilization [60].

In order to investigate TC and other rheological parameters, Kumar et al. [61] conducted investigations utilizing Cu/Zn 0.1–0.5% and several base fluids, including vegetable oil, paraffin oil, and SAE oil. For almost 72 hours, all samples showed improved stability. Abdelrazik et al. [62] employed zeta potential and optical examination to assess the stability of Ti_3C_2-H_2Onanofluids at multiple concentrations containing CTAB and SDBS surfactants. Prolonged storage periods were associated with increased aggregation in the stability of CTAB specimens. The lower concentration CTAB specimens began to precipitate after a single day of preparation, and by day five, each specimen had settled down. But whereas some SDBS specimens remained stable for just a few hours, others did stay stable for a few days with minimal precipitation.

UTILIZATION OF NANOFLUID IN DIFFERENT SOLAR ENERGY HARNESSING SYSTEM

Nanofluids are engineered colloidal suspensions of nanoparticles in a base fluid. They have shown a lot of promise in making solar energy systems work better. Due to enhanced thermal conductivity and heat transfer rate, solar collector performs much better by utilization of nanofluid. In PV/T system, nanofluid is used as a coolant to keep solar panel cool and get maximum out of it. In concentrated solar power (CSP), solar radiation is absorbed by nanofluid and this radiation is stored as thermal energy for further uses. The optical and thermal properties of nanofluid make it more special to enhance the solar system performance.

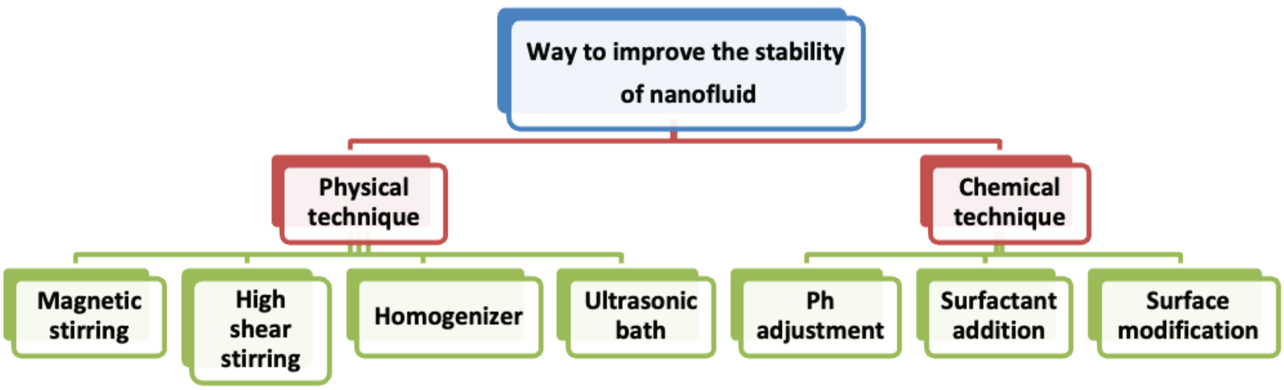

Figure 8. Way to improve the stability of nanofluid.

Solar Concentrator or Collector

A device which collects solar radiation and converts it into heat energy for further utilization is known as solar collector [63]. Figure 9 shows a simple flat plate solar collector. A solar collector's main parts are an absorber plate, a clear cover, insulation, and a system for moving fluid around. The materials such as aluminum, copper are used to make the absorber plate due to its high thermal conductivity. This plate is covered so that heat is not escaped from the plate. Insulation on the back and sides of the collector helps keep the heat it collects [64].

A solar collector works by collecting sunlight and turning it into heat. The absorber plate takes in energy from the sun and turns it into heat. This heat is then transferred to a working fluid (such as water or air) that flows through or across the absorber plate. The heated fluid is either used immediately or stored for later use. The efficiency of the collector depends on the quality of materials used, the design of the collector, and the intensity of the sunlight. Solar collectors are commonly used in residential and commercial settings for water heating, space heating, and even for powering certain types of solar energy systems [65]. The detailed classification of different types of solar collectors is shown in Fig. 10 and the summary of recent research on solar collector for solar energy harnessing is provided in table 3. The mathematical formula used for the calculation of different parameters is mentioned below:

It is possible to assess the flowing fluid's usable heat transfer via

$$Q_u = \overset{0}{m} c_p \left(T_{out} - T_{in}\right) \quad (1)$$

The solar collector thermal efficiency is calculated as

$$\eta_{th} = \frac{Q_u}{Q_s} = \frac{\overset{0}{m} c_p \left(T_{out} - T_{in}\right)}{I A_c} \quad (2)$$

The solar collector exergy efficiency is calculated as

$$\eta_{ex} = 1 - \frac{T_a \overset{0}{S}_{gen}}{\left(1 - \frac{T_a}{T_s}\right) Q_{solar}} \quad (3)$$

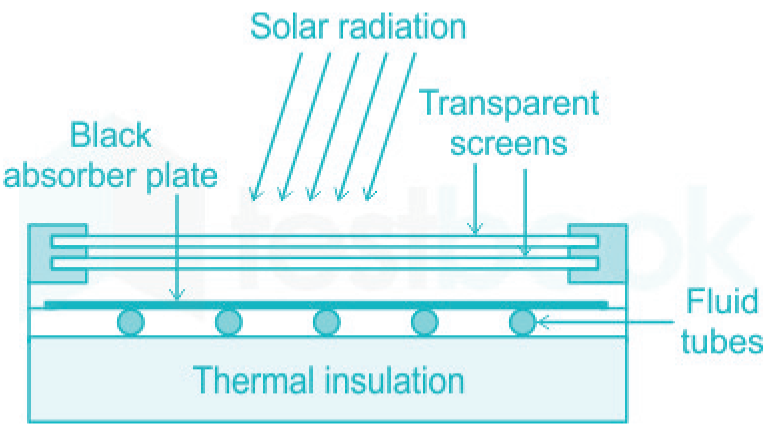

Figure 9. A Simple Flat Plate Solar Collector.

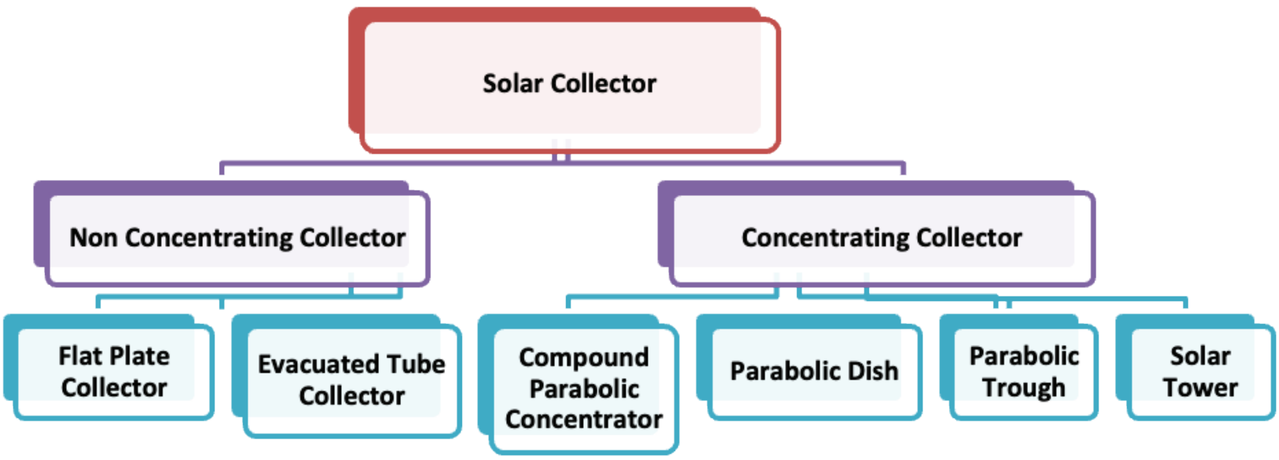

Figure 10. Classification of Solar Collector.

Table 3. Recent Researches Performed on Solar Collector using Nanofluid

Ref. No.	Type of Collector	Nanofluid	Remark
[66], 2016	FPSC	MgO/Water	A 9.34% increase in thermal efficiency is established for a 0.75% component volume fraction.
[67], 2017	FPSC	MWCNT/water, Graphene/water, Cuo-H_2O, Al_2O_3-H_2O, TiO_2-H_2O, SiO_2-H_2O	Maximum improvement in energy efficiency is observed in MWCNT/water that is 29.3%.
[68], 2020	FPSC	Al_2O_3-H_2O, Cuo-H_2O	The HTC can rise to 78.25% when zigzag pipes and CuO/water nanofluid are used.
[69], 2021	FPSC	Al_2O_3-H_2O and TiO_2-H_2O	Maximum 30% increment is observed using TiO_2-H_2O nanofluid
[70], 2022	FPSC	Al_2O_3, MWCNT, MWCNT/ Al_2O_3	For 1.5 l/m, MWCNT/ Al_2O_3 provide an efficiency increase of 26%.
[71], 2023	FPSC	Al_2O_3-H_2O, Cuo-H_2O, Si_2O -H_2O	Efficiency of 2% Al_2O_3-H_2O is 29.75% higher than 1%.
[72], 2024	FPSC	SiC/DW	At a SiC volume percentage of 0.1, the FPSC's energy efficiency climbed to 37.4%.
[73], 2020	PTC	MWCNT/H_2O	49.52% enhancement in thermal efficiency at 0.3% volume concentration
[74], 2020	PTC	Syltherm 800/Copper	When the cermet layer is applied to the bare tubes, the highest improvement is 7.16%.
[75], 2021	PTC	Ag-ZnO/ Syltherm 800, Ag-MgO/ Syltherm 800, Ag- TiO_2/ Syltherm 800	Maximum 31% enhancement in thermal efficiency using Ag-MgO/Syltherm 800 at 4% volume fraction
[76], 2022	PTC	Al_2O_3, CuO	Maximum thermal efficiency is 14.79% using CuO nanofluid at 0.0224 kg/s mass flow rate
[77], 2022	PTC	Al_2O_3, Cu, SWCNT	Maximum energy efficiency 79.9% for SWCNT
[78], 2023	PTC	CuO/H_2O	Highest efficiency increase of 69.07% at mass flow rate of 140 l/h and volume concentration of 0.1%.
[79], 2023	PTC	TiO_2 and Graphite as TES material	85.4% maximum enhancement in energy efficiency using Graphite as TES material
[80], 2023	PTC	ZnO/EG- H_2O	100% increase in Nusselt number at volume fraction 4%
[81], 2023	PTC	Al_2O_3-Cu/ H_2O	A 32.8% decrease in the total amount of entropy generated
[82], 2024	FPSC, PTC	Carbon nanotube/water and carbon nanotube/ EG	80.6% increase in thermal efficiency of PTC using carbon nanotube/ EG nanofluid
[83], 2020	ETSC	MWCNT, SiO_2, TiO_2 and CuO	Maximum thermal efficiency enhancement is 14.0.9% using CuO nanofluid.
[84], 2020	PT-ETSC	Al_2O_3	Maximum gain in thermal efficiency was 69.5% 0.035 kg/s mass flow rate and 0.3% volume fraction.
[85], 2022	ETSC	hBN/H_2O	The ETSC's optimum energy efficiency is increased by 84%.
[86], 2023	ETSC	MgO-MWCNT/H_2O	MWCNT nanoparticles can boost the collector's optical effectiveness by up to 78.1%.
[87], 2023	ETSC	Al_2O_3, CuO, Fe_3O_4, MWCNT	Highest energy and exergy efficiency for 0.01% of MWCNT
[88], 2023	ETSC	MWCNT, Al_2O_3, MWCNT/ Al_2O_3	Maximum energy efficiency obtained is 60% for MWCNT/ Al_2O_3 hybrid nanofluid

Verma et al. [66] tested a FPSC using MgO/water nanofluid with particles measuring 40 nm and an aggregate volume fraction that ranged from 0.25 to 1.5% at various mass flow rates. Thermal efficiency gain of 9.34% is established by experimental evidence for 0.75% component volume fraction at 1.5 lpm flow rate. The variation of efficiency with mass flow rate at varying volume fraction is shown in Fig. 11. For the same composition and flow rate, there was a 32.23% increase in energetic efficiency. Verma et al. [67] again concentrated on a broad range of nanofluids to assess the FPSC effectiveness in terms of several parameters. The results of the experiments show that the energy efficiency of MWCNT/water nanofluid is improved by 29.32% at a particle volume fraction of 0.75% and a mass flow rate of 0.025 kg/s. MWCNT/water nanofluids also have minimal entropy creation, which can be a disadvantage. The greatest

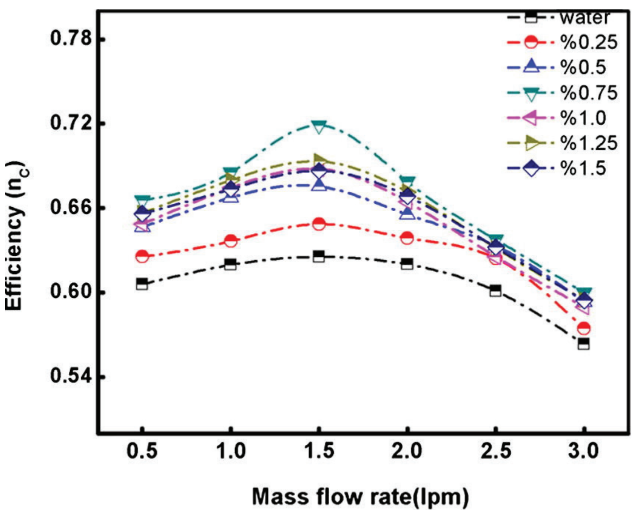

Figure 11. Variation of thermal efficiency of FPSC at varying mass flow rate and volume fraction [From Verma et al. [66], with permission from Elsevier]

measured decrease in production of entropy in MWCNT/water, at 65.55%, has been noticed under identical thermophysical conditions.

Saffarian et al. [68] utilized two different nanofluid Al_2O_3-H_2O and CuO- H_2O having volume fraction varying from 1% to 4% to enhance the heat transfer of FPSC using different shape of flow path. The coefficient of heat transfer and Nusselt number can be greatly increased by employing spiral and zigzag pipes, according to the observations. Furthermore, it is noted that the zigzag pipes exhibit the most pressure decrease. When nanofluid is used in place of water, the coefficient of heat transfer rises in every situation. Gad et al. [69] conducted research, In order to investigate the impact of adding nanoscale Al_2O_3-H_2O and TiO_2-H_2O as an operating fluid on solar collector effectiveness. To improve spreading and decrease amalgamation, 25 nm-sized nanoparticles were employed. A surfactant was incorporated to the produced nanofluids to increase their stability, and their concentration was set at 2% by weight. Regarding base fluid, the largest increases in collector efficiency for Al_2O_3-H_2O and TiO_2-H_2O were approximately 22 and 30%, correspondingly. It was suggested that Al_2O_3-H_2O and TiO_2-H_2O nanofluid be used to improve the efficiency of solar collectors. Elshazly et al. [70] utilized three different nanofluids Al_2O_3, MWCNT and, MWCNT/ Al_2O_3 to analyze the FPSC experimentally. Al_2O_3 substitution for 50% of MWCNT nanofluid results in a smaller efficiency gain and fewer hazards to the environment. According to the findings, employing hybrid MWCNT/ Al_2O_3 offers a 26% boost in efficiency for 1.5 L/m. Desisa [71] utilized Al_2O_3-H_2O nanofluid for heat transfer investigation of FPSC experimentally as well as numerically at different mass flow rate and mean diameter of nanomaterial varying from 15 to 50 nm. Comparing CuO and Si_2O nanoparticles with comparable nanoparticles, they exhibit varying degrees of enhancement. Compared to 1% Al_2O_3-H_2O and H_2O, the thermal efficiency of 2% Al_2O_3-H_2O is 5.3% and 29.75% higher, respectively. Ajeena et al. [72] examined the effects of using SiC/DW nanofluids on a FPSC's efficiency in the climate of Gödöllő, Hungary. The results showed that the inclusion of SiC nanoparticles increased the fluid's TC by as much as 30.3%. A 35.5% increase in thermal efficiency was seen in the FPSC with the addition of 0.1% SiC. At a SiC volume percentage of 0.1, the FPSC's energy efficiency climbed to 37.4%.

Hachicha et al. [73] conducted mathematical and experimental research to examine the impact of MWCNT/H_2O nanofluid with varying concentration (0.05% to 0.3%) for moderate to medium-level temperature PTCs. 49.52% enhancement in thermal efficiency is achieved. At 0.3% concentration, 21% enhancement in Nusselt number is achieved. A thorough analysis of the application of Syltherm 800/Copper nanofluids in a PTC is conducted by Bellos et al. [74].The findings show that situations with larger heat losses exhibit the greatest improvements, indicating that the majority of the bare tube's effectiveness is improved by the incorporation of nanofluids. When the cermet layer is applied to the bare tubes, the highest improvement is 7.16%.

Ekiciler et al. [75] looked into the 3D heat transmission and flow properties of the hybrid nanofluids at different volume fraction (1% to 4%) listed in table 3 under turbulence conditions in a PTC. During investigation, Reynolds number was varied from 10000 to 80000. It is observed that the maximum enhancement in convective heat transfer is 31% by utilizing Ag-MgO/Syltherm 800 nanofluid at 4% volume fraction while Ag-ZnO/Syltherm 800 nanofluid enhance the friction factor approximately by 15%. Farooq et al. [76] used CFD simulation to analyze the PTC with the application of two nanofluids namely Al_2O_3 and CuO at 0.01% concentration for environmental sustainability. Maximum thermal efficiency is 14.79% using CuO nanofluid at 0.0224 kg/s mass flow rate. Copper has consistent temperature dispersion throughout the entire span of the tube used for absorption because of its superior thermal conductivity.

Vahedi et al. [77] investigated the exergoeconomic and thermal performance of PTC using different nanofluid. The energy efficiency movement ran counter to the energy the demise tendency. Additionally, the maximum energy efficiency that achieved was approximately 74.4% for oil, aluminum oxide, and copper, and 79.9% for SWCNT. Ram et al. [78] used CuO/H_2O nanofluid to enhance the performance of PTC with three different volume concentration at two mass flow rate. The increase in efficiency with varying volume concentration and mass flow rate is shown in Fig. 12 and observed that maximum efficiency gain 69.07% at 140 l/h mass flow rate at volume concentration of 0.1%.

Using a variety of techniques, involving the application of nanofluid such as TiO_2 and TES materials, Hamada et al. [79] attempted to improve the energy efficiency of the

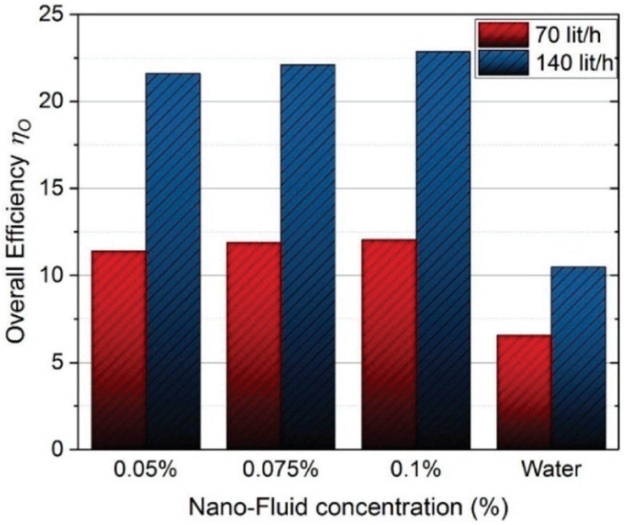

Figure 12. Variation of overall efficiency of PTC at varying mass flow rate and volume fraction [From Ram et al. [78], with permission from Elsevier].

conventional PTC. The result showed that 57.7% enhancement in thermal efficiency using TiO_2 nanofluid and 85.4% using graphite as TES material. The transport and flow properties of ZnO/EG-H_2O nanofluid flowing in a PTC were studied both computationally and experimentally by Ekiciler et al. [80] at various flow rates ranging from 20 l/h to 80 l/h and volume fraction varying from 1% to 4%. The results show that the ZnO/EG- H_2O nanofluid greatly increases the collector's performance. The greatest useable energy was produced using 4% ZnO/EG- H_2O nanofluid at a flow rate of 80 l/h. As opposed to EG- H_2O, the data indicate that using ZnO/ H_2O causes a higher temperature disparity. Esmaeili et al. [81] used Al_2O_3-Cu/ H_2O hybrid nanofluid on PTC to investigate its performance. Heat transmission rises by 35.7% when CHGR are utilized as discs in the absorber tube as opposed to the absence of turbulators. In this instance, there is a 32.8% reduction in the overall creation of entropy. Abu-Zeid et al. [82] investigated the performance of FPSC and PTC using carbon nanotube/ water and carbon nanotube/ EG nanofluid. By employing EG nanofluid, FPSC and PTSC equipment demonstrated a notable increase in mean thermal efficiency of 64.1% and 80.6%, correspondingly.

Yurddaş [83] used CFD modeling to optimize the ETSC's thermal effectiveness after analyzing it with various nanofluids with varying concentration (0.5% to 5%) listed in Table 3. Maximum thermal efficiency enhancement is 14.0.9% using CuO nanofluid. Sasikumar et al. [84] experimentally examined the effectiveness of PT-ETSC with Al2O3 nanofluid at different concentrations (0.1% to 0.3%). Maximum gain in thermal efficiency was 69.5% 0.035 kg/s mass flow rate and 0.3% volume fraction. Kumar and Tiwari [85] use hBN/H_2O nanofluid with different volume fractions (0.25 to 2%) to analyze the thermal effectiveness of an ETSC. Higher thermal conductivity has been proven using hBN/ H_2O nanofluid. The ETSC's optimum energy efficiency is increased by 84%. Henein et al. [86] used MgO-MWCNT/H_2O hybrid nanofluid for 3E analysis of ETSC at different mass flow rate and weight ratio experimentally. According to the findings, increasing the weight ratio of MWCNT nanoparticles can boost the collector's optical effectiveness by up to 78.1%. There has been a boost in mean thermal energy absorption from 240 W to 495 W which is shown in Fig. 13. The use of the hybrid nanofluid results in a 36% decrease in area of ETSC and a 56% increase in the fluid's intake–exhaust variation in temperature.

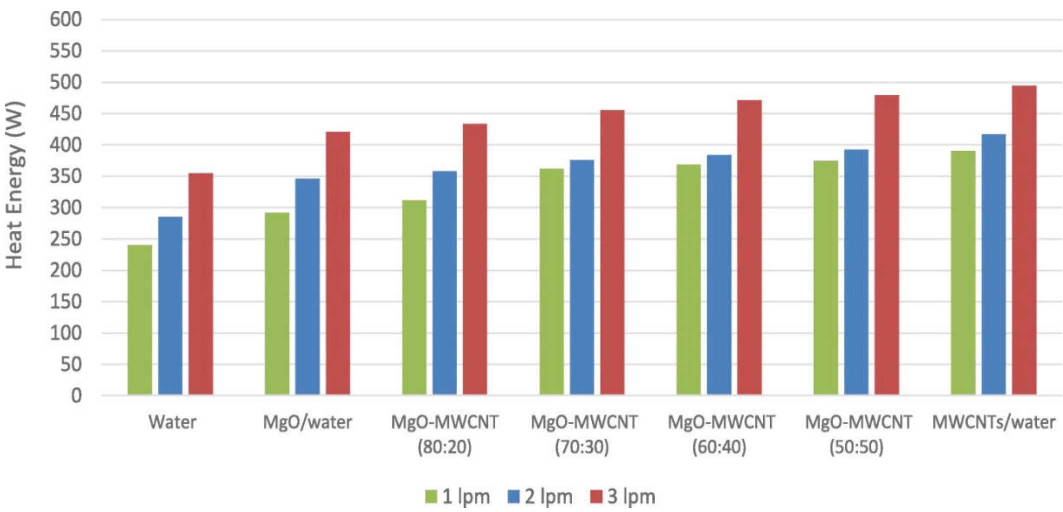

Figure 13. Heat energy gain in different nanofluid at different mass flow rate [From Henein et al. [86], with permission from Elsevier].

By employing several nanofluids listed in table 3 as operational fluids, Tong et al. [87] sought to assess the thermal endurance of an ETSC in a STS. The ETSC demonstrated the maximum energy consumption and energy effectiveness at 33.1% greater compared to the amount of water when the 0.01% MWCNT nanofluid was utilized. In terms of efficiency of energy, the highest value was 3.17 under ideal conditions. Elshazly et al. [88] utilized three different nanofluids as mentioned in table 3 to evaluate the thermal performance of ETSC at different volume fraction varied from 0.5% to 0.005% at three different mass flow rates. The results show that compared to employing Al_2O_3, which has previously been reported, employing hybrid MWCNT/ Al_2O_3 50:50% results in an efficiency improvement of almost 20%. Ultimately, it was discovered that, under identical testing circumstances, the ETSC's energy and energy effectiveness could be increased to 73.5% and 51%, respectively, by using 0.5% MWCNT/H_2O nanofluid at mass flow rate of 3.5 l/m.

Solar Water Heater

A solar water heater is an eco-friendly and energy-efficient system designed to harness solar energy for heating water. It typically consists of solar collectors, usually mounted on rooftops that absorb sunlight and convert it into heat. A solar water heating system is shown in Fig. 14 [89]. This heat is then sent to water, either directly or through a heat exchanger. The water is then kept in an insulated tank for later use. Solar water heaters work best in sunny places and can greatly minimize the need for traditional energy sources, which lowers utility bills and carbon emissions. These systems are great for homes and businesses because they provide a long-lasting means to provide hot water while also helping to protect the environment.

The way a solar water heater works is by turning sunlight into thermal energy, which is then utilized to heat water. Solar collectors, which are normally on rooftops, are what the system uses to capture sunlight. These collectors usually have an absorber plate that gets hot when the sun shines on it. Then, the heat is sent to a fluid, which can be water or a heat-transfer liquid that flows through pipes that are attached to the absorber plate. The heated fluid goes to a storage tank, where the heat is given to the water so it can be used. In passive systems, the fluid moves about on its own thanks to thermosiphon activity. In active systems, pumps move the fluid around. The hot water that is saved is then available for use in the home. A backup heater makes sure that there is always enough hot water, even when solar energy is low. Table 4 summarizes current research on solar water heating systems for solar energy harvesting using nanofluid.

Modi et al. [90] examined the thermal endurance of SWHS utilizing chitosan as an organic and Al_2O_3 as an inorganic nanofluid. The Chitosan produced the highest possible heat elimination factor (0.627) and collector efficiency factor (0.727). Chitosan exhibited a 5.96% and 33.6% better efficiency when compared with Al_2O_3 and H_2O, respectively. The variation of efficiency with time for three different cases is shown in Fig. 15.

Darbari and Rashidi [91] looked into the thermal effectiveness of the flat plate thermosyphon SWH employing the various nanofluids listed in table 4. The inclusion of Cu nanoparticles, subsequent to CuO, across the different nanoparticles produces the most increase in useable energy and effectiveness. Cu and CuO nanoparticles added to the base fluid at a volume percentage of 5% increase the solar collector's usable energy by 6% and 3%, correspondingly. Mandal et al. [92] performed parametric evaluation of SWH using paraffin wax as PCM and CuO-PCM. The highest

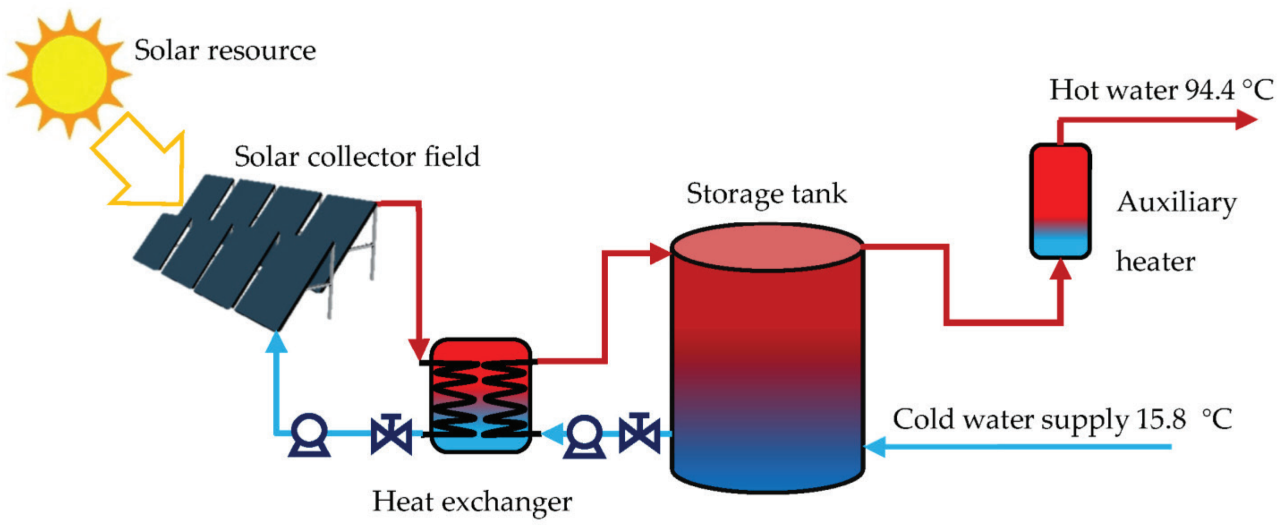

Figure 14. Solar water heating system [From López-Pérez et al. [89], with permission from MDPI].

Table 4. Current research on solar water heating systems for solar energy harvesting using nanofluid

Ref. No.	Type	Nanofluid	Remark
[90], 2020	FPC-SWH	Chitosan, Al_2O_3	It is possible to use chitosan and reach an experimental efficiency of 55.86%.
[91], 2021	FPC-SWH	Al_2O_3, TiO_2, CuO, Cu	Maximum 6% enhancement in thermal efficiency using CuO nanofluid
[92], 2021	FPC-SWH	CuO, CuO-PCM	Maximum heat transfer rate 5.7 kW is observed using CuO-PCM
[93], 2022	Vacuumed tube SWH	Al_2O_3/Oil, TiO_2/Oil	Al_2O_3/oil nanofluid has 31% thermal efficiency as compared to TiO_2/oil nanofluid
[94], 2023	PTC - SWH	DW/ZnO	Thermal efficiency is enhanced using DW/ZnO nanofluid
[95], 2023	ETSWH	TiO_2/engine oil	When only porous material is used, the system's energy efficiency increases by 19.6%.
[96], 2023	ETSWH	TiO_2/engine oil	24.4% thermal efficiency at 0.4% of mass using inserts
[97], 2023	Polymer SWH	Al_2O_3	27.7% increment in thermal efficiency of SWH
[98], 2024	FPC-SWH	TiO_2 –H_2O	Maximum 16.48% increment in SWH efficiency
[99], 2023	SWH	ZrO_2 –H_2O	Maximum 20.68% increment in SWH efficiency
[100], 2024	DTPTSWH	TiO_2, Al_2O_3, CuO, SiO_2	CuO nanofluid had the highest efficiency, at 38.4%.

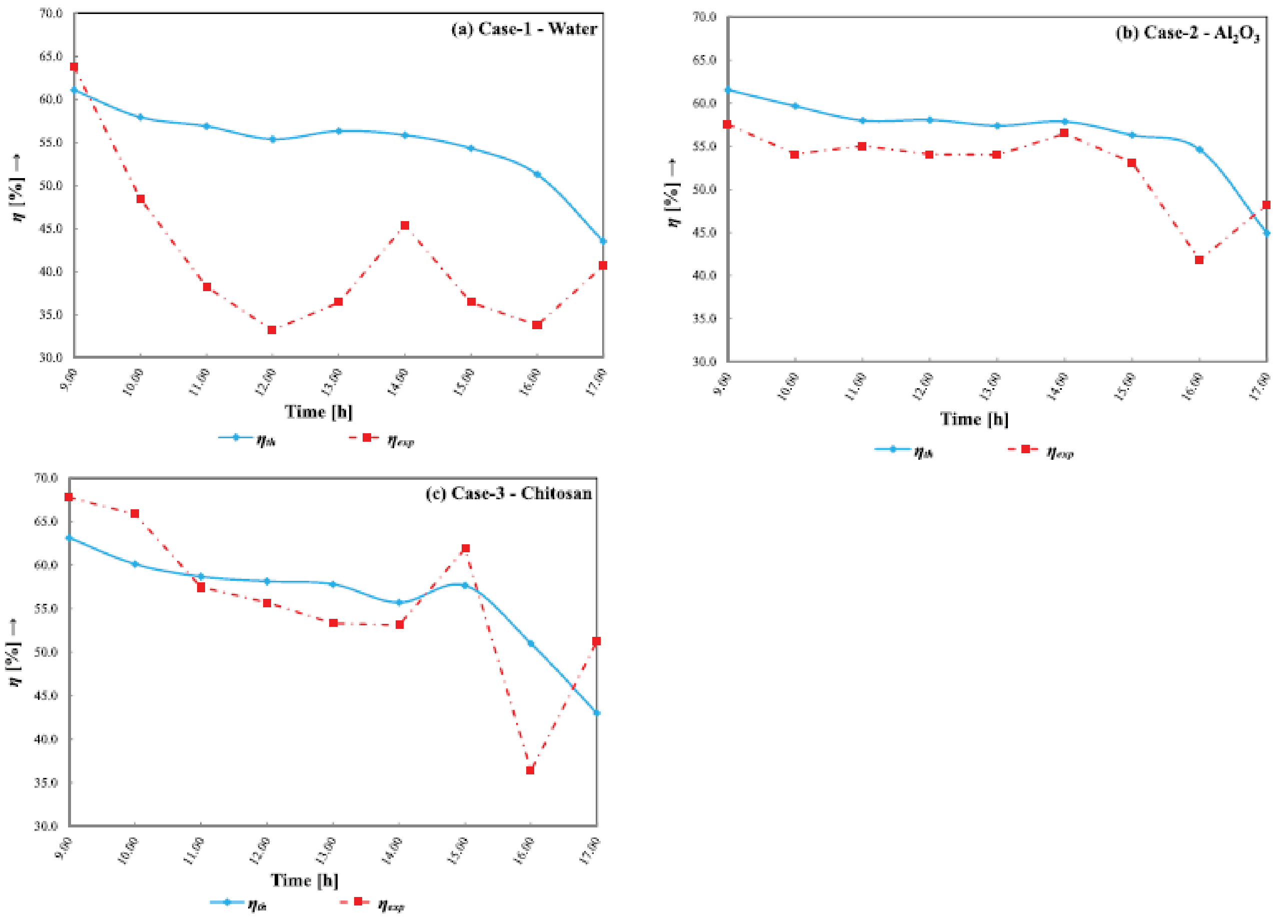

Figure 15. Variation of efficiency of SWH with time with different cases [From Modi et al. [90], with permission from Elsevier].

possible rate of heat transfer for CuO-PCM is found to be 5.7 KW, provided that a gap in air of 40 mm is maintained among the plate that absorbs heat and the outer layer of glazing.

Shafiee et al. [93] used oil based nanofluid in vacuumed tube SWH to evaluated its thermal performance using three different nanofluid mentioned in table 4 at fixed volume fraction of 1wt%. Al_2O_3/oil nanofluid has 31% thermal efficiency as compared to TiO_2/oil nanofluid. When the outcomes were assessed against the standard exergy efficiency calculation, a 6.1% discrepancy was found amongst them. Arun [94] proposed a PTC-equipped SWHS-ZO-NF.A boost in the volume fraction of the nanofluid lowers the exergy loss of the entire system. The thermal effectiveness and energy assessment are improved by the practical outcome of the proposed SWHS-ZO-NF. Firoozzadeh et al. [95] used TiO_2/engine oil nanofluid to thermodynamically analyze the evacuated tube solar water heater (ETSWH) at two different mass concentrations. Consequently, the temperature rises by 6.4 °C when mass % 0.4 % TiO2 in engine oil is merged into a porous substance. The rise in temperature results in an additional 41% increase in thermal effectiveness. Furthermore, there are increases in thermal effectiveness of 5.4% and 19% when a porous medium is used, and when 0.4 mass% TiO2/oil is applied concurrently to a porous medium. The study conducted by Lotfi et al. [96] centered on examining ways to improve the energy and performance of ETSWH installed in the warm weather of Dezful, Iran. Using TiO_2 nanoparticles added in two volume fractions, the investigation particularly assesses the effects of engine oil used as a circulatory fluid inside copper U-tubes placed into evacuated tubes. As a consequence, adding metallic insertion raises the water's temperature by 1.5 °C. Furthermore, a variations of 5.6 °C was noted in the evening hours among the 0.4% volume fraction TiO_2 + insertion and the base case, leading to increased thermal performance and exergy efficiency by 24.52% and 24.4%, correspondingly.

Nishit and Bekal [97] used Al_2O_3 nanofluid to enhance the performance of polymer SWH experimentally. The results of the research showed that compared to polymer SWH using water to serve as the absorption fluid, the inclusion of Al_2O_3 in polymer SWH increased thermal efficiency approximately 27.7%.At two separate flow rate of mass (0.008 kg/s and 0.012 kg/s), as well as mass fractions of 0.4% and 0.2%, Nayak et al. [98] both theoretically and experimentally analyzed an FPC-SWH employing TiO_2 – H_2O nanofluids. The findings show that the energy effectiveness of SWH rises by 3.58% for H_2O when the flow rate is increased. Additionally, for TiO_2 nanofluids with 0.4% and 0.2% mass fraction, correspondingly, the SWH efficiency is increased by 11.64% and 16.48%. Rashmi et al. [99] used ZrO_2/H_2O nanofluid to analyze the performance of SWH at constant mass flow rate. With a mass flow rate of 0.0185 kg/sec, nanofluid was shown to boost the efficiency of SWH by 20.68%. Arun et al. [100] experimentally and also used CFD technique to analyzed DTPTSWH using different nanofluid whose size varied from 10 nm to 15 nm at different volume fraction varied from 0.1% to 0.5%. Best efficiency is obtained for CuO nanofluid which is 38.4%.

Solar Photovoltaic Thermal (PV/T) System

A technology which converts solar energy into both electrical and thermal energy is known as Photovoltaic Thermal (PV/T) system. The energy efficiency of the system is enhanced b PV/T system since it directly transforms solar energy into electrical energy and also captures the remaining energy in the form of heat energy [101]. It is possible due to combination of PV panels and solar collector.

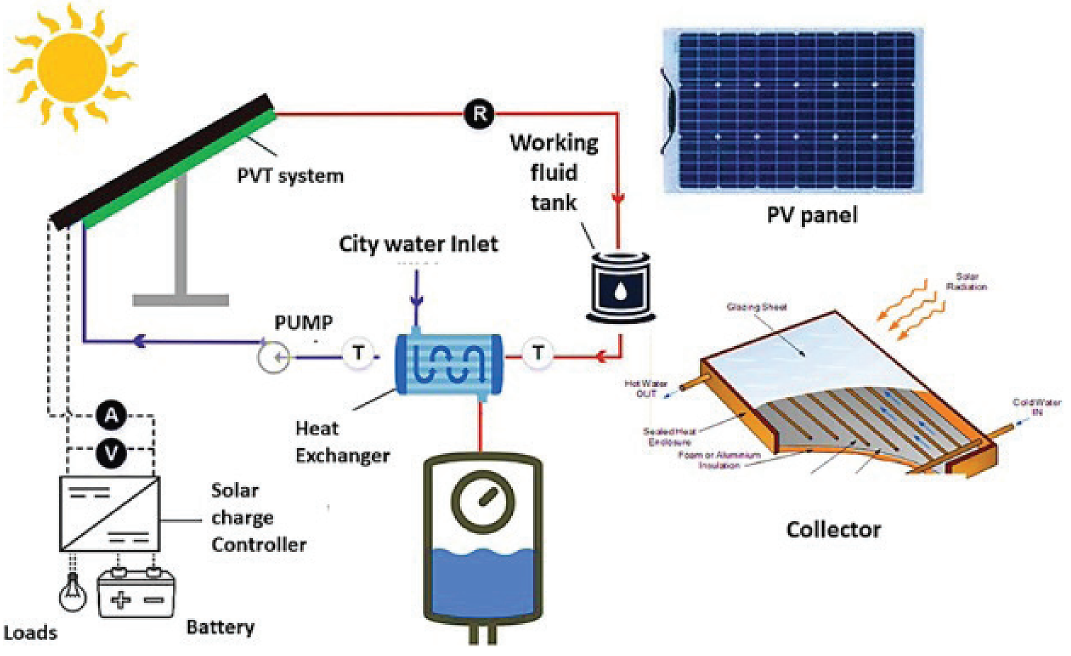

Figure 16. Block diagram of solar photovoltaic thermal system [From Mostakim and Hasanuzzaman [103], with permission from Elsevier].

The energy loss is reduced because of its dual combination and get maximum from solar radiation. Thermal energy is utilized in many appliances such as water heater, air heater etc. The PV/T system is very usefully in industrial application where both thermal and electrical energy is required. PV/T system enhances the energy production per unit area and also it is sustainable resource of renewable energy [102]. A typical block diagram of solar photovoltaic thermal system is shown in Fig. 16 [103].

A Solar Photovoltaic Thermal (PV/T) system works by putting together photovoltaic (PV) panels and a thermal collector. The PV panels make energy and the thermal collector collects heat from the sun. The photovoltaic effect turns sunshine into power, and the panels also soak up extra heat, which can make them less efficient. To stop this from happening, the system uses a cooling medium, like water or air that flows via a heat exchanger that is built into the PV panels. This process takes out the additional heat, which can then be used to heat things like water or air. The PV/T system does this by making the PV panels work better electrically and giving off usable thermal energy. This maximizes the amount of energy that can be generated from the same solar resource. The detailed classification of solar PV/T system is shown in Fig. 17 and the recent research performed on solar PV/T system using nanofluid is summarized in table 5.

Salari et al. [104] used three different nanofluids with varying mass fraction mentioned in table 5 to evaluate PV/T

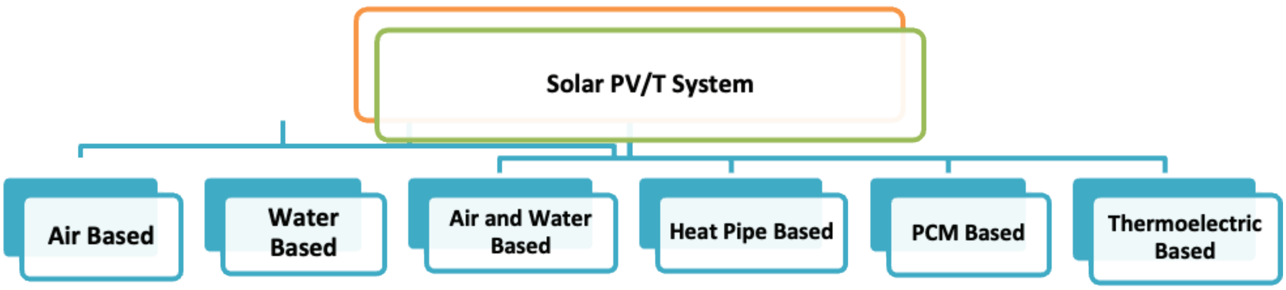

Figure 17. Classification of solar PV/T system.

Table 5. Recent research performed on solar PV/T system using nanofluid

Ref. No.	Nanofluid	Volume fraction	Remark
[104], 2020	MgO, MWCNT, MgO-MWCNT	3% to 6%	Maximum thermal efficiency 61.07% for MWCNT at 6% volume fraction
[105], 2021	CuO-MgO-TiO_2	0.01%	58.38% thermal efficiency of PV/T is obtained
[106], 2022	TiO_2	0.2%	PVS cells currently have an efficiency that is 2.11% more than PV-ground cells
[107], 2020	Ti_3C_2/silicone oil	0.05% to 0.1%	At 0.1 weight percent, the maximum TC augmentation is shown to be 64%
[108], 2024	Non-toxic GNP/water	0.025% and 0.1%	Maximum thermal efficiency is 55.22%, electrical efficiency is 14.05%.
[109], 2023	Sic and Nano-PCM	0.3% and 0.6%	84.74% thermal efficiency and 9.61% photovoltaic efficiency
[110], 2023	TiO_2 and TiO_2-Fe_2O_3	0.2% and 0.3%	47.2% thermal efficiency at hybrid nanofluid at 0.3% volume fraction
[111], 2024	MgO/H_2O and Cu_2SnS_3	-	5.7% greater efficiency is achieved overall with the addition of a reflection.
[112], 2023	CuO/H_2O and CNT/H_2O	0.5% to 2%	Maximum 29.82% increase in thermal efficiency for BVPTM using CNT/H_2O nanofluid
[113], 2023	PCM and micro fin tube	1% paraffin and 0.6% SiC for nanofluid	Maximum 77.5% enhancement in thermal efficiency using micro fin tube nanofluid with 0.6% SiC
[115], 2023	ZnO/ H_2O	0.25%	Highest thermal efficiency of 33.4%
[116], 2023	ND-Co_3O_4/ H_2O	0.05% to 0.15%	Maximum 15.44% enhancement in thermal efficiency
[117], 2023	Ag, CNT, and CNT/Ag	-	9.9% increment in thermal efficiency using hybrid CNT/Ag nanofluid

system numerically as well as experimentally. MgO nanofluid has the least total energy efficiency (55.24%), while MWCNT has the best overall efficiency of energy (61.07%). The system's overall heat capacity is increased when the layer of PCM thickness is increased from 0.5 cm to 1.5 cm, lowering the outside and outflow temperatures. Adun et al. [105] used CuO-MgO-TiO_2 nanofluid in solar PV/T system to evaluate its performance numerically and experimentally. An enhanced electrical efficiency of 13.54% was demonstrated by the outcome. At an ideal fraction of volume of 0.01, additional results included thermal efficiency of 58.38%. The investigation also finds that the introduction of tripartite nanofluid increased the PV/T technique's overall efficiency to an optimum of 11.14%. Arifin et al. [106] used TiO_2 nanofluid PV/T system to evaluate its performance. The fluid's ability to facilitate the exchange of heat provides an explanation for this. PVS cells currently have an efficiency that is 2.11% more than PV-ground cells. The mean PV temperature produced by TiO_2-based PV/T systems is 58.5 °C, which results in a PV efficiency of 13.04%. Aslfattahi et al. [107] used Mxene (Ti_3C_2)/silicone oil nanofluid of varying concentration to enhance the performance of concentrated solar PV/T system. When Ti3C2/silicone oil nanofluid is concentrated to 0.1 weight percent, the maximum TC augmentation is shown to be 64% at 150°C when contrasted with plain silicone oil. The concentration of 0.1 weight percent Ti3C2/silicone oil yields the maximum electrical efficiency of concentrated PV/T across all concentration ratios. At a larger concentration ratio, electrical efficiency is, nevertheless, modest.

Sheikholeslami et al. [108] used non-toxic GNP/water nanofluid to enhance the performance solar PV/T system at two distinct weight fractions in the optimal scenario, there is an improvement in velocity at the inlet, leading to a 5.8% boost in the entire system's electrical efficiency. The best scenario results in an optimal exergy efficiency of 15.32%, an electrical efficiency of 14.05%, and a thermal efficiency of 55.22% when employing GNP nanoplatelets at Reynolds number = 1611 and weight fraction of 0.1%. Al-Aasam et al. [109] assessed the thermal endurance of a PVT collector using Nano-PCM and a twisting absorber tube using Sic nanofluid at two different volume fractions. Thermal efficiency and photovoltaic efficiency for the T-PVT-PCM-SiC-0.6% arrangement were 84.74% and 9.61%, correspondingly. Alktranee et al. [110] use mono TiO_2 nanofluid and an innovative hybrid TiO_2-Fe_2O_3 nanofluid to study the energy efficiency and exergy efficiency of a PV/T technology at different volume proportions. Thermal efficiency is observed 47.2% using hybrid nanofluid at 0.3% of volume fraction. The various efficiency of solar PV/T system is shown in Fig. 18.

Sheikholeslami [111] concentrated on developing a novel PV/T module design that made advantage of a cylindrical reflector. Effectiveness is improved by combining a nanofluid optical filter made of a combination of MgO/H_2O with a TEG sheet made of Cu_2SnS_3 (CTS) inside PV/T. The addition of a filter tube, fins, and a cylindrical reflector improves the effectiveness by 36.3%. An estimated 5.7% and 4.7% aggregate effectiveness gain is achieved when using and not using a nanofluid filtration when a reflector is added to the coated design. Ahmadinejad and

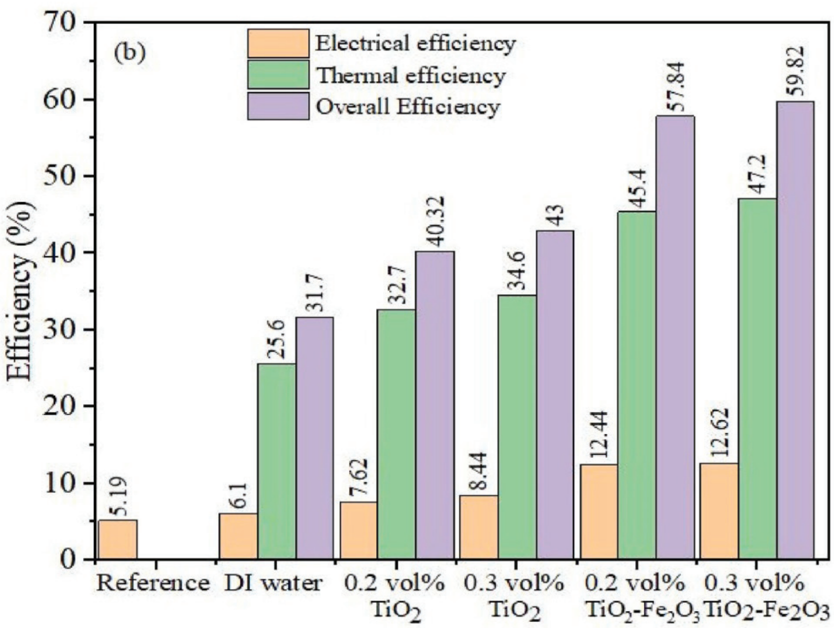

Figure 18. Various efficiency of solar PVT system for different nanofluid at varying volume fraction [From Alktranee et al. [110], with permission from Elsevier].

Moosaviwere [112] used three fluids H_2O, CuO/ H_2O, and CNT/ H_2O nanofluid to study the PV/T system's performance. When compared to the BPVTM using water, the total energy effectiveness enhances by 0.44% and 2.38% using CuO/ H_2O and CNT/ H_2O, correspondingly. Bassam et al. [113] experimentally analyzed PVT system using nano enhanced PCM and micro fins tube as nanofluid. When micro fin nanofluid was employed, the system's maximum thermal efficiency was 77.5%.

Gu et al. [114] modeled and analyzed an innovative bifacial PVT technology using multi-physics. Excellent insulating material and excellent transmissivity combine to provide an outstanding energy efficiency rating of 85.74%.Poor-quality production of heat accounts for the 12.26% total exergy efficiency. It is expected that when the transmission coefficients of the glass and nanofluid both approached 1, the power generated by the bPV/T technology will be greater compared to that of simple bPV. Shen et al. [115] looked at the nanofluid's impact on the PV/T through experimentation. The experimentation was performed using ZnO nanofluid at different mass flow rate varied from 0.008 kg/s to 0.012 kg/s and concentration 0.25%. Considering a hydrogen generation rate of 17.4 milliliters per minute, the highest thermal efficiency of 33.4% was recorded at 0.012 kg/s across the various mass flow rates. Khalili and Sheikholeslami [116] have presented a unique approach for chilling the PV unit employing ND-Co_3O_4 hybrid nanofluid at different mass concentrations ranging from 0.05% to 0.15%. With the mass fraction of 0.05%, the most effective system achieved electrical and thermal efficiencies of around 84% and 15.44%. Xia et al. [117] evaluated the solar spectrum properties of PV/T systems utilizing Ag, CNT, and CNT/Ag nanofluids at varying concentrations. The CNT/Ag nanofluid-based system's electrical and thermal efficiency rose by 15% and 9.9%, correspondingly.

Solar Stills (Evaporator)

A solar still, also known as a solar evaporator, is a device that harnesses solar energy to purify water through the process of evaporation and condensation. It typically consists of a transparent cover and a basin that holds the contaminated water. A simple solar still is shown in Fig. 19. The cover lets sunshine through, which warms the water in the basin and makes it evaporate. The water vapor then turns back into water on the cooler surface of the cover, which slopes into a collection channel where the clean water is stored. Solar stills are great for places with a lot of sun and not a lot of clean water because they are cheap and long-lasting ways to desalinate and clean water [118-119].

A solar still works by copying the natural water cycle. It uses solar energy to clean water by evaporating and then condensing it. The process starts when sunlight goes through the still's clear cover and warms up the dirty or salty water in a basin below. When the water gets hot, it evaporates, leaving behind dirt, salts, and other things that shouldn't be there. The water vapor rises and then collects

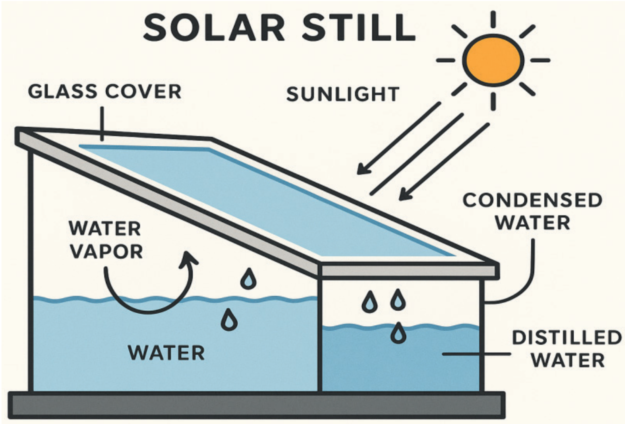

Figure 19. Schematic diagram of solar still.

on the colder, sloped inside of the lid. The cleansed water that has condensed runs down the sloped cover and is collected in a separate channel or reservoir [120]. This simple but effective approach makes it possible to make clean drinking water using only sunshine. This is especially useful in dry areas or places that are hard to get to that don't have easy access to fresh water. The detailed classification of solar still is shown in Fig. 20 and the summary of recent research on solar sill using nanofluid for solar energy harnessing is summarized in table 6.

A solar still works by copying the natural water cycle. It uses solar energy to clean water by evaporating and then condensing it. When the water gets hot, it evaporates, leaving behind dirt, salts, and other things that shouldn't be there. The water vapor rises and then cools down on the inside of the cover, which is usually sloping. The cleansed water that has condensed runs down the sloped cover and is collected in a different channel or reservoir [121]. This process is very simple and also effective to use drinking water in sunshine only. This is especially useful in dry locations or places that are hard to get to and don't have easy access to fresh water [122]. The detailed classification of solar still is shown in Fig. 18 and the summary of recent research on solar sill using nanofluid for solar energy harnessing is summarized in table 6.

Kumar et al. [123] conduct a laboratory study into the effectiveness of a solar still having single slope utilizing hybrid nanofluids and an outside parabolic reflector. The findings showed that using hybrid NFs and an outside parabolic reflector boosts the rate of production. Without utilizing nanofluid, the mean total distillate production was 1005 mL/day; however, productivity climbed to 1432.5 mL/day after employing nanofluids, indicating a 29.84 % additional rise in performance for the whole summer period. The effectiveness of a SSPSS using ordinary H_2O and Al_2O_3/ H_2O nanofluid was compared by Azam and Akhtar [124]. According to the findings, adding Al_2O_3/ H_2O nanofluid to the solar still increases the water distillation yield by

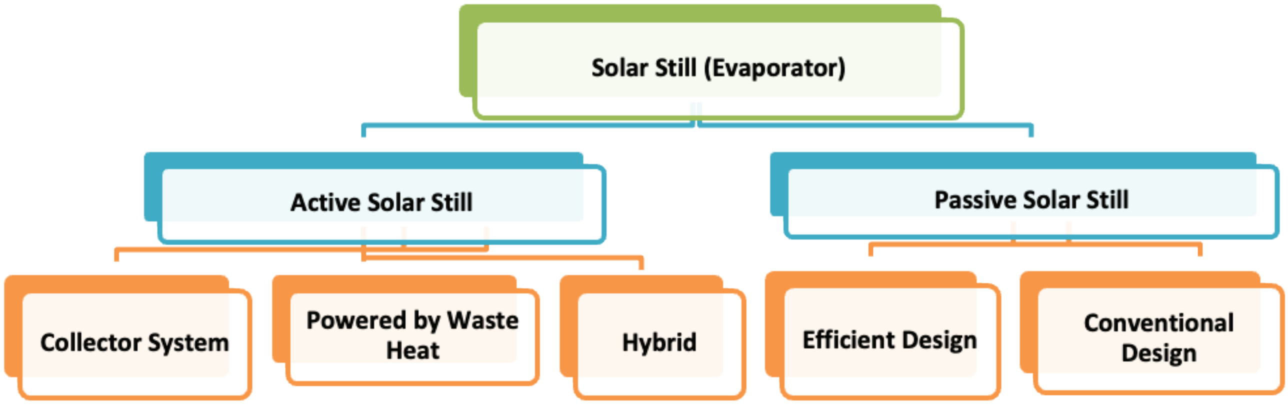

Figure 20. Classification of Solar Still (Evaporator).

Table 6. Summary of recent research performed on solar still system using nanofluid

Ref. No.	Nanofluid	Type	Remark
[123], 2024	hybrid	Single slope	29.84 % additional rise in performance for the whole summer period
[124], 2024	Al_2O_3/ H_2O	Single slope	Solar still increases the water distillation yield by 24.11%
[125], 2024	ZnO, SiO_2 and ZnO - SiO_2	Single slope	Maximum efficiency is achieved using ZnO nanofluid which is 29.5%
[126], 2023	TiO_2/Jackfruit peel nanofluids	Double-effect solar distiller	JPTN-equipped DESS has 41% energy efficiency.
[127], 2020	Ag	SODIS	Maximum enhancement in exergy efficiency is achieved 196% using nanofluid in Tehran
[128], 2021	Al_2O_3- CuO	Conventional solar still	The average energy efficiency increases with hybrid nano by 13.4% in the winter and 12.6% in the summer.
[129], 2021	Al_2O_3-SiO_2/H_2O	Conventional solar still	Hybrid nanofluid resulted in 37.76% thermal efficiency.
[130], 2022	Al_2O_3- TiO_2	Double slope	The solar desalination process improved the environmental characteristics by 12.45%.
[131], 2023	Fe_3O_4+ NbO_2 + paraffin	Stepped solar still	The rate of production is increased by 98% when hybrid NPCM is used in a magnetic environment.
[132], 2023	CuO + Al_2O_3 + ZnO	SBGIDSS	Maximum energy efficiency is enhanced by 78.6%.
[133], 2023	Al_2O_3, MgO, GO	Single slope	38.52% enhancement in production of water distillation using 1% wt of MgO
[134], 2024	ZnO/H_2O and ZnO-WO_3/H_2O	Active solar still	The highest thermal efficiency was 39.9% for mono ZnO nanofluid.

24.11%, with a concentration of 0.15% being the most effective. Additionally, the investigation notes that evaporation heat transmission is more strongly facilitated by Al_2O_3 nanofluids than convection transfer of heat. Sahu and Tiwari [125] utilized three different nanofluids ZnO, SiO_2 and ZnO - SiO_2 to evaluate the performance of solar still having single slope at different depth of water. Maximum efficiency is achieved using ZnO nanofluid which is 29.5%. By using nanofluids, you may increase the rate of heat distribution, reduce the amount of time you need to warm up the water prior using it, and keep the difference in temperature within the container higher for maximal condensing rate. Kumar et al. [126] used different JPTN at different concentrations ranging from 5% to 30% alongside silver color balls to illustrate the DESD's effectiveness. DESS with JPTN has an energy efficiency and exergy efficiency of 41% and 5.63%, respectively. The variation of thermal efficiency with time at different concentration of JPTN is shown in Fig. 21. From Fig. 21, it was observed that the highest thermal efficiency is obtained at 20% JPTN at water depth of 0.8 cm.

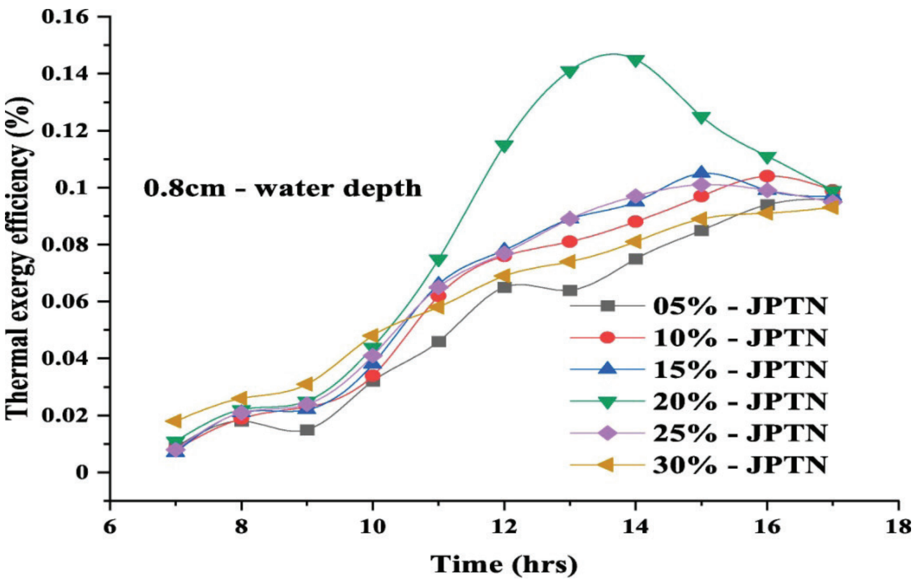

Figure 21. Variation of thermal efficiency with time at different concentration of JPTN [From Kumar et al. [126], with permission from Elsevier].

Parsa et al. [127] used Ag nanofluid to evaluate the performance of solar still at 0.04 wt%. Fig. 22 shows the SEM picture of the Ag nanofluid used in this work. This allows for interface consistency and uniformity to be confirmed, indicating a suitable distribution of nanomaterials in the base fluid. Maximum enhancement in exergy efficiency is achieved 196% using nanofluid in Tehran. From an energetic perspective, solar stills situated at high altitudes achieve the highest exergy efficiency

El-Gazar et al. [128] demonstrated the thermal characteristics of a standard solar still and illustrate the impact of utilizing a hybrid Al_2O_3- CuO nanofluid with fixed concentration of 0.025% on the purification system. According to the findings, the use of hybrid nanofluid increases still daily production by 27.2% and 21.7% in comparison to still with no nanoparticles, reaching 5.5239 kg/m^2·day in the hottest months and 3.1079 kg/m^2·day in the colder months.

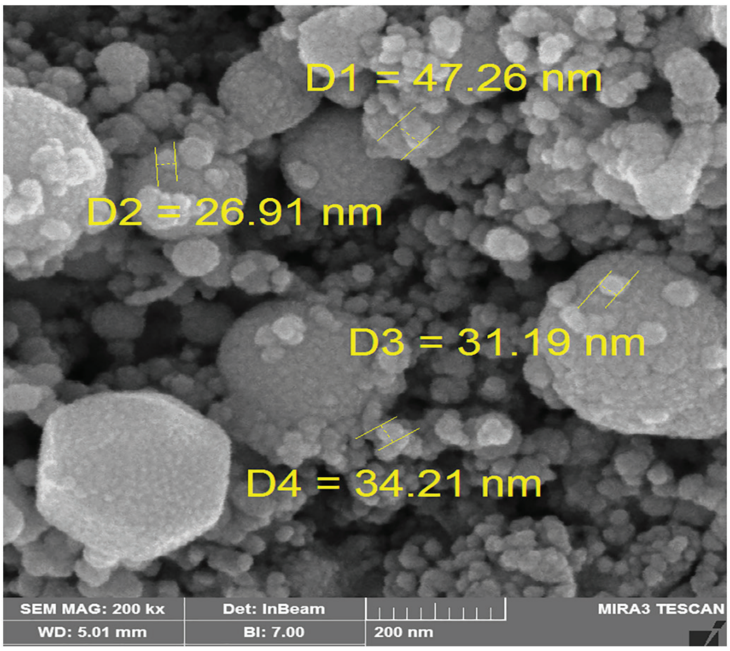

Figure 22. SEM image of Ag nanofluid at 0.4 wt% [From Parsa et al. [127], with permission from Elsevier].

Using Al_2O_3- CuO nanofluid increases the average energy efficiency by 13.4% in the colder months and by 22.5% in the heat of the summer. Rabbi and Sahin [129] used Al_2O_3-SiO_2/H_2O hybrid nanofluid to enhance the performance of solar still. The utilization of hybrid nanofluids yields the greatest results. When hot water was used in the heat exchanger, the effectiveness of the solar still was enhanced. Hybrid nanofluid resulted in 37.76% thermal efficiency. Shoeibi et al. [130] used Al_2O_3- TiO_2 hybrid nanofluid at fixed concentration of 0.4% to evaluate the performance of glass cooled double slope solar still using CFD analysis. According to the computational findings, the application of hybrid nanofluid optical cooling in sun desalination boosted the clean water productivity and energy efficiency by 11.09% and 28.21%, correspondingly, as compared to conventional solar desalination without hybrid nanofluid.

Toosi et al. [131] established and built an innovative stepped solar still incorporating hybrid NPCM underneath steady magnetism. The PCM's thermal conductivity enhanced with the addition of hybrid nanomaterials. Utilizing hybrid NPCM in a magnetic environment increases the stepped solar still's capacity for manufacturing by 98%. A steady magnetic attraction reduced the hybrid NPCM's thermal resistance. Three hours after nightfall, the distillation procedure is carried out utilizing NPCM. Naveenkumar et al. [132] used three different nanofluid mentioned in table 6 having volume concentration of 0.1% to improve the performance SBGIDSS using a vacuum fan operated by solar system. Maximum energy efficiency is enhanced by 78.6% by using vacuum fan and outside condenser. The increase in the rate at which water evaporation occurs in the solar still reservoir results in a 64.29% increase in production rate. Kajal et al. [133] performed comparative analysis using different nanofluid mentioned in table 6 to investigate the performance of solar still. When 1.0% wt MgO nanofluid is used, the highest increase in the amount produced of water from distillation above that obtained with water is around 48.91%. Almohammadi et al. [134] utilized hybrid nanofluid mentioned in table 6 to investigate the performance and productivity of solar still at a volume fraction of 0.035%. Maximum thermal efficiency was 39.9% for ZnO nanofluid. ZnO/H_2O nanofluid is produced 3.14 kg of water per day at 0.035% volume fraction.

APPLICATION OF UTILIZATION OF NANOFLUID IN SOLAR ENERGY HARNESSING

The ultimate objective of this research is to produce maximum energy from solar energy system using nanofluid with highest efficiency and effectiveness. Nanofluid is the mixture of nanoparticles in the base fluid. Their thermal, optimal and chemical properties of much better than basic heat transfer fluid due to which they absorb solar energy much effectively. The performance of solar thermal system is enhanced due to its enhanced thermophysical and optical properties. These fluids are also very useful in PV/T system for cooling of the system which can enhance the system performance and also boost the electrical efficiency. This review article mainly focused on utilization of nanofluid to harness solar energy to make solar system much better and sustainable solution of energy crisis.

Enhanced Thermal Conductivity

Enhanced thermal conductivity of nanofluid makes solar system more effective and prominent solution for renewable energy. The appliances like solar collector, heat exchanger perform much better with enhanced thermal conductivity.

Improved Solar Collector Efficiency

In solar thermal collector, sun light is absorbed and it is converted into thermal energy. Enhanced optical properties of nanofluid maximize the amount of absorbed solar radiation in solar collectors. These are the reasons behind the enhanced performance of all type of solar collectors.

Enhanced Photovoltaic Thermal System

PV/T system used nanofluid to cool the system properly and maximize the system performance. Nanofluids assist keep solar panels at the right operating temperatures by quickly getting rid of heat. This makes them work better and last longer.

Advanced Solar Thermal Energy Storage

Nanofluids can also be used in systems that store thermal energy. In these systems, they can make the materials that store the energy have a higher specific heat capacity and thermal conductivity. This change makes it easier to store and get back thermal energy, which makes solar power plants work better, especially when there isn't any sun.

Potential in Solar Desalination

Nanofluids make solar desalination more efficient by enhancing the transfer of heat between the evaporation and condensation stages. This saves money and energy, especially in places where there isn't much freshwater available.

ENVIRONMENTAL AND ECONOMIC IMPACT OF NANOFLUID IN SOLAR ENERGY HARNESSING

Nanofluids improve the collection of solar energy, which is good for the environment and the economy, but they also come with some problems. Due to enhanced thermal efficiency of solar collector, nanofluid enhanced the conversion of energy, minimising the dominance on fossils fuel and also diminishing the emission of green house gases [135]. The ability to conserve water in CSP makes them more environments friendly while production of nanoparticle for enhancement of energy production can be harmful for environment if it is not handled properly. By improving energy efficiency and lowering operating costs, nanofluids make it possible for solar systems to be more compact and resource-efficient, which can lower the original capital investment [136]. The high production cost and problem

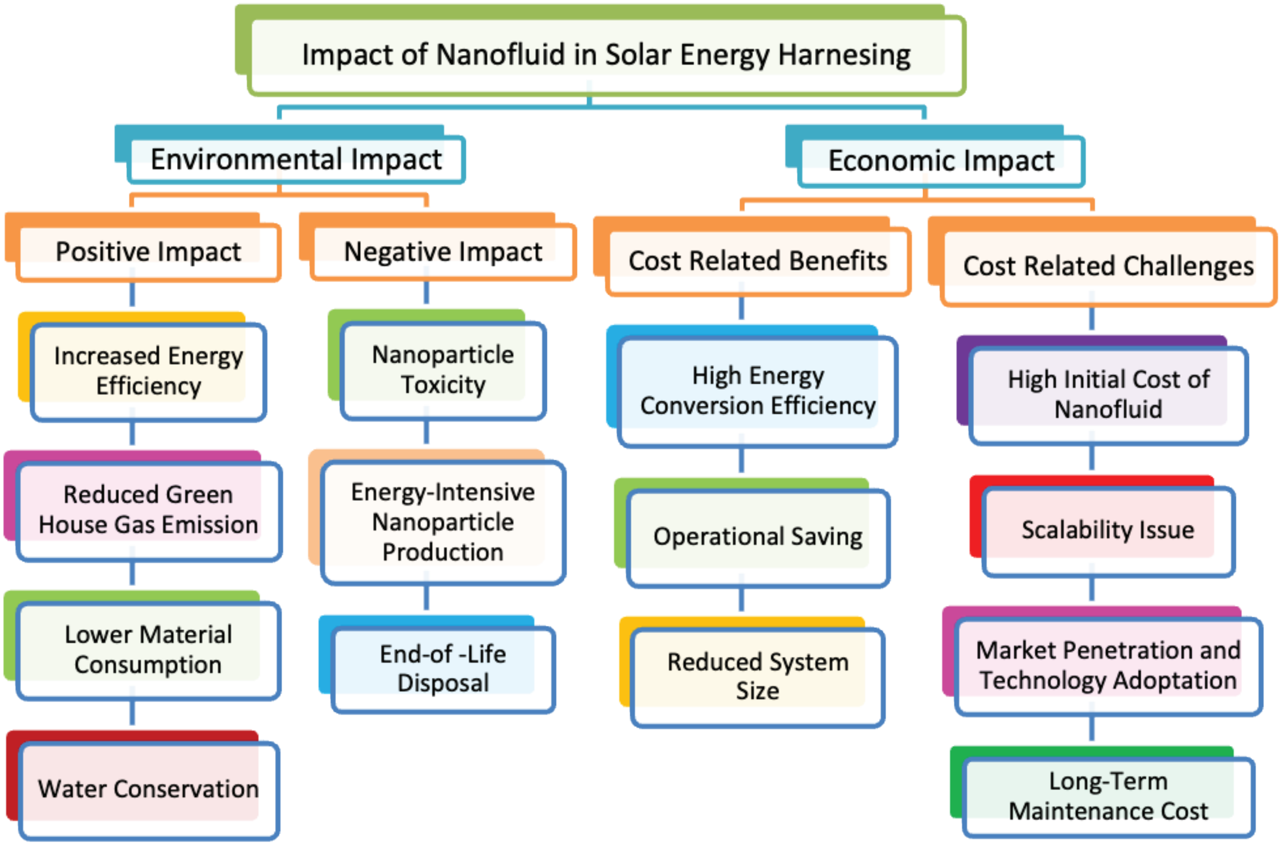

Figure 23. Environmental and Economic Impact of Nanofluid in Solar Energy Harnessing.

of scaling of nanoparticle create problem in its wide utilization. Nanofluids are unstable over period of time therefore its long term maintenance is also very expensive. New kind of research is required to make nanofluid utilization viable in academic and industry for long term utilization. Fig. 23 depicted the environmental and economic impact of nanofluid utilization in solar energy harnessing systems.

Environmental Impact

Solar thermal system performance is enhanced due to better thermal conducting capacity of nanofluid. Therefore the performance of solar system is enhanced and dependency on fossils fuel is minimized [137]. Nanofluids can help reduce greenhouse gas (GHG) emissions over time by making solar energy more efficient. Improved solar thermal technology could help the world move away from coal, natural gas, and oil, which would lower carbon footprints. Because nanofluids transport heat better, solar collectors might be able to do the same job with fewer or smaller components. This would mean that fewer building materials, including glass, metal, and plastic, would be needed. This cuts down on resource exploitation and lessens the overall impact on the environment [138]. Nanofluids can help make concentrated solar power (CSP) systems more efficient at transferring heat, which means they need less water to cool down. This is a big deal in places where water is scarce [139].

The effects of Al_2O_3-MWCNT/H_2O hybrid nanofluids on how well energy is used and how well the environment works Nanofluids offer better thermal qualities, like increased thermal conductivity, which can make solar thermal systems work better. This means that solar energy can be captured and used more effectively, which could mean less dependency on fossil fuels [137]. Nanofluids can help reduce greenhouse gas (GHG) emissions over time by making solar energy more efficient. Improved solar thermal technology could help the world move away from coal, natural gas, and oil, which would lower carbon footprints. Because nanofluids transport heat better, solar collectors might be able to do the same job with fewer or smaller components. This would mean that fewer building materials, including glass, metal, and plastic, would be needed. This lessens the overall environmental impact and the amount of resources that need to be extracted [138]. Nanofluids can help improve the thermal efficiency of concentrated solar power (CSP) systems, which means they use less water for cooling. This is a big deal in places where water is hard to come by [139].

How Al_2O_3-MWCNT/H_2O hybrid nanofluids affect energy efficiency and the environment was examined by Mahhadian et al. [140] in a DAPTC at different volume fractions. By employing hybrid nanofluid, the thermal performance of DAPTC has been improved by 197.1%, 69.2%, and 6.1% in comparison to water, Al_2O_3, and MWCNT nanofluids of 0.4% concentration. In order to examine the financial and environmental effects of ZnO/H_2O, Al_2O_3/H_2O, and TiO_2/H_2O nanofluids at 0.2% volume fraction on the PV/T system, Abadeh et al. [141] conducted experimental research on these materials. In comparison to a PV system, it has been demonstrated that the nanofluid-based PV/T system reduced environmental emissions by 17%.A thorough investigation of the 4E was conducted by Said et al. [142] employing Ti_3C_2 nanoparticles in a PTC at different volume fractions (0.05% to 0.1%). Using Ti_3C_2 nanofluid, it was shown that 2.25 to 2.3 tons of CO_2 were mitigated annually.

Economic Impact

Nanofluids can make solar thermal systems (such flat-plate or parabolic trough collectors) work much better, which could cut the levelized cost of energy (LCOE). This makes investing in solar energy more cost-competitive with other types of electricity [143]. Nanofluids can lower the expenses of running solar power plants by making heat transfer more efficient. For example, they might let systems work with less fluid or at lower temperatures, which would save energy and make equipment last longer [144]. More efficient heat transfer means that you may utilize smaller solar collectors to make the same amount of energy. This can lower the upfront costs of land, infrastructure, and materials, which makes solar projects cheaper [145]. It's evident that nanofluids work better, but making nanoparticles and mixing them into fluids is still rather expensive. This could make people less likely to use it, especially in marketplaces where pricing is important. It is very difficult to produce nanofluid on mass level for industrial utilization since it requires huge amount of energy, nanoparticles are rare and also very expensive [146]. Nanofluid offers many advantages but still not utilized in mass level because the process of making nanofluid is very difficult, testing and characterization of nanomaterials are not easily available. A lot of funds are required to make nanofluid research available at commercial level [147-148]. The summary of economic impact of nanofluid in solar energy harnessing is presented in table 7.

Lari and Sahin [145] looked into the economics of a silver nanofluid with volume fraction of 0.5% in PV/T system. The recommended approach was shown to have reduced home electricity prices by 82%, and the initial expenditure paid for itself in just over two years. Lari and Sahin [149] conducted additional research on the impact of retrofitted on Ag/H_2O nanofluid in PV/T systems using PCM-thermal batteries. The predicted price repayment time frame for the recovery of investments was 5.5 years, resulting in a 58.71% decrease in energy produced costs when weighed against the cost of household power. Additionally, the release of 10,195.91 tons of CO_2 into the environment per year must be stopped. Stalin et al. [150] focused on 3E research of a FPSC using CeO_2/H_2O nanofluid with varying concentration of (0.01% to 0.1%). At 0.05% concentration, the collector efficiency is enhanced by 28.07% and energy augmentation of 5.8% was attained. The use of CeO_2/H_2O in FPSC resulted in a longer payback period of 2.12 years, and reduced CO_2 emissions to the environment by 175 kg. The 3E and financial advantages of a redesigned ETSWH with CuO nanomaterials having concentration of 0.5% were investigated by Saxena and Gaur [146]. In comparison to the standard design, the ETSWH required a larger initial expenditure, a longer payback period, and a longer time. Additional power is saved, maintenance expenses are decreased, and the transmission of heat is improved with the updated ETSWH. The impacts of $GAMWCNT/H_2O$ nanofluid at different concentrations (0.025 wt% to 0.1 wt %) on the economic and environmental implications of FPSC were studied by Amar et al. [151]. According to experimental results, at a weight concentration of 0.1%, the maximum enhancement in efficiency of energy is 30.88%. It emerged that using GAMWCNT nanofluid instead of H_2O as base fluid reduced the dimensions of FPSC and saved 321.72 MJ of intrinsic energy. When GAMWCNT nanofluids were used at 0.1 weight percent in FPSC, the time to pay back became 1.897 years, that's 6.228% less than when H_2O was used as the heat transmission fluid.

Table 7. Summary of Economic Impact of nanofluid in Solar Energy Harnessing

Ref. No.	Nanofluid	System	Remark
[86], 2023	MgO-$MWCNT/H_2O$	ETSC	There is a drop of 36.2% and 34.6%, correspondingly, in the Carbon Repayment Period and Conventional Payback Time.
[145], 2017	Ag/H_2O	PV/T	82% reduction in house electricity prices.
[146], 2020	CuO	ETSWH	Due to enhanced ETSWH, energy is conserved, reduces the maintenance cost and heat transmission is enhanced
[149], 2018	Ag/H_2O	PV/T	The predicted price repayment time frame for the recovery of investments was 5.5 years.
[150], 2020	CeO_2/H_2O	FPSC	Resulted in a longer payback period of 2.12 years, and reduced CO_2 emissions to the environment by 175 kg.
[151], 2023	GAMWCNT	FPSC	When GAMWCNT nanofluids were used at 0.1 weight percent in FPSC, the time to pay back became 1.897 years, that's 6.228% less than when H_2O was used

KEY STRATEGIES FOR OPTIMIZATION OF NANOFLUID PROPERTIES IN SOLAR ENERGY HARNESSING

Optimizing nanofluid properties for solar energy harnessing involves adjusting several parameters to enhance the overall efficiency of solar thermal systems. Nanofluids, which are engineered by dispersing nanoparticles into conventional base fluids like water, ethylene glycol, or oil, improve thermal conductivity, heat transfer rates, and optical absorption, which are critical for solar energy applications like solar collectors and photovoltaic thermal systems. The key strategies for optimizing nanofluid properties for solar energy harnessing are represented in Fig. 24.

Choice of Nanoparticles

Use nanoparticles with high thermal conductivity such as copper (Cu), silver (Ag), carbon nanotubes (CNT), and aluminum oxide (Al_2O_3) to enhance heat transfer. Select nanoparticles with excellent solar absorption characteristics like graphene, carbon black, or titanium dioxide (TiO_2). This makes it easier for solar radiation to be absorbed and cuts down on reflection losses. To get more surface area and less chance of particles sticking together, change the size and shape of the particles (usually between 10 and 100 nm). Smaller particles have a larger surface-to-volume ratio, which makes them more stable and helps heat transfer. Spherical nanoparticles are usually more stable, but rod- or plate-like forms may make optical characteristics better.

Nanoparticles Concentration

Too many nanoparticles can make solar collectors less efficient by making them thicker and harder to pump. Usually, concentrations of 0.1% to 5% by volume strike a good balance between improving heat conductivity and keeping viscosity levels reasonable. Make sure that the particles are properly dispersed so that they don't clump together. This can lower the thermal performance and dirty up solar thermal equipment.

Base Fluid Selection

The thermal conductivity, specific heat, and density of the base fluid are very important. Water is the most frequent base fluid since it has great thermophysical qualities. However, for some conditions, such high-temperature settings, mixes like ethylene glycol-water or oil-based fluids can also be used. The base fluid should stay stable over a wide variety of temperatures so that it works the same way in different amounts of solar energy.

Figure 24. Key Strategies for Optimization of Nanofluid Properties in Solar Energy Harnessing.

Surfactants and Stabilizers

The clogging problem of nanofluid is improved by adding surfactant because it make nanoparticle to spread out throughout the base fluid. Addition of surfactant makes nanofluid stable over certain period of time and hence improves its characteristics and ultimately the performance of solar system is enhanced.

pH Optimization

The stability of nanofluid is measured by optimizing the Ph of nanofluid. A tinny amount of electroststic repulsion between nanoparticles makes them more stable over certain time period due to which heat transfer of nanofluid is enhanced.

Viscosity Optimization

Viscosity plays a major role in enhancement of thermal conductivity of nanofluid. Proper volume concentration of nanofluid enhances its thermal conductivity and improves the heat transfer rate and ultimately improves the solar system

Thermal Stability and Operating Temperature Range

Heat transfer in solar thermal system is enhanced due to their enhanced thermal conductivity of nanofluid. Nanofluids express excellent thermal conductivity at high temperature operations ranging from 50°C to 400°C. This temperature range depends on the various factors such as volume fraction, type of base fluid, type of solar system and many more.

Hybrid Nanofluids for Synergy

When you mix different kinds of nanoparticles, like metal with oxide or carbon-based with metallic, you can get synergistic effects. For example, adding copper to alumina or graphene can make both thermal conductivity and optical absorption better.

Advanced Characterization Techniques

Advanced characterization techniques are very useful to know the stability condition of nanofluid. Many characterization techniques are available now these days such as SEM, TEM, dynamic light scattering (DLS) and many more to make nanofluid applicable for wide range of industrial applications.

LONG-TERM STABILITY AND SCALABILITY OF NANOFLUID

Enhanced properties of nanofluid make it stable for long term and scalable. Proper dispersion of nanoparticles within base fluid and advanced stabilization technique improves the performance of nanofluid. Over time, instability can reduce heat transfer efficiency and increase system maintenance costs [152-153]. Scalability, on the other hand, addresses the challenges of producing large volumes of nanofluids cost-effectively while maintaining consistent

Table 8. Summary of Characterization Techniques to Enhance the Stability of Nanofluid in Solar Energy Harnessing

Ref. No.	Nanomaterials	System	Particle Size	Surfactant	Characterization Technique
[66], 2016	MgO/Water	FPSC	40 nm	Cetyl Trimethyl Ammonium Bromide	TEM
[67], 2017	Al_2O_3, TiO_2, SiO_2, Cuo, Graphene, MWCNT	FPSC	45 nm, 44 nm 10 nm,42 nm 20 nm, 7 nm	Triton 100X	TEM
[69], 2021	Al_2O_3, TiO_2	FPSC	25 nm	Triton-X100	SEM, TEM, XRD
[70], 2022	Al_2O_3, MWCNT	FPSC	30 nm, 10-40 nm	-	SEM, TEM, TGA
[72], 2024	SiC	FPSC	45-65 nm	-	XRD, TEM, FESEM
[73], 2020	MWCNT	PTC	8-15 nm	Arabic gum	Zeta Potential
[78], 2023	CuO	PTC	10 nm	-	-
[82], 2024	MWCNT	FPSC, PTC	50 nm	SDBS	Zeta Sizer
[84], 2020	Al_2O_3	PT-ETSC	40 nm	-	-
[88], 2023	MWCNT, Al_2O_3	ETSC	10-40 nm, <30 nm	-	TEM, XRD
[90], 2020	Chitosan, Al_2O_3	FPC-SWH	15 nm	Polyvinyl pyrrolidone (PVP–K30)	-
[92], 2021	CuO-PCM	FPC-SWH	-	-	FESEM
[110], 2023	TiO_2 and TiO_2-Fe_2O_3	PV/T	-	-	TEM, XRD
[126], 2023	TiO_2	Double-effect solar distiller	10 nm	-	-

quality. As production scales up, ensuring that the properties of the nanofluid—such as thermal conductivity, viscosity, and optical absorption—remain uniform becomes more difficult. Solutions include improving nanoparticle synthesis techniques and enhancing dispersion methods that are adaptable for industrial-scale operations [154-155]. Together, long-term stability and scalability are essential for making nanofluids a viable option in commercial solar energy systems and other high-performance heat transfer applications. The various characterization techniques to enhance the stability of nanofluid in solar energy harnessing are mentioned in table 8.

CONCLUSION

Using nanofluids to collect solar energy is a big step forward in the field of renewable energy. Solar systems such as solar collector, PV/T, solar still perform much better due to enhanced thermal characteristics of nanofluid. It is one of the best choices for solar energy conversion since it enhanced the heat transfer rate and ultimately enhanced the optical performance of the system. The major concern behind the utilization of nanofluid is its stability over long period of time, cost of production and environmental sustainability. If further research in this field improves these problems associates with nanofluid then definitely nanofluid will be a major player in the field of solar system to improve its performance and also this kind of research will be very helpful for future renewable system and diminish the dependency on fossils fuels.

The thermal management system of engine is also improved by utilization of nanofluid due to its enhanced properties. This result in better engine performance and emission of fuel is lowered. But nanofluids have a higher viscosity, especially when there are more nanoparticles in them, which mean they may need more energy to move around, which could cancel out any efficiency advantages. So, while nanofluids in engines could improve performance, their commercial viability depends on finding the right mix between better engine performance, cost-effectiveness, and long-term reliability.

Every researchers and scientists have believed on the utilization of nanofluid in solar system to harness its energy with enhanced efficiency and effectiveness of the system. The present research, nevertheless, took a comprehensive approach, covering a wide range of solar energy collecting equipment not before addressed in details. This investigation yields numerous investigations areas, gaps, various consequences. Furthermore, a detailed discussion on the recent development and nanofluid utilization in solar system discussed with its theoretical, experimental and also computational approach. The important findings from this review article are mentioned below:

- Maximum 85.4% gain in thermal efficiency of solar collector using graphite as TES material.
- Maximum 38.4% enhancement in efficiency of solar water using CuO/H_2O nanofluid.
- Maximum 84.74% enhancement in thermal efficiency of PV/T system $SiC\text{-}H_2O$ with NEPCM.
- 196% enhancement in exergy efficiency of solar evaporator using Ag/H_2O nanofluid
- The utilization of multi walled carbon nanotube in all solar energy harnessing system improves the system performance. In case of solar desalination system, it improves the productivity of the system also.
- From recent research, it is observed that the utilization of hybrid nanofluid compared to mono nanofluid improves the performance of solar energy harnessing.
- Nanofluids speed up the evaporation process, which means that the solar still can purify water faster and make more distilled water in a shorter amount of time than ordinary water.
- Nanofluids can make solar stills work better even when the sun isn't shining very brightly, like on cloudy days or in the early morning and late afternoon. This makes sure that the still works well all day long.

FUTURE RESEARCH DIRECTION

Although, a lot of research has been performed on solar energy harnessing using nanofluid but still various works that need to be addressed for better performance which are mentioned below:

- More research is needed to make nanofluids more stable over time. This includes looking into problems like nanoparticles sticking together and settling to make sure they work the same way over lengthy periods of time.
- To search new technique for production nanofluid at low cost to make it more viable at commercial and industrial level utilization.
- New kind of research is also required to produce hybrid nanofluid to get maximum from solar system with highest effectiveness and efficiency.
- Characterization technique of nanomaterials must be improved to make it stable over long period of time and also environment friendly.
- Combining nanofluid with hybrid solar system is the new challenge for researcher and scientist. Future research must focus on it for enhancement of the system.
- Nanofluid preparation technique must be improved in future to make it environment friendly with low cost production to make it viable for commercial utilization.

CHALLENGES AND LIMITATIONS OF USING NANOFLUID IN SOLAR ENERGY SYSTEM

A thorough and organized review of high-quality past research has found many ways to improve the efficacy of solar energy collecting equipment. Even if the use of nanofluids has been successful, there are still certain issues that should be taken very seriously since they restrict the use of solar energy harnessing systems that use nanofluids. The key challenges and limitations for performing research on the utilization of nanofluids in solar energy harnessing are mentioned below:

- Ensuring the stability of nanoparticles within the fluid is a major challenge, as nanoparticles tend to agglomerate or settle over time, leading to reduced effectiveness and inconsistent thermal properties.
- Nanofluids are hard to make and mix because high-quality nanoparticles are expensive and it's hard to get them to distribute evenly. This makes it hard to do a lot of research and use them in a lot of different ways.
- The behavior of nanofluids in heat transmission is intricate and not yet completely understood. Because of this complexity, it's hard to anticipate how well they'll do, which requires advanced research and a lot of money.
- Limited data exists on the environmental and health impacts of producing, using, and disposing of nanofluids, raising concerns about their safety and sustainability, which complicates securing research funding and regulatory approval.
- No standardized methods exist for preparing, testing, or evaluating nanofluids, complicating data comparison across studies and hindering the development of universal guidelines.
- Translating lab scale research findings to practical solar energy systems is challenging. For instance, nanofluid properties must be tailored to suit diverse environments and system configurations.
- There is a huge difference between optical and thermal properties of nanofluid due to concentration of base fluid, nanoparticle type etc. This difference requires very tough optimization technique and also requires much better characterization and testing.
- It is hard to make sure that nanofluids will last a long time when they are exposed to high temperatures, UV radiation, and other environmental conditions for a long time. This is because degradation can make solar energy systems less effective over time.
- The system's operation and maintenance become more complex due to the need for precise control and supervision of nanofluid characteristics.
- Experimental results can be very different from each other because of changes in how nanofluids are made, how systems are designed, and how they are used. This makes it hard to know how to use them in real life.

NOMENCLATURE

A	Solar collector area (m^2)
c_p	Specific heat capacity (kJ/kgK)
I	Solar radiation flux (W/m^2)
m°	Mass flow rate (kg/s)
η_{th}	Thermal efficiency
Q_u	Usable heat transfer (kW)
Q_S	Solar irridation availability (kW)
Q_{solar}	Collector input solar energy (kW)
S^0_{gen}	System entropy generation (kJ/K)
T_{out}	Outlet temperature (K)
T_{in}	Inlet temperature (K)
T_a	Ambient temperature (K)
T_a	Sun temperature (K)

Abbreviations

3E	Energy, Economy and Environment
4E	Energy, Exergy, Economy and Environment
BVPTM	Baffled PVT module
Bpv	Bifacial photovoltaic
bPV/T	Bifacial photovoltaic-thermal
CTAB	Cetyltrimethylammonium bromide
CHGR	Conical helical gear rings
DSC	Differential Scanning Calorimetry
DESD	Double-effect solar distiller
DTPTSWH	Dimple tube parabolic trough solar water heater
EG	Ethylene glycol
ETSC	Evacuated tube solar collector
ETSWH	Evacuated tube solar water heater
FPSC	Flat plate solar collector
FPC-SWH	Flat plate collector- Solar water heater
FESEM	Field emission scanning electron microscopy
GAMWCNT	Gallic acid-treated multiwall carbon nanotubes
GNP	Graphene nanoplatelets
GO	Graphene Oxide
HTC	Heat transfer coefficient
JPTN	Jackfruit peel TiO_2 nanofluids
MWCNT	Multi walled carbon nanotube
Nano-PCM	Nanoparticle-enhanced phase change material
NPCM	Nano phase change material
PCM	Phase change material
PTC	Parabolic trough collector
PV/T	Photovoltaic thermal system
PVS	Photovoltaic solar
PV	Photovoltaic
PT-ETSC	Parallel type evacuated tube solar collector
SODIS	Solar water desalination
SBGIDSS	Single-basin glasswool-insulated double-slope solar still
SSPSS	Single-slope passive solar still
SDBS	Sodium dodecyl benzene sulfonate
SWCNT	Single walled carbon nanotube
SWHS-ZO-NF	Solar water heating system using zinc oxide-based nanofluid
SHC	Specific heat capacity
STS	Solar thermal system
SWH	Solar water heater
SEM	Scanning electron microscopy

TEM	Transmission electron microscopes
TC	Thermal conductivity
TES	Thermal energy storage
TEG	Thermoelectric generator
TGA	Thermal gravimetric analysis
XRD	X-ray diffraction

AUTHORSHIP CONTRIBUTION

All the authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the manuscript.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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