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Analysis of the Application of Nanofluids in the Capture and Utilization of Renewable Energy

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Abstract

Solar energy is becoming a viable and alternative renewable energy source. The sun generates solar energy, whereas fossil fuels are extracted, which is detrimental to the environment. The availability of fossil fuels is diminishing, although solar energy is plentiful. The utilization of fossil fuels to fulfil our requirements, such as electricity, produces energy applicable to diverse purposes. The combustion of fossil fuels generates detrimental gasses, resulting in air, water, and soil pollution, thereby adversely impacting the ecosystem. Simultaneously, it adversely impacts both humans and wildlife. The second point is that the combustion of fossil fuels induces climate change, which affects the ecology and ecosystem. Climate change is causing the extinction of several animal and plant species on Earth. Fossil fuels emit greater quantities of detrimental gasses that exacerbate the likelihood of the greenhouse effect. In the future, solar energy will serve as an exemplary alternative to fossil fuels due to its lack of adverse impacts. Considering these significant factors, we have provided an extensive overview of the growing technology involving the application of nanofluid in solar energy harvesting systems, which enhances the performance of solar systems using nanofluid. A proficient approach to enhancing the thermal efficiency of solar energy systems is the utilization of nanofluid as a superior heat transfer fluid with enhanced thermophysical characteristics. This review study aims to examine recent advancements in the comprehensive applications of nanofluids in solar energy harvesting systems, including solar water heaters, solar concentrators or collectors, solar PV/T systems, and solar stills. This review will examine the impacts of fossil fuel utilization, followed by an analysis of nanomaterials and their characteristics. Lastly, we will examine the various applications of nanofluids in diverse solar energy systems.

Subject Areas

Environmental Chemistry, Materials Engineering

Keywords

Sustainable Energy, Nanofluid, Solar Energy, Thermal Conductivity, Solar Collector

1. Introduction

In recent decades, energy has emerged as the paramount factor for the development of any nation. It also impacts the nation's economy. In recent decades, fossil fuels have been essential in meeting energy demand. Nonetheless, the accessibility of fossil fuels is diminishing progressively. It is the obligation of all researchers and scientists to create a technology that can substitute fossil fuels. The demand for energy is contingent solely upon two factors: the population of the country and its economic growth. In the past decade, the global population has been observed to be expanding concurrently. It also precipitates a global energy catastrophe. **Figure 1** illustrates the carbon emissions from 1990 to 2021 [1]. Energy is a fundamental and essential component necessary for progress in daily life. The International Energy Agency (IEA) has made a critical observation: worldwide energy consumption is projected to increase by 44% from 2016 to 2030. The consequences indicate that, owing to technological advancements and the increasing standard of living in industrialized countries, traditional energy sources will be unable to satisfy future energy demands. Currently, renewable energy is derived from natural resources, including solar, wind, and geothermal energies, which serve as the optimal alternative to traditional fossil fuels [2]-[5].

Current scenarios indicate that renewable energy resources are emerging as a compelling domain of study due to the finite nature of fossil fuels (**Figure 2**) [6].

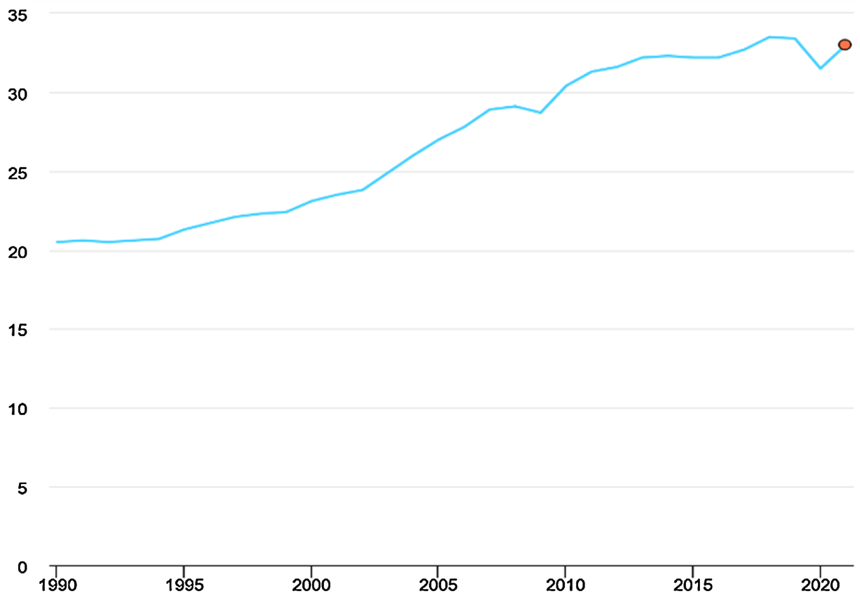

Figure 1. Global energy-related CO_2 emissions1990-2021 [1].

illustrates the daily availability of energy resources on Earth. The conclusion of fossil fuel usage is inevitable in the forthcoming years. Numerous species of renewable resources exist, including solar energy, wind power, hydropower, and bioenergy. Among all these options, solar energy has superior efficacy in harnessing energy. The sun's rays offer a beneficial service to humanity at no expense. Solar systems harness these beams and transform solar radiation into usable heat or electricity. The improvement of heat transfer in the solar system enhances the device's efficiency by facilitating energy transfer that conserves energy and contributes to a more compact system. Incorporating nanosized solid particles into the base fluid can significantly enhance the system's capacity to retain solar radiation (heat) [7]

In the high atmosphere, solar radiation has been measured at 174,000 terawatts (TW), with 70% of this radiation being efficiently absorbed by the atmosphere, land, and seas. Only 120,000 terawatts of energy can be harnessed for various applications. **Figure 3** illustrates the global generation of heat generated by solar radiation. It has been observed that we are unable to utilize the sun's rays to their fullest extent [8] [9]. Numerous methods have been used or will be established in the future to harness solar radiation.

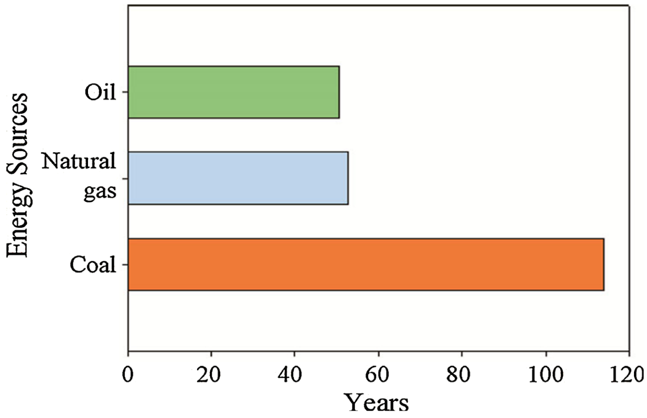

Figure 2. Availability of fossil fuels left [6].

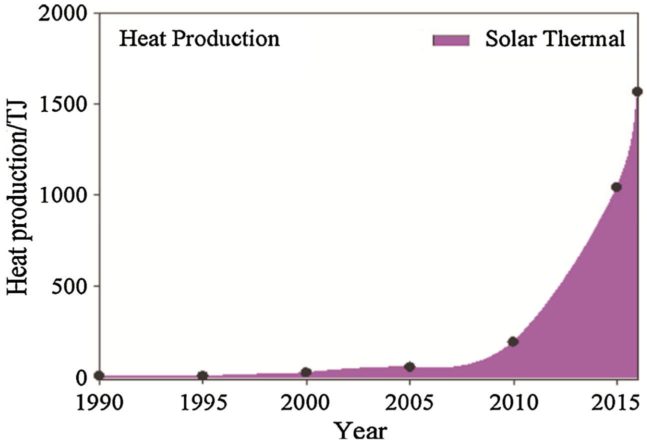

Figure 3. Production of heat from sun rays [6].

2. Nanofluids and Nanomaterials

To improve heat transmission in solar energy harvesting devices, a specialized fluid known as nanofluid is typically utilized. This fluid can serve as a working fluid in the system due to its superior thermo-physical properties. This method is the most effective alternative for enhancing the thermal efficiency of solar-harvesting systems. Nanofluids are formed by dispersing nano-sized solid particles, typically within the range of 10^{-9} m, referred to as nanoparticles, as seen in **Figure 4** [10]. Due to their superior efficiency compared to conventional fluids, numerous researchers have lately employed these nanofluids in water heaters, solar concentrators, solar cooling systems, solar stills, absorption refrigeration systems, solar cells, and various solar device units [11]. Nanofluids possess distinct features, which are summarized below [12]-[24]. Numerous researchers present these qualities in their publications.

- The presence of nanoparticles in the base fluid enhances its thermal conductivity. Additionally, the utilization of nanofluids prevents sedimentation, clogging, and fouling in pipes and pumps due to the nanoparticles' diminutive size.
- The nanoparticles possess a substantial surface area, hence enhancing their capacity to absorb solar energy and heat significantly.
- The optical properties of nanofluids surpass those of normal fluids.
- Utilizing nanofluid will enable thermal absorption devices to require a reduced heat transmission area. This attribute reduces the total expense of the solar harnessing system.
- Nanofluids often exhibit low specific heat of nanoparticles, high density, and elevated convective heat transfer coefficients, enhancing the efficiency of heat-absorbing apparatus.

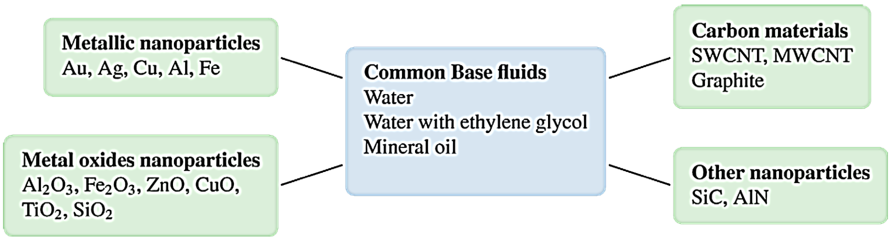

Figure 4. Types of nanomaterials and base fluids are generally involved in nanofluids.

Particles smaller than one micrometre are classified as nanosized particles, referred to as nanomaterials. The categorization of nanomaterials is predicated on particle morphology and architecture, including nanoemulsions, nanoparticles, and nano-clays, as depicted in **Figure 5** [25]. Nanoparticles are categorized into organic and inorganic types, as seen in **Figure 6**. Organic nanoparticles comprise lipid-based, carbon, and polymer nanoparticles. Inorganic nanoparticles are composed of metal and ceramic materials. Nanoclays are coated with silicate minerals, specifically kaolinite and saponite. Nonetheless, the mechanisms of oil-in-water, water-in-oil, and bi-continuous nanoemulsions suspensions [26]-[35].

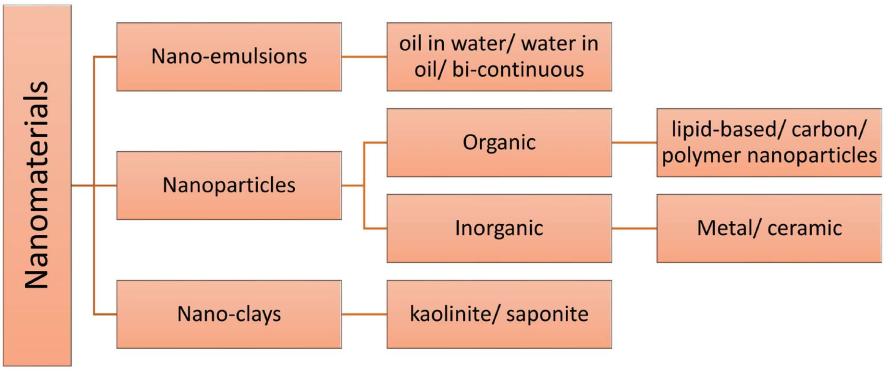

Figure 5. Categorization of nanomaterials.

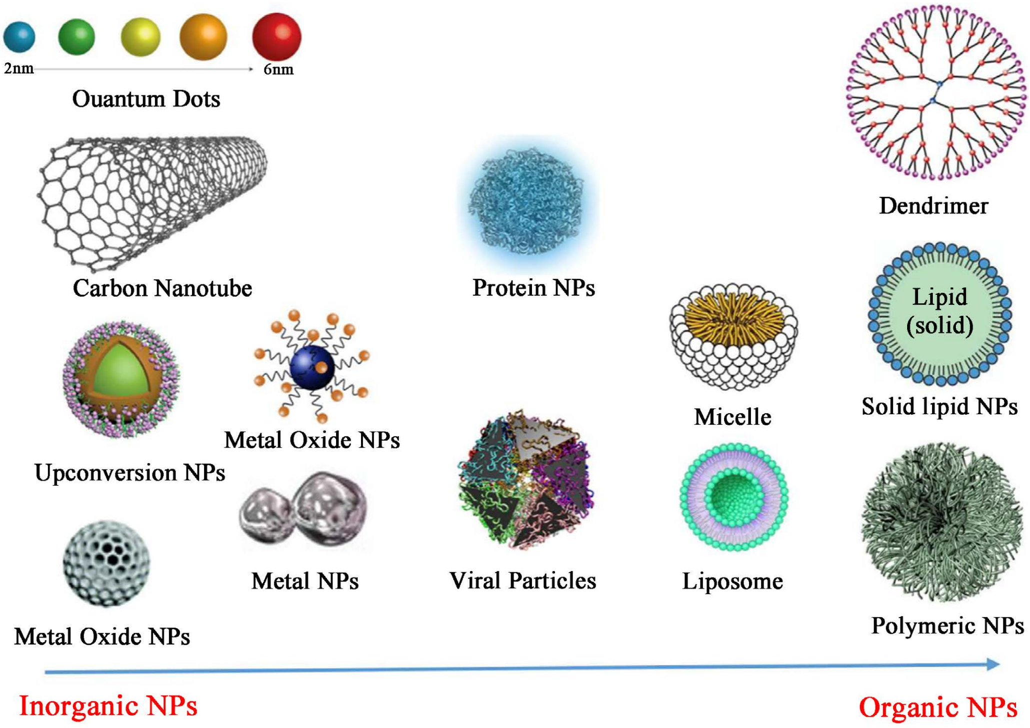

Figure 6. Types of organic and inorganic nanoparticles.

Metal and metal oxide nanoparticles (Au, Ag, Pt, Pd, ZnO, CuO, Cu, NiO, Ni, TiO_2) augment the characteristics of base fluids, including mechanical, chemical, thermal, electrical, and electromagnetic capabilities. Owing to their porous characteristics, ceramic nanoparticles are utilized in extreme conditions (temperature and pH) as they are included in heat and pressure applications. Polymer nanoparticles are produced using monomer polymerization, hydrophilic polymer coacervation, and ionic gelation. They are employed to formulate antireflection coatings on solar cell surfaces, facilitating increased light penetration into the solar cell and enhancing overall efficiency. Semiconducting nanoparticles are employed in several technologies due to their corrosion-resistant coatings and catalytic properties. Carbon-based nanoparticles can be included in energy storage devices, including supercapacitors and lithium-ion batteries, to improve their energy density and charge/discharge rates, hence increasing their suitability for storing solar-generated electricity. In concentrated solar collectors (CSC), thermal storage components can be insulated using nano clays, thereby minimizing heat loss and improving the efficiency of solar thermal energy storage and capture. Nano-emulsion-based nanoparticles serve as lubricants in solar tracking collectors, enabling solar panels to align with the sun's trajectory for optimal energy absorption. This lubrication diminishes the wear of the tracking mechanism, hence enhancing the durability and longevity of solar-absorbing devices [36]-[42].

3. Properties of Nanomaterials

Currently, nanomaterials are utilized extensively. Nanomaterials demonstrate significant efficacy in applications like solar energy systems, thermal storage, and medicine. The favourable outcome of nanomaterials can be attributed to two factors: their surface effects and quantum effects that distinguish them from conventional materials. These two effects are crucial in nanomaterials because of their diminutive size and elevated surface-to-volume ratio. Nanomaterials are defined as having dimensions of 100 nm as their surface area increases relative to their volume. This results in an increased number of atoms and molecules occupying the surface. The atoms of a molecule exhibit distinct properties at a microscopic scale compared to the bulk properties of the same material. The surface atoms exhibit increased surface energy due to varying shapes and bonding arrangements. This modification results in distinct outcomes in the chemical, thermal, mechanical, and optical characteristics of nanomaterials. Conversely, quantum effects are crucial for understanding the behaviour of particles at the atomic scale. This phenomenon constrains the movement of electrons inside the first three dimensions of the nanomaterial. This limitation results in an enhancement of energy bands and characteristics [43]-[45]. The subsequent discussion pertains to the physical properties of nanoparticles.

3.1. Mechanical Characteristics

Mechanical properties refer to the characteristics of materials under various situations, environments, and external forces. A standard material possesses ten distinct mechanical properties: ductility, brittleness, toughness, hardness, fatigue strength, elasticity, plasticity, rigidity, strength, and yield stress. Additionally, several inorganic nanoparticles exhibit distinct mechanical properties; for instance, FeAl alloy powder demonstrates commendable ductility and strength, accompanied by enhanced plasticity. Numerous inorganics, non-metallic nanoparticles exhibit brittleness and lack significant ductility, toughness, plasticity, or elasticity capabilities [46] [47].

3.2. Thermal Characteristics

The heat transmission of nanoparticles is contingent upon the energy conduction facilitated by electrons and photons. The primary elements of improving thermal conductivity, thermal stability, and heat capacity are outlined below. The size of nanoparticles significantly influences thermal conductivity. The surface area to volume ratio increases hyperbolically as nanoparticle size diminishes. The surface-to-volume ratio of nanoparticles influences molecular heat conduction. A higher ratio indicates a greater availability of electrons for heat transfer. In conclusion, nanoparticles facilitate a greater quantity of electrons for thermal conduction than the majority of the material. Nonetheless, the microconvection phenomenon in nanoparticles improves their thermal conductivity [48] [49].

3.3. Magnetic Characteristics

Nanomaterials exhibit distinct magnetic properties attributable to their diminutive size and structural characteristics. A material exhibits superparamagnetic when its nanomaterial size is below 10 nm. This indicates their ability to alter their magnetic configuration without an external magnetic field, rendering them advantageous for applications such as data storage. These materials exhibit increased magnetic moments per unit volume relative to bulk materials. Consequently, enhanced magnetic characteristics have been achieved with an equivalent quantity of material. Similar to FeAl, it is non-magnetic in bulk form; nevertheless, it exhibits magnetic properties when in the form of nanoparticles. The crystallographic structure, vacancy defects, magnetic anisotropy, and composition are essential for ascertaining the magnetic characteristics of bulk materials. In the case of nanoparticles, their magnetic characteristics are dictated by their dimensions and morphology [50]-[52].

3.4. Optical Characteristics

The optical qualities are contingent upon the size and structure of nanoparticles, as these characteristics are crucial for the effective absorption of solar radiation. Numerous metallic nanoparticles, such as silver and gold-based nanomaterials, can exhibit plasmonic resonance, as illustrated in Figure 7. This feature results from the collective excitation of conductive electrons in metals, known as plasmons. Consequently, the absorption rate and scattering of light are augmented. These diverse features influence numerous solar energy technologies, including photovoltaics, solar thermal systems, and photodetectors. A multitude of scientists

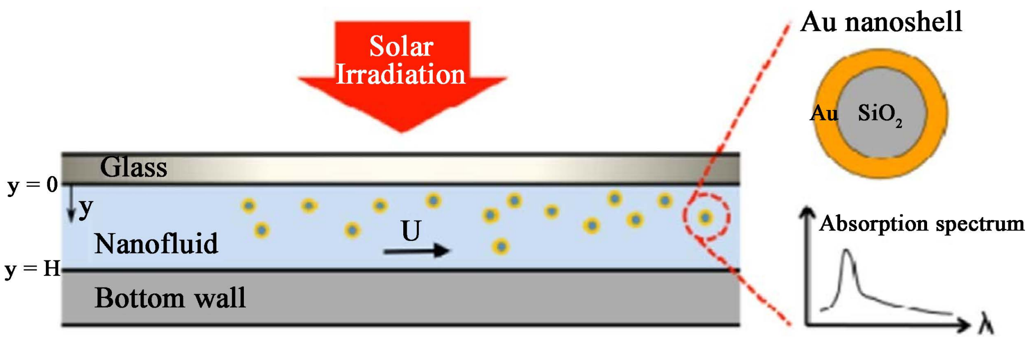

Figure 7. Schematic view of plasmonic resonance.

continues to explore nanomaterial-based techniques to enhance solar absorption and the efficiency of solar energy conversion devices [53]-[55].

4. Utilization of Nanofluid in Different Solar Applications

Nanofluids are specialized fluids that exhibit superior thermophysical properties compared to traditional fluids. The thermophysical parameters include thermal conductivity, specific heat, thermal diffusivity, density, and heat transfer coefficient. The exceptional characteristics of nanofluid enhance the effectiveness of solar energy harvesting devices. Nanofluid captures solar radiation (heat), and the accumulated thermal energy can be utilized in diverse applications, as elaborated in this section.

4.1. Solar Concentrators or Collectors

Solar concentrators, also known as collectors, are apparatuses designed to concentrate sunlight onto a designated region. **Figure 9** illustrates the many types of solar collectors. These collectors typically capture solar radiation and transform it into thermal energy, which is subsequently transmitted to a fluid circulating through the concentrator. Various types of concentrators have been examined through tests utilizing different nanomaterial-based nanofluids, with their results comprehensively presented in **Table 1**. These concentrators were developed as environmentally sustainable heat exchanger devices and enhanced solar system efficiency. Consequently, numerous researchers must investigate and formulate a highly optimal nanofluid for various applications. Similar to Genc *et al.* [56], they employed an Al_2O_3 nanoparticle-based nanofluid with varying volumetric contents. The thermal property of nanofluid is influenced by the concentration of nanoparticles (1%, 2%, and 3%) in the base fluid. The mass flow rate is also

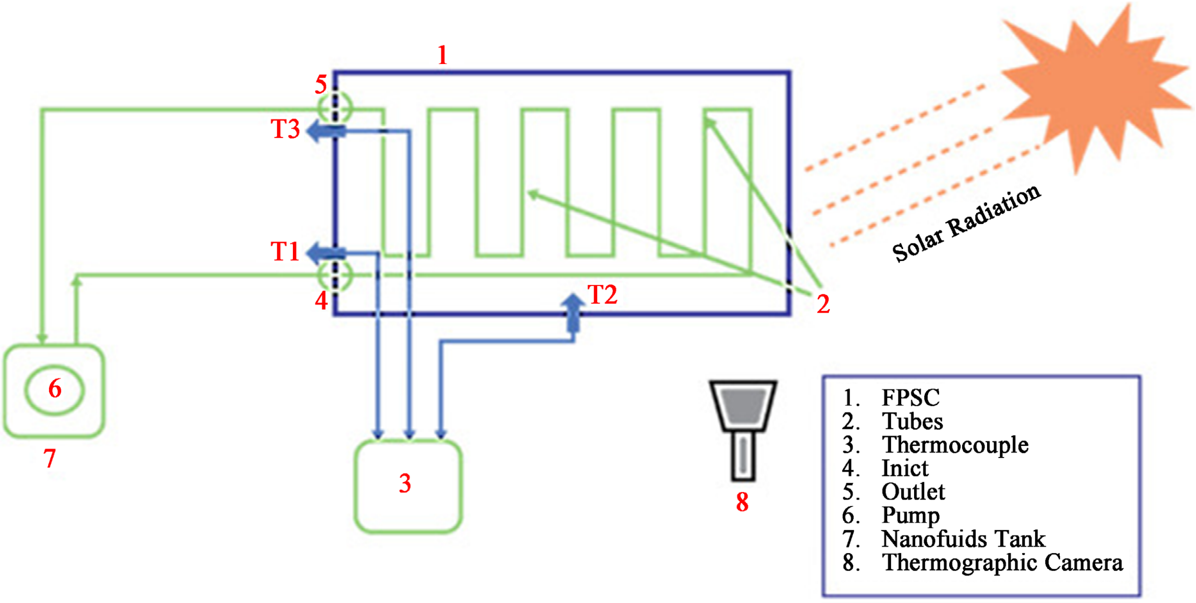

Figure 8. Systematic positioning of FPSC receiving solar radiation.

Table 1. Summarized view of different nanofluids used in different solar collectors [59]-[71].

Refs. [No]	Solar Collector used	Nanofluid used	Results
59	FPSC	Al_2O_3/water	-System efficiency increased by 28.3%. -By utilising surfactant in nanofluid, efficiency enhanced by 15.63%.
60	FPSC	Al2O3/water	-Better optical efficiency obtained, *i.e.*, 24.1%. -The thermal conductivity of the nanofluid rose as the concentration and nanoparticle size dropped.
61	FPSC	TiO_2/water	-Efficiency increased by around 0.6% - 7%.
62	FPSC	CuO/H_2O, SiO_2/H_2O, TiO_2/H_2O and Al_2O_3/H_2O	-CuO/water-based nanofluid is the excellent choice to have maximum efficiency.
63	FPSC	CuO/H_2O, SiO_2/H_2O, TiO_2/H_2O and Al_2O_3/H_2O	-Maximum heat transfer observed in CuO/ H_2O nanofluid.
64	Evacuated Tube	MWCNT/water	-Efficiency increased by 4% by utilising nanofluid.
65	Evacuated Tube	Single-walled carbon nanotubes/water	-The change in efficiency occurs by 48.57% and 93.43% at 0.05 vol% and 0.2 vol% of nanofluid.
66	Conical	SiO_2/water	-The change in efficiency occurs by 48.57% and 93.43% at 0.05 vol% and 0.2 vol% of nanofluid.
67	PTC	Aluminum/Therminol VP-1	-Causes the enhancement of efficiency by 10%.
68	PTC	CuO/Oil	-CuO/Oil nanofluid shows enhanced absorption in comparison to oil base fluid.
69	PTC	Al_2O_3/synthetic oil	-By increasing the concentration of the particle size, the change in the absorber decreases.
70	PTC	Cu/H_2O	-When the absorption radiation increases, the thermal effectiveness increases for both collectors.
71	PTC	CuO/water	-Increase in thermal efficiency obtained from 19% to 53%, on rising in volume fraction from 0.003% to 0.008%.

influenced by varying climatic conditions. Their research indicates that the outlet temperature of the flowing Al_2O_3-water-based nanofluid reaches its peak at a 3% volumetric concentration. Otanicar *et al.* [57] employed a direct absorption solar concentrator and utilized several nanomaterial-based nanofluids, including carbon nanotubes, graphite, and silver. The effectiveness of the concentrator was improved by approximately 6% by the utilization of the specified nanomaterial-based nanofluid. Their findings indicate that the absorption capacity of a used concentrator surpasses that of a surface-mounted concentrator. Mahamude *et al.* [58] conducted an experimental study on the application of hybrid nanofluids (graphene and CNC) in flat-plate solar concentrators, as illustrated in **Figure 8**. The hybrid nanofluid exhibited 194% more conductivity at 80˚C compared to the standard nanofluid, which is 3.05 times more viscous than the basic fluid. The improved optical and thermal characteristics of a hybrid nanofluid augment the efficiency of a solar energy harvesting device.

A subsequent investigation conducted by Hordy *et al.* [72] utilized a multi-walled carbon nanotube-based nanofluid as the working fluid. They suspended these nanotubes in denatured alcohol and observed an enhanced heat absorption efficiency of over 100% of the incoming solar radiation using a small volume of fluid. They also examined whether the employed nanofluid exhibited enhanced stability without agglomeration over several cycles of boiling and condensation. Bouslimi *et al.* [73] did an experimental investigation on parabolic trough concentrators due to their remarkable efficiency and low cost. They utilize Cu and Ag nanoparticle-based nanofluids suspended in sodium alginate as a shuttering agent. The thermal efficiency of Cu-SA is stated to be superior to that of Ag-SA, with an enhancement ranging from 1.7% to 4.8%.

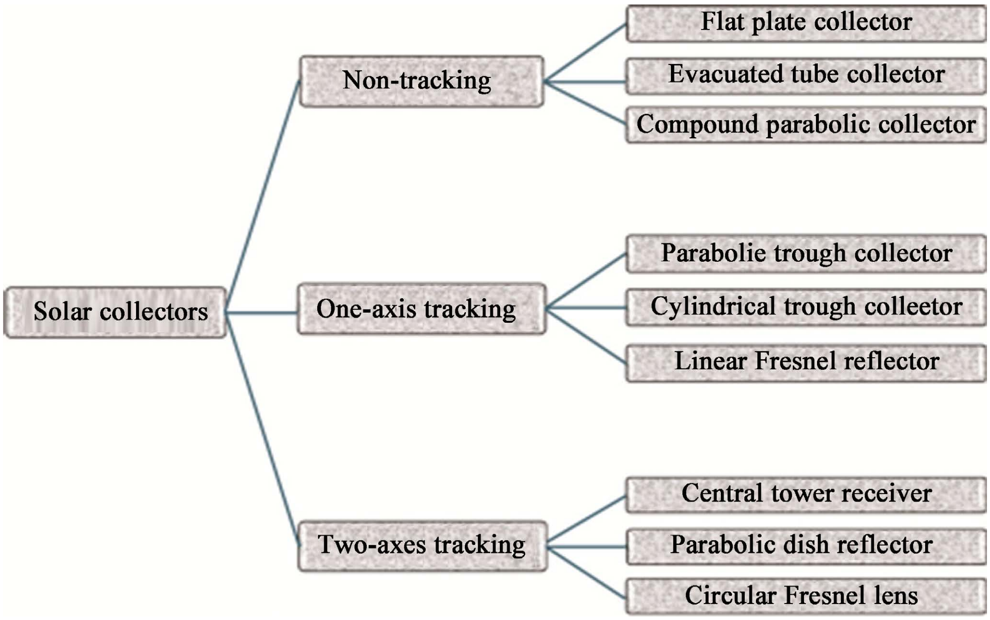

Figure 9. Different types of solar collectors.

4.2. Solar Water Heater

A solar water heater is an apparatus that utilizes solar radiation to elevate water temperature for diverse industrial, commercial, and residential applications. The primary advantages of employing this water heating method include decreasing electricity expenses, utilizing renewable energy sources, and minimizing carbon emissions. This solar water heater system employs a mostly evacuated tube solar collector to capture solar energy. Evacuated-type solar collectors with nanofluid offer numerous advantages over conventional collectors, including increased heat transfer rates, improved absorption, and superior thermal conductivity of the nanofluid. The evacuated tube solar collector comprises various components. An absorber tube is situated within the evacuated tube, where it captures heat from solar light. **Figure 10** illustrates a properly labeled design of the evacuated tube collector [74] [75]. This absorptive tube is affixed to a heat pipe. The absorber plate is generally composed of aluminum and copper due to their superior heat conductivity. The principal coating on the absorber plate is a distinctive material that conveys the fluid through the heat pipe. The copper plate is situated within a conventional heat exchanger connected to a storage tank. Ultimately, cold water is heated throughout the day, and hot water can be utilized at night owing to the sufficient insulation of the storage tank. A considerable amount of studies have been conducted to compare conventional and evacuated-type solar collectors [76] [77]. The expense is little, and the installation and transportation of evacuated tube solar collectors are equally straightforward. This gadget is operable under adverse weather and high-moisture situations [78].

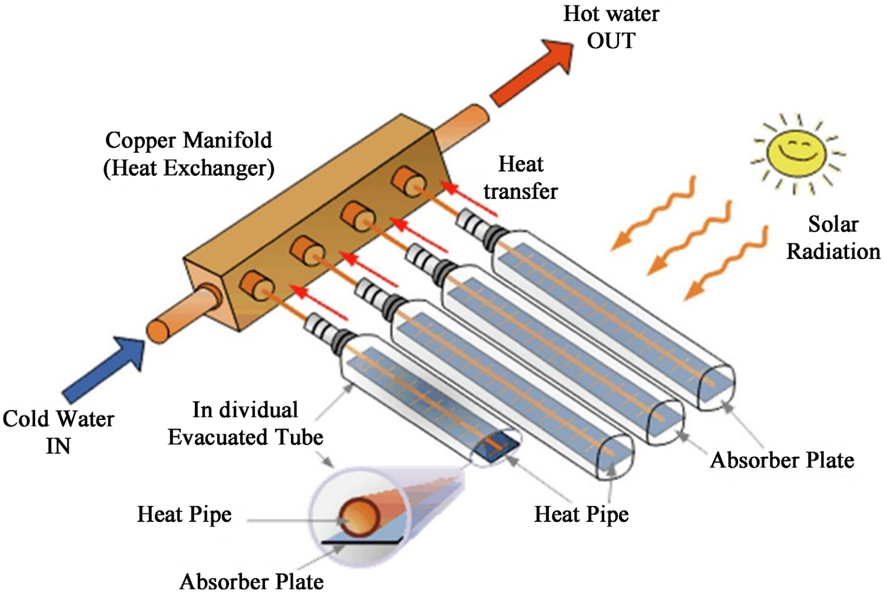

Figure 10. Evacuated tube solar collector used in heating water [75].

Tong *et al.* [79] conducted experimental research and developed a closed-circuit evacuated solar collector. They utilize multi-walled carbon nanotubes or water-based nanofluids as the working fluid and assess the effectiveness of the collector. The collector exhibits superior performance with nanofluid compared to conventional fluid. The system's efficiency reportedly improved by 4%. Sabiha *et al.* [80] utilized single-walled carbon nanotubes as a fluid in their experimental investigation of evacuated tube solar collectors. Various concentrations of nanofluid were utilized in the experiment, including 0.05 vol%, 1 vol%, and 2 vol%. The mass flow rate of the nanofluid is sustained between 0.009 and 0.025 kg/s. They observed that augmenting the concentration and mass flow rate of a nanofluid enhanced the collector efficiency. The rate of heat transmission and thermal conductivity increase with the augmentation of nanoparticle volume concentration.

Liu *et al.* [81] assessed the experimental results of a parabolic trough collector combined with an evacuated tube solar collector utilizing a CuO/water-based nanofluid as the working fluid. The utilization of CuO/water-based nanofluid enhances the efficiency of evacuated tube solar collectors by 12.5%. Their observations indicated that the improvement of the heat transfer coefficient remained constant regardless of mass concentration. Sumit and AK Tiwari [82] conducted a thermal performance investigation, illustrated in **Figure 11**, of a U-tube evacuated tube solar collector utilizing hexagonal boron nitride (hBN/water) nanofluid as the working fluid. To achieve volumetric concentrations, they utilized a 50-nm hBN-sized nanoparticle suspended and ultrasonicated in distilled water. They ensured stability by employing six distinct surfactants combined with nanofluid in various proportions. A zeta potential test is conducted to evaluate the stability of the nanofluid. They examined various thermophysical properties by sustaining distinct volumetric concentrations (0.25 vol% to 2 vol%) of nanofluid at varying temperatures (25˚C to 50˚C). The performance of the collector was evaluated at various mass flow rates (0.0085 to 0.051 kg/s), achieving a maximum energy efficiency of 72.14% at a volumetric concentration of 1.5 vol% and a mass flow rate of 0.051 kg/s. This achieved efficiency is 84% superior to that of water with a comparable flow concentration. It was observed that hBN/water nanofluid exhibits superior thermal conductivity and viscosity.

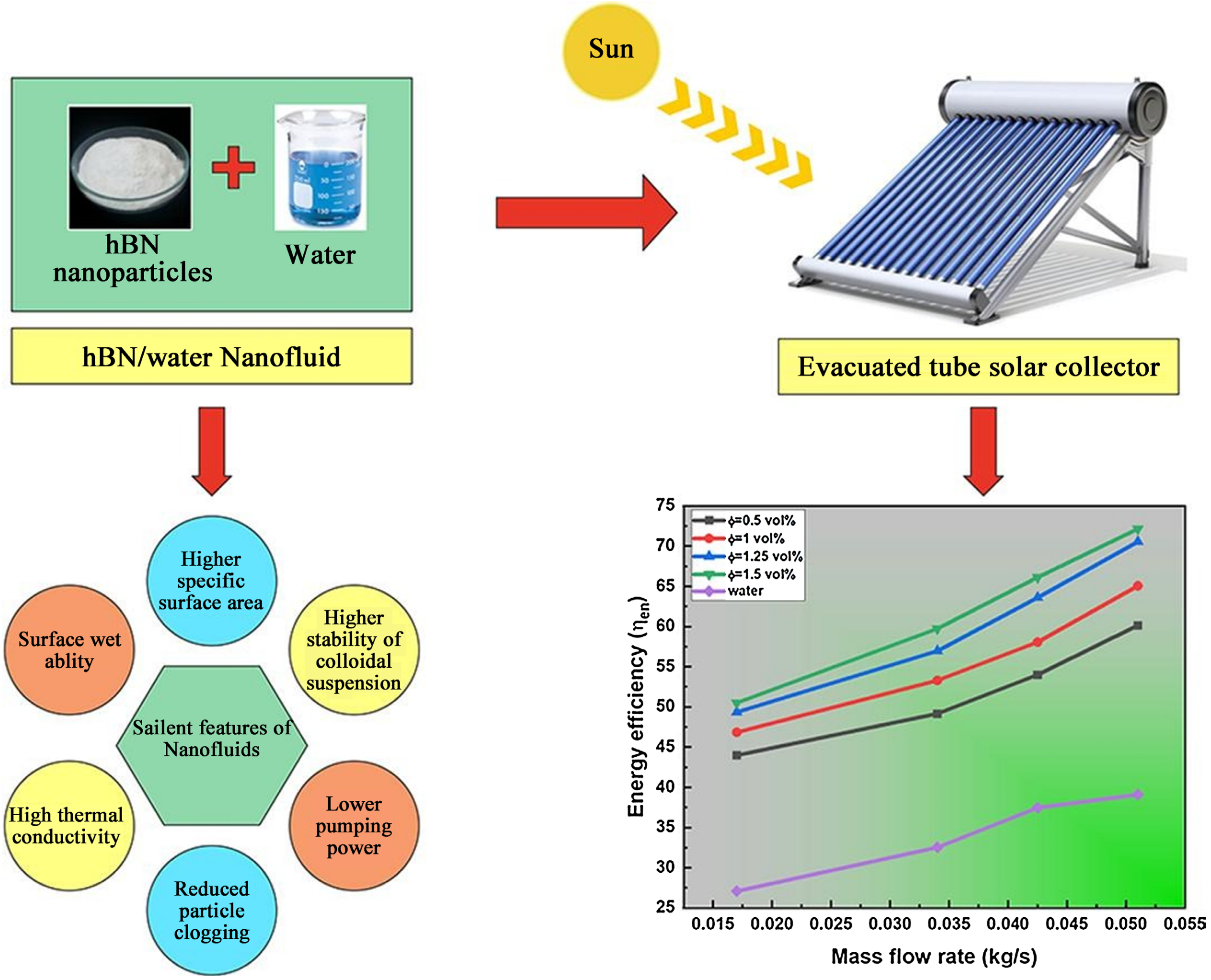

Figure 11. Performance analysis on hBN/water-based nanofluid in evacuated tube solar collector.

4.3. Solar Photovoltaic/Thermal System

A solar photovoltaic or thermal system is mostly known as a PV solar system. This device harnesses solar radiation and transforms it into electrical and heat energy. Photovoltaic solar systems consist of photovoltaic cells or panels, which are comprised of several solar cells built from semiconductor materials that capture solar radiation and convert it into direct current electricity. The energy conversion occurs by positioning a photovoltaic cell on a distinct solar collector, as illustrated in **Figure 12** [83], which effectively absorbs sunlight. Nevertheless, a photovoltaic cell or solar panel cannot absorb the entirety of photons across the complete spectrum of solar rays. This is the sole limitation that impacts the efficiency of solar photovoltaic systems. This limitation is addressed solely by integrating solar cells with a collector that optimizes the system's efficiency [84] [85].

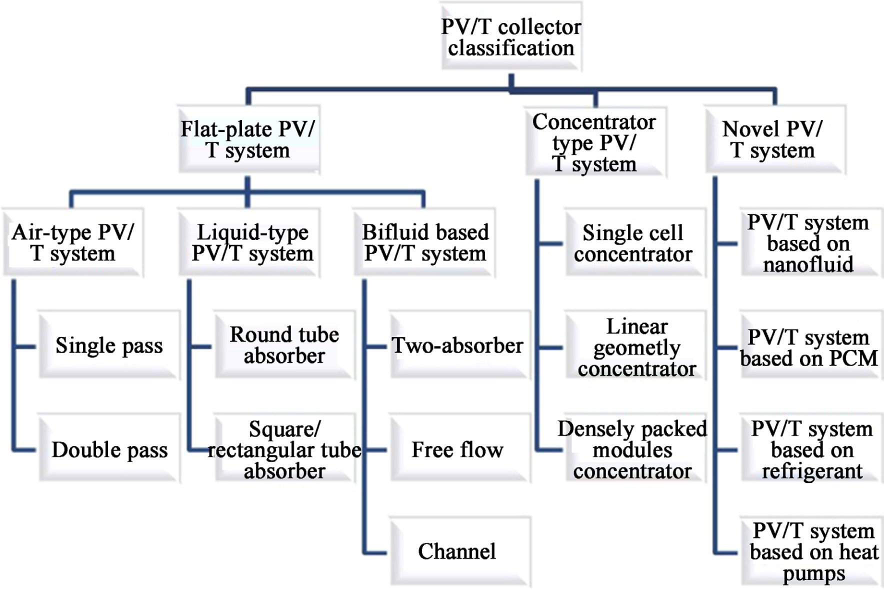

Figure 12. Categorization of PV/T collectors.

In recent years, numerous researchers have employed nanofluids as working fluids in PV/T systems to enhance efficiency. The system employs various distinct nanoparticle-based nanofluids and evaluates their feasibility using different characterization approaches, as illustrated in **Table 2**. Utilizing various nanofluids, they attained enhanced thermal and electrical performance. The electrical efficiency of solar photovoltaic systems is contingent upon the temperature of the cell. The PV/T system converts merely 20% of the solar spectrum into energy, with an additional 20% dissipated as heat into the surrounding air, resulting in an elevated cell temperature. Consequently, it absorbs a reduced quantity of solar radiation heat due to the pre-heating of the PV cell, which influences the absorption rate. The electrical efficiency of a cell is inversely related to its temperature. Consequently, a cooling fluid is employed to remove heat from the cell, enabling the PV/T to absorb additional heat from radiation. Nanofluids are integral to

Table 2. Characterization technique is used in photovoltaic/thermal systems [88]-[91].

Ref. [No].	Nanofluid used	Characterization Technique	Results
88	Molten salt-based nanofluid SiO_2, Al_2O_3	SEM, EDX, XRD, DSC & CZA	The wet dissolving process yields salt with twice as high Cp. Take note that the research is independent of the salt's nanoparticle content. Relative to the pure carbonate salt made using the wet technique, the melting performance of the salt was altered by including the nanoparticles.
89	CNT/SDS	UV–Vis spectrophotometer	The excess CNT proportion for the bare CNT solution decreases by up to 50% after 500 hours of sedimentation, while the addition of SDS only causes a 15% decrease. Furthermore, CNT/SDS dispersions show remarkable stability with no precipitation after 150 hours. Surfactants that have a single straight-chain hydrophobic segment and a terminal hydrophilic section can alter the interface between CNTs and the suspending media, hence preventing CNT aggregation for extended periods of time.
90	Polyamidation (PAMAM) amine-terminated dendrimers.	Zeta potential test	In general, nanoparticles having zeta potentials of less than −30 mV or higher than +30 mV are classified as strongly anionic, whereas those with zeta potentials between −10 and +10 mV are regarded as roughly neutral.
91	Al_2O_3/H_2O	TEM	At 3 and 5 hours of ultrasonication, improved particle distribution, shorter aggregation sizes, and greater zeta potentials were noted for the 50% and 25% of sonicator power amplitudes, respectively.

photovoltaic/thermal (PV/T) systems. In this context, nanofluid is crucial for cooling the cell, and the thermal energy stored in the nanofluid can be utilized for many applications. Nanofluid possesses elevated thermal conductivity, which significantly improves the heat transfer rate essential for cooling photovoltaic/thermal (PV/T) systems [86]. **Figure 13** [87] illustrates the well-delineated systematic organization of nanofluid application within the PV/T system.

4.4. Solar Stills (Evaporator)

This represents an additional application or, alternatively, another method of employing nanofluid. Solar stills are apparatuses utilized for water purification through a method known as solar distillation. These evaporators utilize solar energy to evaporate water, thereby leaving pollutants and toxins behind and subsequently condensing the vapor to obtain clean, potable water. This technology is applicable in areas experiencing a scarcity of potable water. These stills are primarily beneficial in regions with restricted access to potable water sources. This procedure represents the optimal solution for free water cleaning or purification. A straightforward and sustainable approach or design will be implemented for the stills depicted in **Figure 14** [92].

The application of nanofluid in solar stills is optimal due to its thermophysical features, which improve the efficiency of these systems. It enhances the heat absorption rate due to nanoparticles possessing a high surface area, enabling them to effectively absorb a greater amount of solar radiation. This results in accelerated heating within the solar cells. Nanofluid can augment the thermal conductivity of the working fluid in the water undergoing purification. Enhanced heat transfer

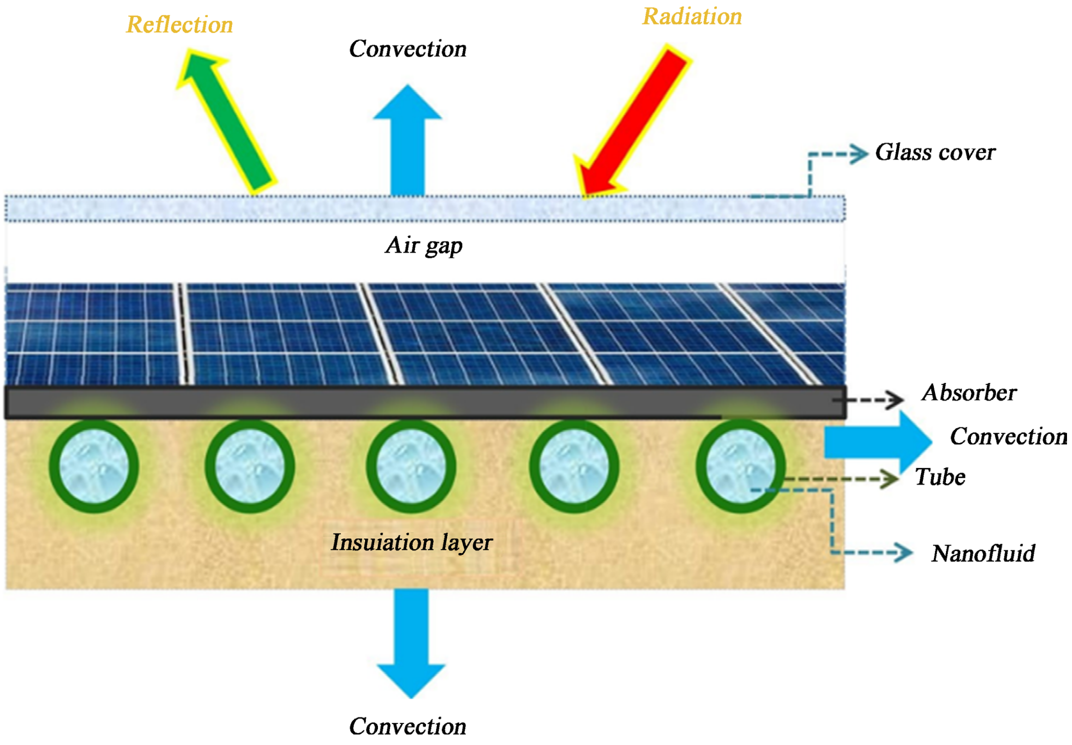

Figure 13. Schematic view of utilization nanofluid in PV/T system.

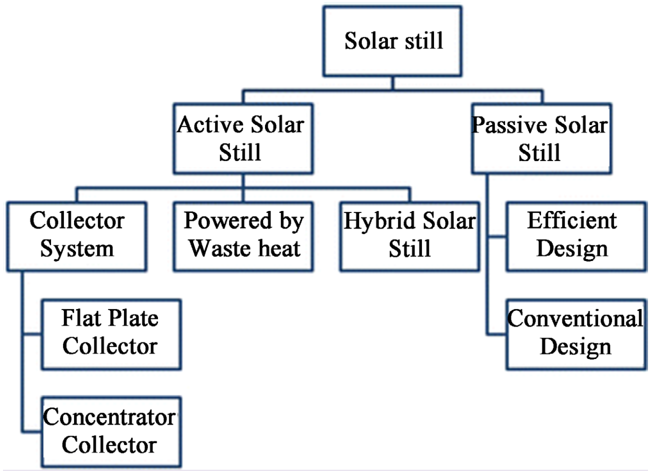

Figure 14. Classification of solar stills.

between the solar collector and the water to be cleaned significantly improves the efficiency of solar stills. The application of nanofluid can diminish heat loss to the environment. Consequently, elevated temperatures within the sills will be sustained, which is crucial for the optimal operation of solar stills. Nanoparticles can expedite the evaporation process, leading to heightened water vapor generation. Improvements in heat absorption, heat transmission, and evaporation rates can enhance freshwater yields from the solar still, increasing its efficiency in converting seawater or brackish water into potable water [93]. **Figure 15** [94] illustrates the systematic operation of nanofluid-based solar stills. The thermophysical

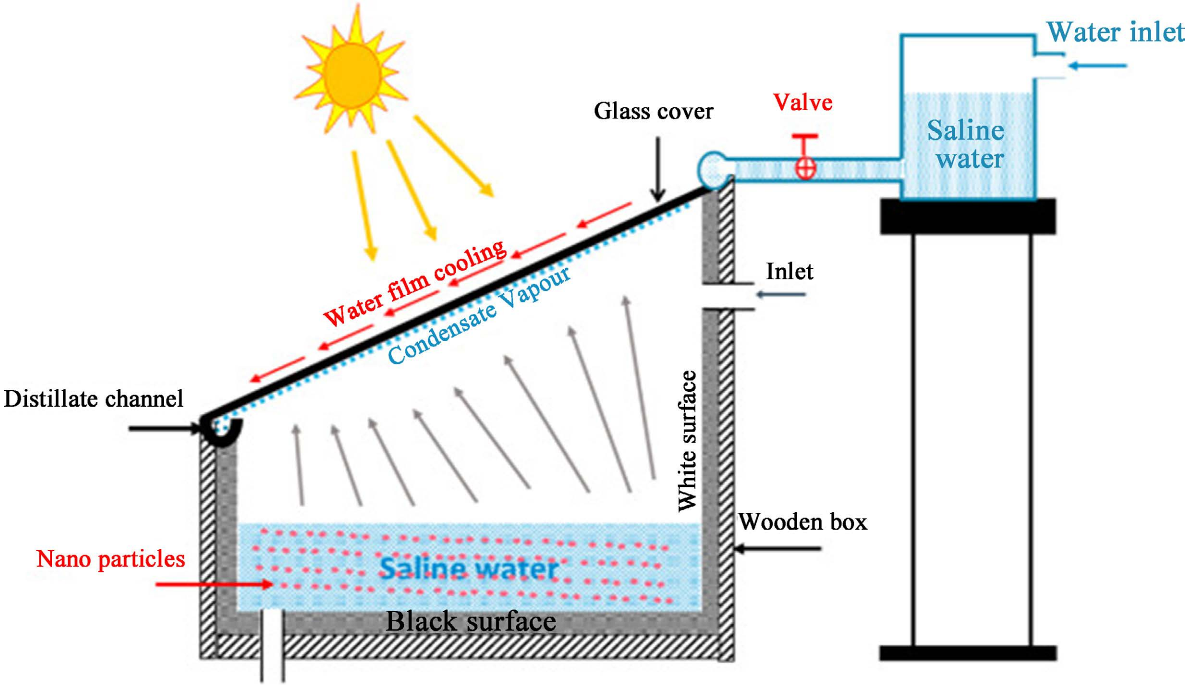

Figure 15. Schematic diagram of solar still working.

features of nanofluids render them ideal for solar stills, prompting numerous researchers to utilize nanofluids as the working fluid within these systems to enhance efficiency. Nanofluid nanoparticles have enhanced wavelength absorption, demonstrating a superior ability to absorb solar energy in water. A multitude of studies employ various nanoparticle-based nanofluids, with their findings comprehensively detailed in Table 3.

5. Conclusions

The investigation of nanofluids in solar energy use has revealed a viable avenue for enhancing the efficiency and sustainability of solar thermal systems. This thorough analysis emphasizes the substantial progress achieved in comprehending the complex relationship between nanofluid characteristics and their influence on heat transfer improvement in solar collectors. The incorporation of nanofluids into solar energy systems has significant promise for optimizing energy conversion processes through better thermal conductivity and enhanced heat absorption capacities. Although the scientific environment is abundant with potential advancements, obstacles and areas for additional exploration persist. Long-term stability, cost-effectiveness, and environmental impacts must be resolved to enable the widespread application of nanofluid-based solar solutions. Interdisciplinary collaboration will be essential in surmounting these challenges and realizing the complete potential of nanofluids in solar energy applications. The global quest for sustainable energy solutions is intensifying, and this analysis highlights the critical need for further research and development in the application of nanofluids. By persistently exploring and innovating, we can leverage nanotechnology to

Table 3. Summary of the utilization of different nanofluid in solar stills [95]-[99].

Ref [No].	Nanofluid	Conclusion
95	Copper Oxide, Graphite	They investigated that the efficiency of solar still systems increased by 44.91% and 53.95%. The system's efficiency rose by 73.8% when phase transition material was combined with a flake of graphite nanoparticles.
96	Cuprous and Aluminium Oxides	They investigated the performance of solar stills with and without a vacuum inside the stills. They noted that the cuprous oxide/water nanofluid has higher efficiency than the aluminum oxide/water nanofluid. They also mentioned that the solar still has an external condenser as a result of the addition of aluminium oxide. They found that using nanofluid and integrating an exterior condenser with the still increased productivity by 116%.
97	Al_2O_3, ZnO, Fe_2O_3, and SnO_2/Water	Because of their poor stability, Fe_2O_3 nanoparticles were not used in this investigation. When compared to regular water, Al_2O_3 (29.95%), SnO_2 (18.63%), and ZnO (12.67%) yielded the highest production gains.
98	SiO_2/Water and Cu/Water	They investigated that the use of heat exchangers does not affect the solar still's inlet temperature. When comparing the solar still with the heat exchanger installed, the intake temperature rises by over 200%. They claimed that compared to SiO_2/water-based nanofluid, Cu/water-based nanofluid is far more efficient.
99	Al_2O_3	The use of nanofluid increases water's thermal conductivity by up to 10.5%. Using nanoparticles increases water production effectiveness in the integrated solar still by around 116%. Comparing the overall efficacy to traditional solar desalination, there has been an almost 54% gain.

advance solar energy capture into a new epoch of efficiency, cost-effectiveness, and sustainability. The pursuit of a cleaner, greener energy future is undeniably arduous, yet the findings from this analysis indicate that nanofluids possess the potential to significantly influence the development of solar energy technology in the foreseeable future. The subsequent principal points are derived from this research article:

- The nanomaterials possess a size of 100 nm, resulting in an increased surface area relative to their volume. This results in an increased number of atoms and molecules occupying the surface. The atoms of a molecule exhibit distinct properties at a microscopic scale in contrast to the bulk properties of the same material.
- The sole limitation impacting the effectiveness of solar photovoltaic systems is their inability to absorb the whole spectrum of solar energy. This limitation is addressed solely by integrating solar cells with a collector that optimizes system efficiency.
- Accessing the appropriate nanoparticle size in a base fluid is challenging since it influences the efficacy of a solar harvesting system that employs nanofluid as a heat transfer medium. Extensive analysis and testing are necessary to determine the optimal nanoparticle size for heat transfer applications.
- The introduction of nanofluid in solar energy systems can diminish environmental heat loss. Consequently, elevated temperatures within the system chamber will be sustained, which is crucial for the optimal operation of solar systems such as solar stills.

- The sole problem regarding this growing technology is the requirement for elevated production expenses. Similarly, nanoparticles do not agglomerate well and remain unstable in the base fluid. This issue requires resolution in subsequent efforts.
- The implementation of nanofluid in solar energy systems enhances both thermal and electrical efficiency due to its superior thermal conductivity relative to traditional fluids.

Conflicts of Interest

The authors declare no conflicts of interest.

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