

# NANOFLUIDS IN FLAT-PLATE SOLAR COLLECTORS: A SYSTEMATIC REVIEW OF PERFORMANCE EVALUATION, EMERGING TRENDS, AND FUTURE RESEARCH DIRECTIONS

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**Abstract :** This systematic review explores the use of nanofluids in flat-plate solar collectors (FPSCs), covering experimental, numerical, and combined studies published over the past decade. Following PRISMA 2020 guidelines, four databases were systematically searched and studies were assessed for reporting quality. Water-based fluids dominated (88.3%), while Al<sub>2</sub>O<sub>3</sub> (24.6%), CuO (14.2%), and TiO<sub>2</sub> (9.0%) were the most studied nanoparticles. Hybrid nanofluids featured in 22.3% of studies, with 55.3% using concentrations ≤0.5 vol%. Despite promising thermal enhancement, inconsistent reporting of uncertainty, stability, and base-fluid conditions limits cross-study comparison. The review highlights the need for standardised reporting practices to improve reproducibility and comparability in FPSC nanofluid research.

**IndexTerms** - Flat-plate solar collectors, Nanofluids, Systematic review, PRISMA, Thermal efficiency, Hybrid nanofluids, Exergy analysis.

## NOMENCLATURE

| Symbol         | Description            | Unit                                 |
|----------------|------------------------|--------------------------------------|
| A              | Area                   | m <sup>2</sup>                       |
| c <sub>p</sub> | Specific heat capacity | kJ·kg <sup>-1</sup> ·K <sup>-1</sup> |
| k              | Thermal conductivity   | W·m <sup>-1</sup> ·K <sup>-1</sup>   |
| T              | Temperature            | °C                                   |
| μ              | Dynamic viscosity      | kg·m <sup>-1</sup> ·s <sup>-1</sup>  |
| ρ              | Density                | kg·m <sup>-3</sup>                   |
| φ              | Solid volume fraction  | vol%                                 |
| η              | Thermal efficiency     | —                                    |
| Nu             | Nusselt number         | —                                    |
| Re             | Reynolds number        | —                                    |
| Ra             | Rayleigh number        | —                                    |

## I. INTRODUCTION

Global energy demand continues to rise, intensifying reliance on fossil fuels and the environmental and economic burdens that accompany them. Constrained conventional supply, volatile fuel prices, tightening emissions regulation and the wider move toward sustainable development have together directed attention in both developing and developed economies toward renewable energy systems. Solar energy is the most abundant of these resources, and solar-thermal collectors convert incident radiation directly into useful heat in a carrier fluid.

Solar collectors are conventionally divided into non-concentrating (fixed) and concentrating types. Non-concentrating collectors absorb radiation across a single flat surface and serve low- to medium-temperature duties; concentrating collectors use reflective or refractive surfaces to focus radiation onto a reduced receiver area and reach the higher temperatures required for power generation and industrial process heat. Among non-concentrating designs, the flat-plate solar collector (FPSC) is the most widely installed and commercially mature technology worldwide, valued for its simple construction, low maintenance requirement and low manufacturing cost.

The thermal efficiency of an FPSC is limited in part by the transport properties of the working fluid. Conventional heat-transfer liquids — water, ethylene glycol and their binary mixtures — have modest thermal conductivity, and this has motivated sustained interest in nanofluids, which are engineered suspensions of nanometre-scale solid particles in a conventional base fluid. Since the concept was formalised by Choi at Argonne National Laboratory in 1995, nanofluids have been investigated extensively for solar-thermal duty, and a large experimental and numerical literature on their use in FPSCs has accumulated over the past decade [38, 65, 66, 89].

That literature is now substantial enough that narrative summary is no longer sufficient. Reported enhancements span from a few per cent to more than one hundred per cent in Nusselt number [45], and these figures are quoted against base fluids, operating conditions, collector geometries and performance definitions that differ from study to study. Existing reviews have catalogued this material usefully, but they have generally not documented a reproducible search strategy, explicit eligibility criteria or a quality appraisal, which leaves their aggregate statistics difficult to verify and their comparisons difficult to interpret.

This review addresses that gap. It applies a pre-specified systematic-review protocol, reported in accordance with PRISMA 2020, to the FPSC nanofluid literature published between January 2015 and June 2025. The specific objectives are:

- (1) to document a reproducible search, screening and extraction procedure for this literature, and to deposit the resulting dataset so that all reported statistics can be independently recomputed;
- (2) to quantify the distribution of study types, base fluids, nanoparticle chemistries and volume concentrations across the included study, with explicit denominators;
- (3) to appraise the reporting quality of the included studies against criteria relevant to nanofluid collector experimentation, in particular uncertainty analysis and suspension stability;
- (4) to examine the comparability of reported enhancement percentages across studies, and to identify the methodological conditions under which such percentages can legitimately be compared; and
- (5) to set out reporting requirements and research priorities for future work in the field.

Section 2 sets out the review methodology. Sections 3 and 4 give the necessary background on flat-plate collectors and nanofluids respectively. Section 5 synthesises the included literature chronologically. Section 6 reports the quantitative distributions and the quality appraisal. Section 7 presents the comparative survey tables. Section 8 develops the argument concerning base-fluid control and cross-study comparability. Section 9 identifies research gaps, Section 10 concludes.

## II. REVIEW METHODOLOGY

This review was conducted according to a protocol specified before screening began and is reported in accordance with the PRISMA 2020 statement. The protocol was not pre-registered; this is acknowledged as a limitation in Section 9.4.

### 2.1 Research questions

The review was designed to answer five questions:

- RQ1. Which nanoparticle chemistries, base fluids and volume concentrations have been investigated in flat-plate solar collectors between 2015 and 2025, and in what proportions?
- RQ2. What magnitudes of thermal and exergetic enhancement are reported, and against what baselines?
- RQ3. How has the balance of experimental, numerical and hybrid methodologies evolved over the period?
- RQ4. What is the reporting quality of the included studies, particularly with respect to measurement uncertainty and suspension stability?
- RQ5. To what extent are reported enhancement percentages comparable across studies?

### 2.2 Information sources and search strategy

Four bibliographic databases were searched: Scopus, Web of Science Core Collection, ScienceDirect and Google Scholar. Google Scholar was used only for backward and forward citation chasing, not as a primary source, because its result set is not reproducible. Searching was restricted to peer-reviewed journal articles published between 1 January 2015 and 30 June 2025 and written in English. Reference lists of all included studies and of prior reviews were screened manually for additional eligible records (backward snowballing). The final search was executed in July 2025.

The following Boolean strategy was applied to title, abstract and keyword fields, with database-specific syntax adjustments:

*("nanofluid\*" OR "nano-fluid\*" OR "nanoparticle suspension") AND ("flat plate solar collector" OR "flat-plate solar collector" OR "FPSC" OR "flat plate collector" OR "solar water heater") AND ("thermal efficiency" OR "energy efficiency" OR "exergy" OR "heat transfer" OR "Nusselt")*

### 2.3 Eligibility criteria

Records were assessed against the following criteria, applied in order.

**Inclusion criteria.** A record was eligible if it (i) reported an original experimental, numerical or combined investigation; (ii) concerned a flat-plate solar collector or a flat-plate photovoltaic-thermal collector operating in solar-thermal mode; (iii) employed a nanofluid or hybrid nanofluid as the working fluid; (iv) reported at least one quantitative thermal performance outcome (thermal efficiency, energy efficiency, exergy efficiency, Nusselt number, heat-transfer coefficient, useful heat gain, outlet temperature rise or thermal conductivity of the working fluid); and (v) was published in a peer-reviewed journal between January 2015 and June 2025.

**Exclusion criteria.** A record was excluded if it (i) concerned only evacuated-tube, parabolic-trough, linear Fresnel or dish collectors, except where a flat-plate collector was included as a directly compared configuration; (ii) was a review, editorial, conference abstract, book chapter or thesis; (iii) reported nanofluid property measurements without any collector-level performance outcome; (iv) concerned direct-absorption or nanofluid-based photovoltaic cooling without a flat-plate thermal collector; (v) presented insufficient methodological detail to permit extraction of the fields listed in Section 2.5; or (vi) was not available in English.

## 2.4 Study selection

Records retrieved from the four sources were merged and de-duplicated. Titles and abstracts were screened against the eligibility criteria, and the full text of every record surviving that stage was retrieved and assessed. Screening was performed independently by both authors; disagreements were resolved by discussion, and inter-rater agreement at the title-and-abstract stage was recorded. The selection process is summarised in the PRISMA 2020 flow diagram (Figure 1), and the decision for every screened record is given in the supplementary dataset.

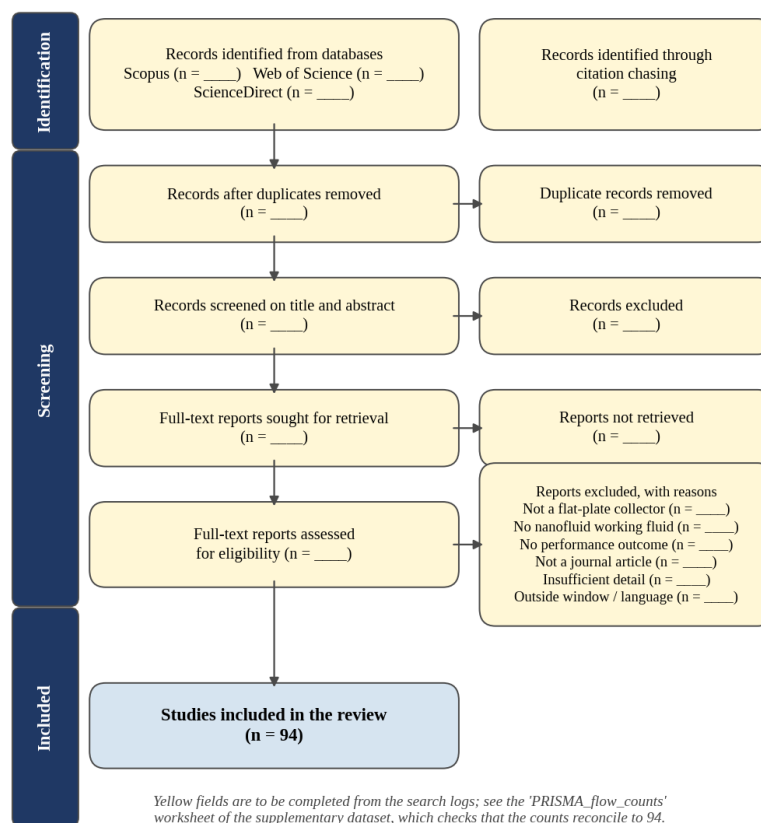


Figure 1: PRISMA 2020 flow diagram for the identification, screening and inclusion of studies.

Ninety-four studies met all eligibility criteria and were retained for extraction and synthesis. Each is supported by a full bibliographic record, so that the reference list contains exactly one entry per included study and the corpus can be reconstructed from the reference list alone.

## 2.5 Data extraction

A standardised extraction form was applied to every included study. The following fields were recorded: first author and year; study type (experimental, numerical or combined); collector configuration and circulation mode where stated; base fluid; nanoparticle chemistry; whether the formulation was single-component or hybrid; nanoparticle size where reported; concentration values and the unit in which they were expressed (vol% or wt%); surfactant or functionalisation where used; reported stability duration; the performance metric reported; the numerical value of that metric; the baseline against which any enhancement was expressed; and whether an uncertainty analysis was reported. Extraction was performed by the first author and independently verified by the second on a randomly selected 20% of the study.

Concentration units were recorded as reported and were not converted, because the particle densities required for a vol%–wt% conversion are unstated in many source articles. Where a study reported a range of concentrations, the maximum tested value was used for the banding analysis in Section 6.4, and this convention is stated explicitly wherever those figures are quoted.

## 2.6 Quality and risk-of-bias appraisal

No established risk-of-bias instrument exists for nanofluid collector experiments, so a seven-item reporting-quality checklist was developed for this review, drawing on the reporting elements that determine whether a reported enhancement can be interpreted and reproduced. Each item was scored as reported (1) or not reported (0), giving a score from 0 to 7. The items are:

- Q1. Is the collector geometry specified (aperture area, riser diameter, tilt angle)?
- Q2. Is the nanoparticle size and the synthesis or procurement route specified?
- Q3. Is the suspension preparation method described, including surfactant or functionalisation where used?
- Q4. Is suspension stability assessed, and over what duration?
- Q5. Is a propagated measurement uncertainty or error analysis reported?
- Q6. Is the baseline against which enhancement is expressed explicitly identified, and was it measured on the same rig?
- Q7. Are the ambient or boundary conditions during testing reported (irradiance, ambient temperature, flow rate)?

Scores were assigned during full-text assessment and are reported per study in the supplementary dataset. Studies were not excluded on the basis of their score; the appraisal is used in Section 6.6 to characterise the evidence base and to weight the confidence attached to aggregate statements. Items Q5 and Q6 are treated as the principal indicators of risk of bias, because a study

that reports neither an uncertainty band nor an identified baseline cannot support a claim that a given percentage enhancement is distinguishable from experimental scatter.

## 2.7 Synthesis method and denominator conventions

A formal meta-analysis was not attempted. The included studies differ in collector geometry, circulation mode, irradiance conditions, performance definition and baseline fluid to an extent that pooling effect sizes would produce a figure without physical meaning. The synthesis is therefore structured and quantitative but not meta-analytic: distributions are reported with explicit denominators, and enhancement magnitudes are reported by category rather than pooled.

Two denominator conventions are used throughout and are stated at every point of use, because their conflation is a recurring source of error in this literature:

- (1) Share of studies. The denominator is the 94 included studies. A study is counted once. This convention is used for study type, base fluid, hybrid prevalence and concentration band.
- (2) Share of pairings. The denominator is the 134 distinct nanoparticle-family / study pairings recorded, since a single study frequently tests several chemistries. This convention is used for nanoparticle prevalence, and figures computed on it do not sum to the number of studies.

Where a study tested several concentrations, the maximum tested value determines its band. Where a study tested several base fluids, it is counted once under each. These conventions, and the raw data, are supplied in the deposited dataset so that any alternative convention can be applied by a reader who prefers it.

## 2.8 Availability of the extracted dataset

The complete extracted dataset underlying every quantitative statement in this review is provided as supplementary material (see Availability of Data and Materials). It contains one row per included study, the extraction fields listed in Section 2.5, the quality-appraisal scores from Section 2.6, and the derived category assignments used in Section 6. A further worksheet reproduces each aggregate statistic reported in this paper together with the formula and cell range from which it was computed, so that every percentage can be traced to the underlying records.

## III. FLAT-PLATE SOLAR COLLECTORS

The flat-plate solar collector is the most widely deployed solar collector configuration, and the simplest to design, install and maintain. In essence it is a shallow rectangular enclosure with a transparent cover, typically tempered glass or polycarbonate, selected to admit solar radiation with minimal reflection and absorption loss (Figure 2). An absorber plate of steel, copper or aluminium, coated with a selective absorbing layer, intercepts the transmitted radiation and transfers the absorbed energy to a working fluid circulating through bonded riser tubes.

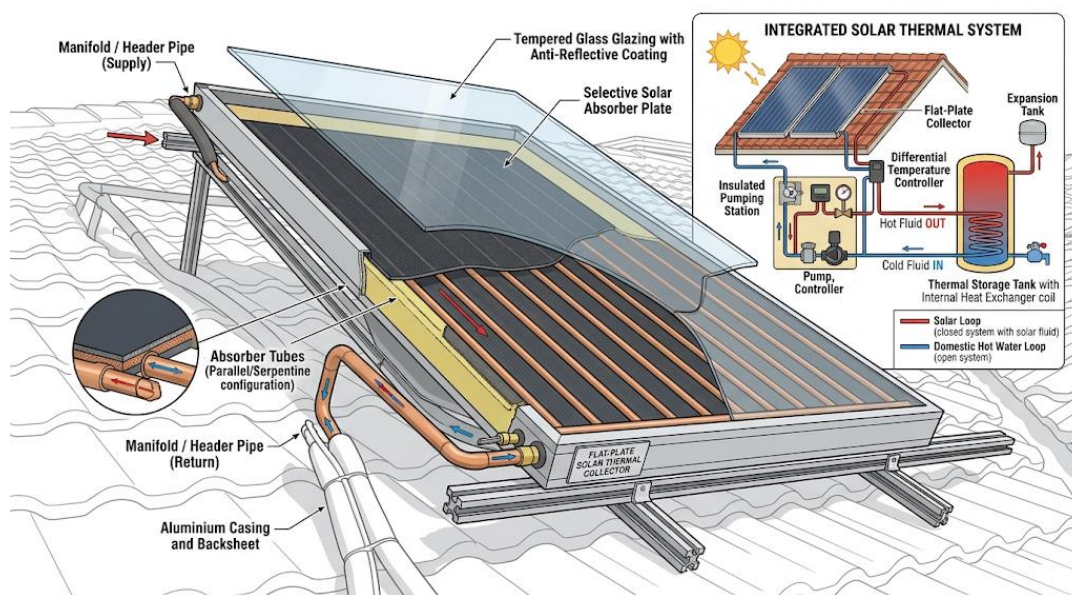


Figure 2: Flat-plate solar thermal collector installation.

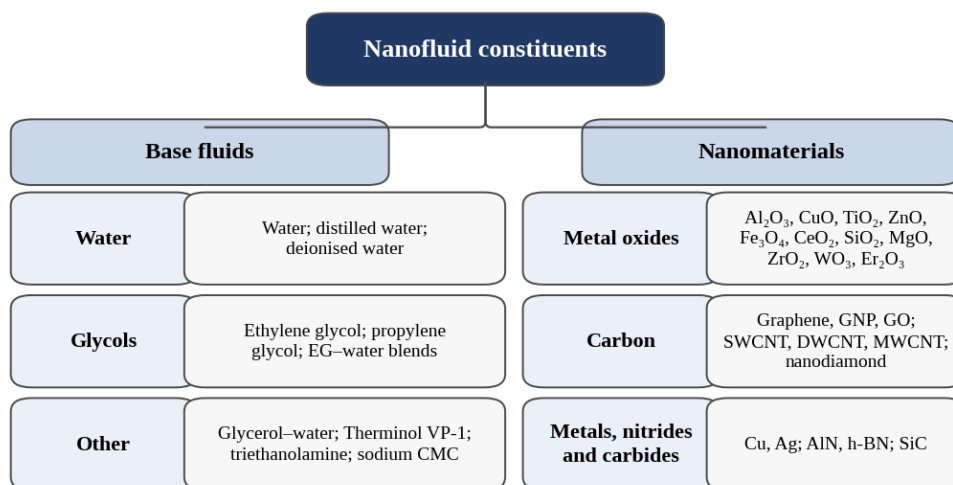
Flat-plate collectors are normally installed at a fixed orientation chosen to maximise annually integrated incident radiation. In the northern hemisphere the collector faces south, and the tilt angle from horizontal is set approximately equal to the local latitude, adjusted by  $\pm 10\text{--}15^\circ$  according to whether winter or summer performance is prioritised. Because flat-plate collectors accept both direct and diffuse radiation, they perform acceptably across a wide range of climates, and they are applied in solar-assisted heat pumps, solar desalination, industrial process heat, space heating and domestic hot-water production.

## IV. NANOFLUIDS

Nanofluids are engineered heat-transfer fluids in which nanometre-scale solid particles are stably dispersed in a conventional base fluid. The concept was introduced formally in 1995 by Choi at Argonne National Laboratory, who showed that suspending nanoparticles in a base fluid could substantially raise its effective thermal conductivity. Nanofluids have since been investigated for solar energy systems, heat exchangers, refrigeration, electronics cooling and biomedical devices.

The nanoparticles employed fall into several families (Figure 3): metals such as Cu and Ag; metal oxides such as  $\text{Al}_2\text{O}_3$ , CuO,  $\text{TiO}_2$ , ZnO,  $\text{Fe}_3\text{O}_4$ ,  $\text{CeO}_2$ ,  $\text{SiO}_2$  and MgO; carbon allotropes including graphene nanoplatelets, graphene oxide and single-, double-

and multi-walled carbon nanotubes; metal nitrides such as AlN and hexagonal boron nitride; and metal carbides such as SiC. More recent work has introduced nanodiamond and rare-earth oxides such as Er<sub>2</sub>O<sub>3</sub> [71]. The most widely used base fluids are water, ethylene glycol, propylene glycol and their binary mixtures, with specialised fluids such as Therminol VP-1 [45], glycerol–water blends [85] and pentaethylene glycol [8] appearing in a small number of studies.



*Magnetite is Fe<sub>3</sub>O<sub>4</sub>. Formulae combining two or more of the nanomaterials above are classified as hybrid nanofluids (22.3% of the reviewed corpus).*

Figure 3: Classification of base fluids and nanomaterials used in flat-plate solar collector studies.

The thermophysical properties of interest for solar-thermal duty are increased effective thermal conductivity, modified viscosity and density, altered specific heat capacity, improved surface wettability and changed radiation-absorption characteristics. A well-formulated nanofluid offers high colloidal stability, a large particle specific surface area, lower clogging propensity than conventional slurries, and thermal properties that can be tuned through particle type, size, shape and volume fraction.

Practical deployment nonetheless faces several persistent obstacles: long-term stability and particle sedimentation; increased viscosity and the associated pumping penalty at higher loadings; potential toxicity and environmental concerns; production cost and scale-up; and inconsistency in reported thermophysical property data between laboratories. These constraints have motivated continued work on surface functionalisation [7], surfactant selection and green synthesis routes [9], and they bear directly on the quality-appraisal items.

## V. SYNTHESIS OF THE INCLUDED LITERATURE

This section synthesises the 94 included studies chronologically, in five periods. Individual results are reported as stated by their authors; the comparability of the percentages quoted is examined critically in Section 8, and readers should note in advance that enhancement figures drawn from different studies are expressed against different baselines.

### 5.1 Establishing baselines (2015–2017)

The earliest period in the review window is characterised by systematic experimental evaluation of single-component nanofluids, establishing the performance improvements attainable in principle. He et al. [38] conducted one of the first comparative experimental studies, reporting that Cu nanoparticles dispersed in water at 0.1 and 0.2 vol% produced base-fluid temperature increases of 12.24% and 24.52% respectively. Meibodi et al. [53] showed that SiO<sub>2</sub> nanoparticles in an ethylene-glycol–water mixture at loadings up to 1 vol% yielded collector efficiency improvements of 4–8%. Shojaeizadeh et al. [76] reported that an Al<sub>2</sub>O<sub>3</sub>–water nanofluid permitted reductions in optimal inlet temperature and fluid mass flow rate of approximately 2% and 68% respectively, indicating scope for more compact collector configurations.

Colangelo et al. [27] investigated Al<sub>2</sub>O<sub>3</sub> at 3 vol% and reported a thermal efficiency increase of 11.8%. Said et al. [67] modelled SWCNTs in water numerically and obtained maximum exergy and energy efficiencies of 26.25% and 95.12%. Sabiha et al. [65] demonstrated experimentally that SWCNT nanofluid raised collector efficiency by 71.84% relative to pure water, while Said et al. [66] reported a 6% thermal conductivity enhancement with TiO<sub>2</sub>–water nanofluid together with energy and exergy efficiency improvements of 76.6% and 16.9%. Verma et al. [89] investigated MgO nanoparticles in water and reported thermal and exergetic efficiency enhancements of 9.34% and 32.23%.

Ahmadi et al. [2] reported an 18.87% thermal efficiency enhancement at very low graphene-nanoplatelet loadings of 0.01–0.02 vol%. Vincely and Natarajan [92] confirmed an 11.5% collector efficiency increase at 0.02 vol% graphene oxide, and Salavati Meibodi et al. [54] reported an exergy efficiency of 62.7% for SiO<sub>2</sub> in an ethylene-glycol–water mixture. Verma et al. [90] conducted a comparative experimental study across five nanoparticle types (Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, TiO<sub>2</sub>, CuO and graphene) in water at 0.75 vol%, finding that carbon nanotubes delivered the highest exergy and energy efficiencies at 29.32% and 23.47%. Tahat and Benim [87] investigated a hybrid Al<sub>2</sub>O<sub>3</sub>/CuO nanofluid in ethylene-glycol–water and reported collector efficiency improvements of up to 45%, among the highest gains reported in this period. Kang et al. [42] achieved a heat efficiency of 74.9%, representing a 14.8% improvement over the base fluid with Al<sub>2</sub>O<sub>3</sub> nanoparticles. The efficiency improvements reported across this period are compared in Figure 4.

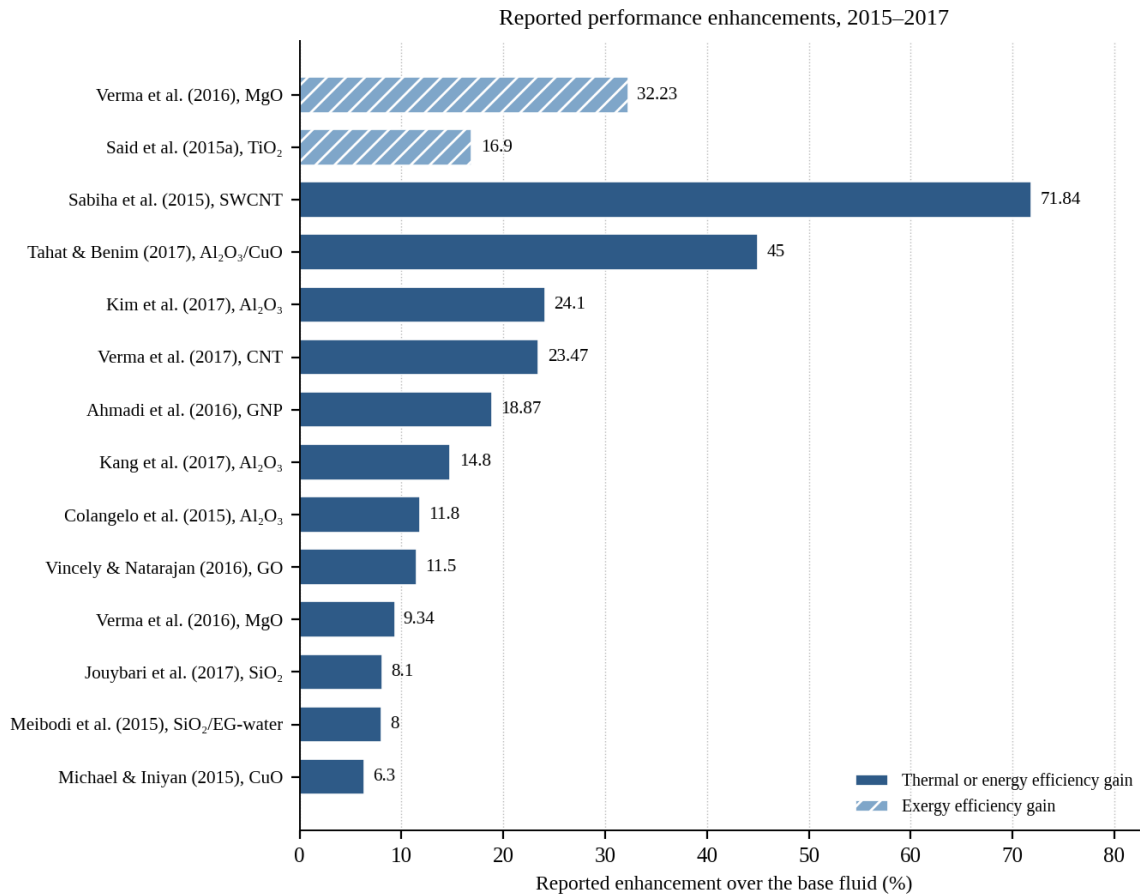


Figure 4: Reported performance enhancements over the base fluid, 2015–2017 studies.

## 5.2 Hybrid nanofluids and diversification (2018–2019)

Research into hybrid nanofluids, comprising two or more nanoparticle types, expanded during 2018–2019 in pursuit of synergistic property improvements. The hybrid concept for FPSCs was validated by Farajzadeh et al. [33], who showed that combining Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> nanoparticles at 0.1 vol% produced a 26% increase in thermal efficiency. Ameri and Eshaghi [14] reported a system thermal efficiency of 83.97% with an Fe<sub>3</sub>O<sub>4</sub>–water nanofluid, a notable result for a single-component formulation. Ziyadanogullari et al. [94] compared Al<sub>2</sub>O<sub>3</sub>, CuO and TiO<sub>2</sub> and found a maximum collector performance improvement of 63.71%, while Kiliç et al. [47] found that TiO<sub>2</sub> at 2 vol% raised peak efficiency to 48.67% against 36.20% for pure water.

Verma et al. [91] extended their earlier work by simulating a hybrid CuO/MgO/MWCNT nanofluid numerically, reporting energy-efficiency and collector-energy improvements of 25.1% and 16.28%. Sundar et al. [79, 80] carried out extensive experimental studies with Al<sub>2</sub>O<sub>3</sub>–water nanofluids, reporting collector performance improvements of up to 24.1% and thermal efficiency increases of 18%. Michael et al. [56] used CeO<sub>2</sub> nanoparticles in water to reach a maximum efficiency of 78.2%, 21.5% above pure water. Akram et al. [5] assessed environmentally treated graphene nanoplatelets and achieved a maximum thermal efficiency of 78%. Gangadevi and Vinayagam [35] reported peak electrical and thermal efficiencies of 15% and 82% with a hybrid Al<sub>2</sub>O<sub>3</sub>/CuO nanofluid, and Alawi et al. [8] used treated graphene nanoplatelets in pentaethylene glycol to raise efficiency by 13.3%. The enhancements reported across this period are compared in Figure 5.

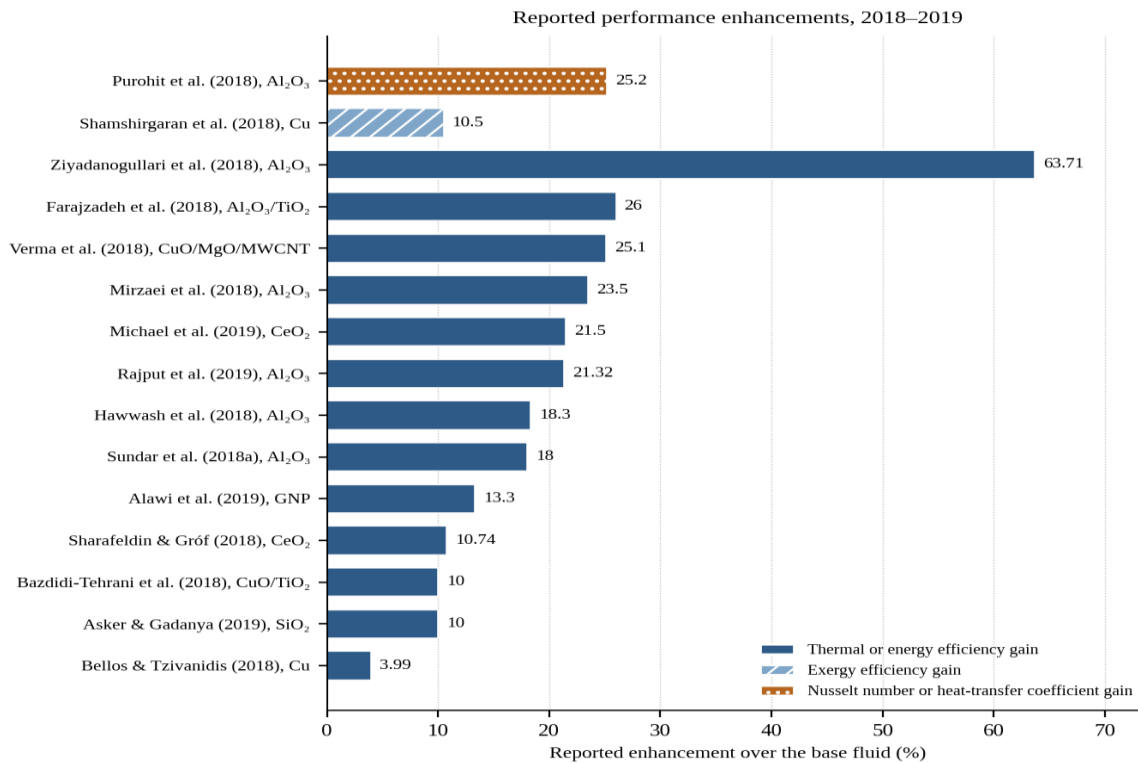


Figure 5: Reported performance enhancements over the base fluid, 2018–2019 studies.

### 5.3 High-efficiency hybrid systems (2020–2021)

The 2020–2021 period is notable for the number of studies reporting collector efficiencies above 80%, particularly from hybrid formulations, and for the increasing use of numerical modelling alongside experiment. Hussein et al. [39] reported a hybrid h-BN/CF-GNP with CF-MWCNT nanofluid in distilled water achieving a collector efficiency of up to 85%, with increasing nanoparticle concentration raising both thermal output and outlet temperature. Lee et al. [51] used a hybrid MWCNT/ $\text{Fe}_3\text{O}_4$  nanofluid in water at 0.003–0.015 vol% to reach a maximum efficiency of 80.3%, 17.6% above the base fluid. Sundar et al. [82] studied nanodiamond nanoparticles in water and reported heat transfer and Nusselt number increases of 52.33% and 32.31%, highlighting the potential of non-traditional carbon-based particles. Stalin et al. [78] found that  $\text{CeO}_2$  in water achieved efficiencies 28.07% above the base fluid.

Bezaatpour and Rostamzadeh [21, 22] investigated  $\text{Fe}_3\text{O}_4$  nanofluids numerically at several concentrations, reporting collector energy efficiency improving from 44.4% to 61.7% in one configuration and energy and exergy gains of 5.83% and 3.21% in another. Eltaweel et al. [32] reported that MWCNT nanofluids at very low loadings (0.005–0.05 vol%) raised the average Nusselt number by nearly 48%. Kumar et al. [49] demonstrated 24% thermal efficiency gains with graphene nanofluids, and Khetib et al. [46] found a 63.46% increase in Nusselt number using a double-walled carbon nanotube– $\text{TiO}_2$  hybrid. The enhancements reported in this period are summarised in Figure 6.

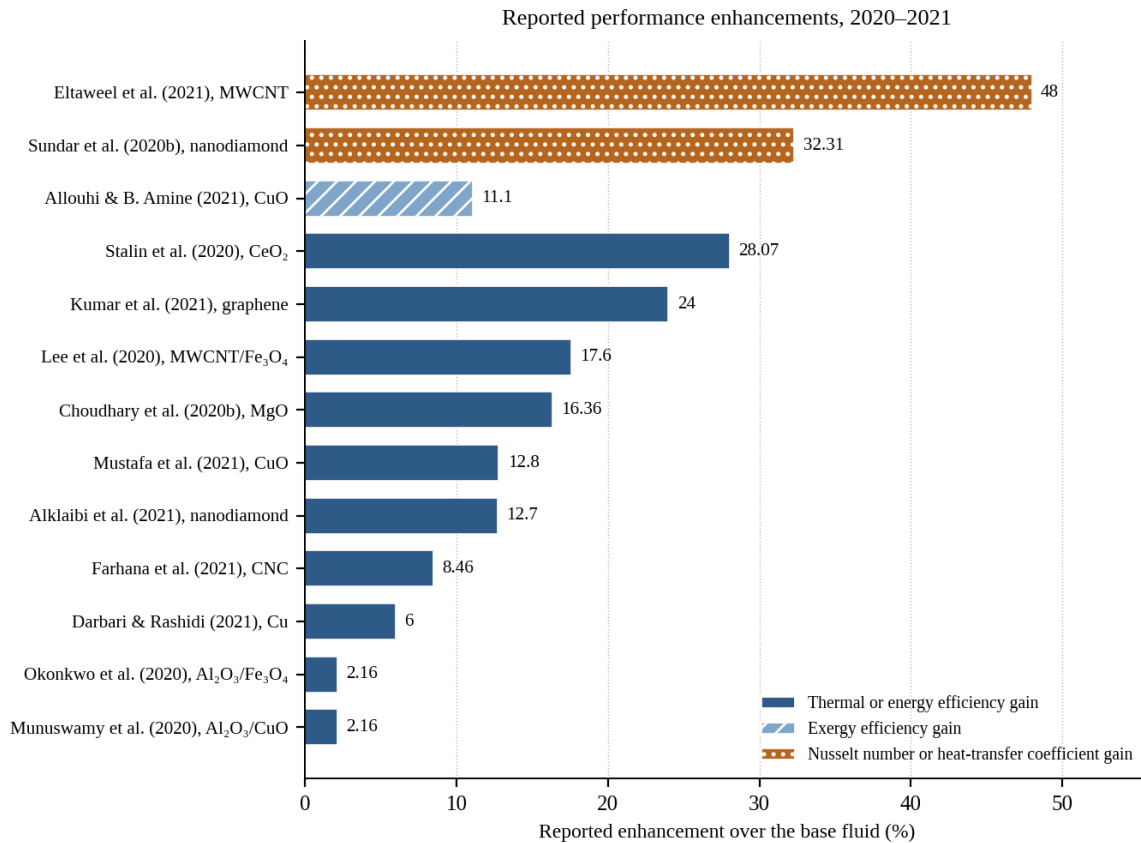


Figure 6: Reported performance enhancements over the base fluid, 2020–2021 studies.

#### 5.4 Machine learning and emerging nanoparticles (2022–2023)

Between 2022 and 2023 the field shifted toward more sophisticated formulations, integration with thermal storage, and the application of machine learning to modelling and optimisation. Suthahar et al. [86] achieved an average instantaneous thermal efficiency of 84.85% using Al<sub>2</sub>O<sub>3</sub> in water at 0.1–0.5 vol%, and Ashour et al. [16] documented an average efficiency of 81.64% with a ZnO–CuO hybrid. Elshazly et al. [30] contributed to the economics of hybrid formulations by showing that a 50:50 MWCNT/Al<sub>2</sub>O<sub>3</sub> mixture offered efficiency increases of up to 29% while also recommending it on environmental-safety grounds relative to pure MWCNT nanofluids.

Sundar and Chandra Mouli [84] combined experiment with artificial neural network modelling, using the Levenberg–Marquardt algorithm to predict the performance of an MgO–water nanofluid system, and reported a maximum Nusselt number increase of 37.28% at 1.0 vol%. Akram et al. [7] demonstrated the importance of particle stability by showing that covalent functionalisation of Fe<sub>3</sub>O<sub>4</sub> magnetite with polyethylene glycol maintained suspension stability for 30 days while achieving a 13.83% thermal efficiency enhancement — one of the few studies in the study to report a stability duration alongside a performance figure (Section 6.6). Ajeena et al. [3] achieved a 26.2% thermal efficiency improvement and an exergy efficiency of approximately 16.05% using ZrO<sub>2</sub> nanoparticles at 0.1 vol%, one of the strongest results obtained at so low a loading. The enhancements reported across this period are compared in Figure 7.

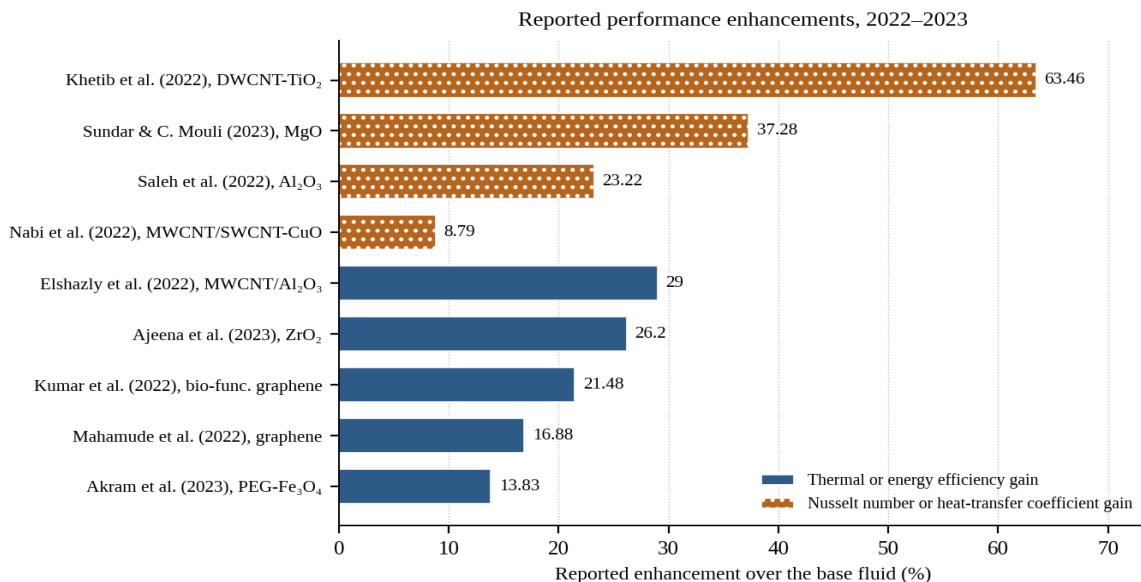


Figure 7: Reported performance enhancements over the base fluid, 2022–2023 studies.

## 5.5 Integration, green synthesis and rare-earth nanofluids (2024–2025)

The most recent studies reflect a maturing field increasingly concerned with integration alongside complementary technologies (phase-change materials, vortex generators, thermosyphons), with sustainability, and with novel nanoparticle chemistries. Bashirnezhad et al. [18] achieved a peak energy efficiency of 86.34% and an exergy efficiency of 32.7% using a hybrid CuO–MWCNT nanofluid with perforated twisted-tape inserts, illustrating the synergy between nanofluid enhancement and passive turbulence promotion.

Chen et al. [24] optimised a solar water-heating system combining nanofluids with phase-change materials, finding that a CuO nanofluid with 20 vol% PCM achieved a thermal storage efficiency of 94.2%. Alktranee et al. [11] corroborated the PCM–nanofluid approach, demonstrating a 26% efficiency enhancement with an MWCNT–Al<sub>2</sub>O<sub>3</sub> hybrid at 0.2 vol%. Khan et al. [45] employed a two-phase CFD mixture model to study FPSCs with vortex generators and a hybrid GO/SiO<sub>2</sub> nanofluid in Therminol VP-1, reporting Nusselt number enhancements of up to 107.4% — the highest enhancement factor for this parameter in the study, and one that reflects the compounding of geometry-based flow enhancement with improved nanofluid conductivity rather than a nanoparticle effect alone.

Alfellag et al. [9] introduced a green-synthesised hybrid nanofluid combining clove-treated MWCNTs and hexagonal boron nitride, achieving an 18.33% energy efficiency gain and an 18.2% reduction in required collector area. Sathish and Santhosh [71] conducted the first study to employ rare-earth erbium(III) oxide nanoparticles in FPSCs, finding that higher concentrations yielded thermal efficiency peaking at 61.6% alongside measurable CO<sub>2</sub> mitigation. Sundar et al. [85] investigated a SiO<sub>2</sub>–glycerol/water nanofluid in a thermosyphon configuration using ANN modelling, reporting a 25.87% increase in thermal conductivity at 100 °C and a 4.33-fold increase in exergy efficiency at midday relative to the base fluid.

Abu-Zeid et al. [1] conducted a direct comparative study of FPSCs and parabolic-trough collectors using MWCNT/ethylene-glycol nanofluids, reporting average thermal efficiencies of 64.1% and 80.6% respectively together with significant CO<sub>2</sub> savings. Ajeena et al. [4] demonstrated that SiC nanoparticles increased thermal conductivity by 30.3% and achieved a peak thermal efficiency of 77.43%, a 35.53% improvement over the base liquid. The performance enhancements reported in this period are summarised in Figure 8.

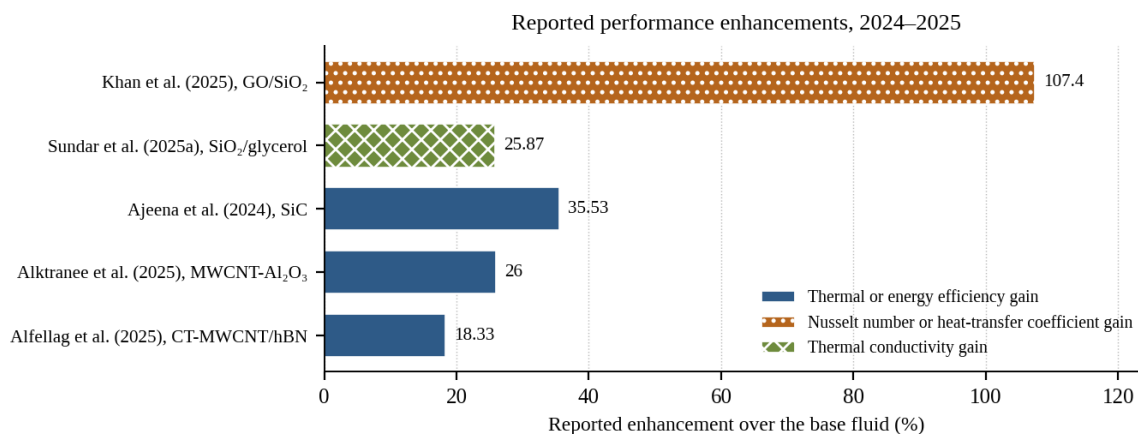


Figure 8: Reported performance enhancements over the base fluid, 2024–2025 studies.

## VI. QUANTITATIVE SYNTHESIS

This section reports the distribution of the included study across study type, base fluid, nanoparticle chemistry and concentration, together with the reporting-quality appraisal. Every figure quoted below is accompanied by its denominator and can be recomputed from the deposited dataset (Section 2.8). Where a figure differs from that given in earlier reviews of this literature, the difference is usually attributable to the denominator convention rather than to the underlying records, and this is noted where relevant.

### 6.1 Study type

Experimental investigations account for 63 of the 94 included studies (67.0%). Purely numerical studies account for 24 (25.5%) and combined experimental–numerical studies for 7 (7.4%). The dominance of experimental work reflects the empirical character of nanofluid research, in which real-world validation remains essential given the difficulty of predicting suspension behaviour from first principles. The proportion of numerical and combined work has nonetheless grown markedly in the post-2020 period, driven by the adoption of computational fluid dynamics and, more recently, artificial neural network frameworks [84, 85]. The distribution is given in Table 1.

Table 1: Distribution of included studies by methodology. Denominator: 94 included studies.

| Study type                          | n  | % of 94 studies |
|-------------------------------------|----|-----------------|
| Experimental                        | 63 | 67.0%           |
| Numerical                           | 24 | 25.5%           |
| Combined experimental and numerical | 7  | 7.4%            |
| Total                               | 94 | 100.0%          |

## 6.2 Base fluid

Water in some form is the dominant base fluid, appearing in 83 of the 94 included studies (88.3%). Disaggregated, plain water accounts for 70 studies (74.5%) and distilled or deionised water for a further 12 (12.8%); one study used water with a sodium carboxymethyl cellulose additive [18]. The dominance of water reflects its high heat capacity, wide availability, low cost, low viscosity and environmental compatibility.

Ethylene glycol and ethylene-glycol–water mixtures constitute the principal alternative, appearing in 8 studies (8.5%), and are used predominantly where freeze protection is required in cold climates [1, 15, 26, 43, 53, 54, 87]. The remaining base fluids each appear once: pentaethylene glycol [8], Therminol VP-1 [45] and a glycerol–water blend [85]. The choice of base fluid materially influences suspension viscosity, stability and overall heat-transfer performance, and it also determines the baseline against which enhancement is measured — a point developed in Section 8. The full distribution is given in Table 2.

Table 2: Distribution of included studies by base fluid. Denominator: 94 included studies; studies testing more than one base fluid are counted once under each.

| Base fluid                               | n  | % of 94 studies |
|------------------------------------------|----|-----------------|
| Water (plain)                            | 70 | 74.5%           |
| Distilled or deionised water             | 12 | 12.8%           |
| Ethylene glycol or EG–water              | 8  | 8.5%            |
| Water with sodium CMC                    | 1  | 1.1%            |
| Pentaethylene glycol                     | 1  | 1.1%            |
| Therminol VP-1                           | 1  | 1.1%            |
| Glycerol–water (30:70)                   | 1  | 1.1%            |
| All water-based (sum of rows 1, 2 and 4) | 83 | 88.3%           |

## 6.3 Nanoparticle chemistry

Nanoparticle prevalence is reported here as a share of nanoparticle-family / study pairings rather than as a share of studies, because 27 of the 94 studies tested more than one chemistry. The 94 studies yield 134 such pairings. Reporting prevalence against the study denominator instead would cause the categories to sum to substantially more than 100%, and the conflation of these two denominators is a recurrent source of confusion in this literature.

On the pairing denominator,  $\text{Al}_2\text{O}_3$  is the most extensively studied nanoparticle, accounting for 33 pairings (24.6%), followed by CuO with 19 (14.2%) and  $\text{TiO}_2$  with 12 (9.0%). Carbon nanotubes also account for 12 pairings (9.0%) and the graphene family — graphene, graphene nanoplatelets and graphene oxide — for 10 (7.5%), reflecting their exceptional intrinsic thermal conductivity.  $\text{SiO}_2$ ,  $\text{Fe}_3\text{O}_4$  and the ferrites, metallic particles (Cu, Ag), MgO,  $\text{CeO}_2$  and ZnO account for the remainder of the single-component work. The complete distribution is given in Table 3.

Table 3: Distribution of nanoparticle chemistries. Percentages quoted in the text use the pairing denominator (134).

| Nanoparticle family                                                                                                 | Pairings | % of 134 pairings | % of 94 studies |
|---------------------------------------------------------------------------------------------------------------------|----------|-------------------|-----------------|
| $\text{Al}_2\text{O}_3$                                                                                             | 33       | 24.6%             | 35.1%           |
| CuO                                                                                                                 | 19       | 14.2%             | 20.2%           |
| $\text{TiO}_2$                                                                                                      | 12       | 9.0%              | 12.8%           |
| Carbon nanotubes (S/D/MWCNT)                                                                                        | 12       | 9.0%              | 12.8%           |
| Other and novel ( $\text{SiC}$ , nanodiamond, $\text{Er}_2\text{O}_3$ , h-BN, $\text{ZrO}_2$ , $\text{WO}_3$ , CNC) | 11       | 8.2%              | 11.7%           |
| Graphene family (graphene, GNP, GO)                                                                                 | 10       | 7.5%              | 10.6%           |
| $\text{SiO}_2$                                                                                                      | 8        | 6.0%              | 8.5%            |
| Metallic (Cu, Ag)                                                                                                   | 8        | 6.0%              | 8.5%            |
| $\text{Fe}_3\text{O}_4$ and ferrites                                                                                | 7        | 5.2%              | 7.4%            |
| MgO                                                                                                                 | 5        | 3.7%              | 5.3%            |
| $\text{CeO}_2$                                                                                                      | 5        | 3.7%              | 5.3%            |
| ZnO                                                                                                                 | 4        | 3.0%              | 4.3%            |
| Total                                                                                                               | 134      | 100.0%            | —               |

Hybrid nanofluids, comprising two or more nanoparticle types in a single suspension, appear in 21 of the 94 included studies (22.3%), and are the fastest-growing category in the study: of these 21 studies, 16 were published in 2020 or later. Combinations showing particularly strong reported results include MWCNT– $\text{Al}_2\text{O}_3$  [11, 30], CuO–MgO–MWCNT [91],  $\text{Al}_2\text{O}_3$ –CuO [35, 59, 87], DWCNT– $\text{TiO}_2$  [46] and GO– $\text{SiO}_2$  [45]. Novel nanoparticle types introduced recently include  $\text{SiC}$  [4], nanodiamond [82],  $\text{Er}_2\text{O}_3$  [71], h-BN [9], clove-treated MWCNTs [9],  $\text{ZrO}_2$  [3] and bio-functionalised graphene [50], expanding the material palette available for solar-thermal duty.

## 6.4 Nanoparticle volume concentration

Volume concentration is one of the principal determinants of nanofluid thermal performance, and the study shows clearly that appreciable improvement is attainable at low loading. Studies are banded here by their maximum tested concentration, since most test a range; the convention is stated because banding by minimum or by mean would yield a materially different distribution.

On this convention, 28 studies (29.8%) test no higher than 0.1 vol%, and a further 24 (25.5%) test between 0.1 and 0.5 vol%, so that 52 studies (55.3%) operate entirely at or below 0.5 vol%. Fourteen studies (14.9%) extend to between 0.5 and 1.0 vol%, 12 (12.8%) to between 1.0 and 2.0 vol%, and 13 (13.8%) above 2.0 vol%. Three studies (3.2%) do not state a concentration in a form permitting banding. The concentration is expressed as wt% rather than vol% in 5 studies; these were banded on their stated numerical value without conversion, since the particle densities required for conversion are not reported. The banding is summarised in Table 4.

Table 4: Distribution of included studies by maximum tested nanoparticle concentration. Denominator: 94 included studies.

| Maximum tested concentration | n  | % of 94 studies |
|------------------------------|----|-----------------|
| ≤ 0.1 vol%                   | 28 | 29.8%           |
| > 0.1 and ≤ 0.5 vol%         | 24 | 25.5%           |
| > 0.5 and ≤ 1.0 vol%         | 14 | 14.9%           |
| > 1.0 and ≤ 2.0 vol%         | 12 | 12.8%           |
| > 2.0 vol%                   | 13 | 13.8%           |
| Not stated in bandable form  | 3  | 3.2%            |
| Cumulative ≤ 0.5 vol%        | 52 | 55.3%           |
| Total                        | 94 | 100.0%          |

## 6.5 Reported thermal and exergy efficiency

The included studies report a wide span of outcomes, from enhancements of a few per cent to a 107.4% increase in Nusselt number [45]. These figures are not commensurable with one another, and the distribution must be read with that in mind: the study reports at least six distinct performance metrics (instantaneous thermal efficiency, average thermal efficiency, energy efficiency, exergy efficiency, Nusselt number and heat-transfer coefficient), expressed sometimes as an absolute value and sometimes as an enhancement relative to a baseline. Aggregating these into a single distribution of ‘efficiency gains’, as earlier reviews have done, conflates quantities with different physical meanings.

The highest absolute thermal efficiencies documented in the study are 86.34% peak energy efficiency with a hybrid CuO–MWCNT nanofluid and perforated twisted tape [18]; 85% with an h-BN/CF-GNP/CF-MWCNT hybrid [39]; 84.85% with Al<sub>2</sub>O<sub>3</sub> [86]; 83.97% with Fe<sub>3</sub>O<sub>4</sub> [14]; and 82% with a hybrid Al<sub>2</sub>O<sub>3</sub>/CuO formulation [35]. Notable exergy efficiency values include 62.7% with SiO<sub>2</sub> in ethylene-glycol–water [54], 32.7% with hybrid CuO–MWCNT and perforated tape [18], 32.23% with MgO [89] and 26.25% with SWCNTs [67]. Exergy analyses, reported in a substantial minority of studies, provide a thermodynamically more rigorous measure of the quality rather than merely the quantity of energy converted, and their wider adoption is recommended in Section 9.

## 6.6 Reporting quality and risk of bias

The seven-item appraisal defined in Section 2.6 was applied to all 94 included studies. The appraisal is not a judgement of the validity of individual results; it characterises whether each study reports the information a reader needs in order to interpret and reproduce its findings.

Reporting is strongest on the items that describe the apparatus and the suspension, and weakest on the items that establish the reliability of the reported enhancement. Collector geometry (Q1), particle characterisation (Q2) and preparation method (Q3) are the best-reported items across the corpus. Suspension stability over a stated duration (Q4) and a propagated measurement uncertainty (Q5) are the least-reported. Explicit identification of the baseline (Q6) is the item that bears most directly on the argument of Section 8: a number of studies report an enhancement percentage without stating whether the baseline was measured on the same rig under the same conditions, or taken instead from a property correlation or an earlier publication.

Two implications follow for the synthesis. First, aggregate statements about the magnitude of nanoparticle-attributable enhancement should be read as indicative rather than precise, because a number of the underlying studies do not report an uncertainty band against which their reported gain can be judged. Second, the comparability problem set out in Section 8 is not a peripheral concern: it is a direct consequence of the Q6 reporting deficiency observed across the corpus.

## VII. COMPARATIVE SURVEY OF INCLUDED STUDIES

Table 5 presents the comprehensive survey of all included studies. The tables reproduce the principal extraction fields; the complete extraction, including quality-appraisal scores, stability durations, particle sizes and baseline identification, is given in the deposited dataset.

Table 5: Comparative survey of nanofluid studies in flat-plate solar collectors, 2015–2025. Abbreviations: Exp., experimental; Num., numerical; EG, ethylene glycol; DW, distilled water. Hybrid formulations are identified by “(hybrid)” in the nanoparticle column.

| Author / Year                    | Study type  | Base fluid           | Nanoparticle                                                                                | Concentration   | Main findings                                                | Ref. |
|----------------------------------|-------------|----------------------|---------------------------------------------------------------------------------------------|-----------------|--------------------------------------------------------------|------|
| Abu-Zeid et al. (2024)           | Exp.        | Water and EG         | MWCNTs                                                                                      | 1 wt%           | FPSC thermal eff. 64.1%, PTSC 80.6%; CO <sub>2</sub> savings | [1]  |
| Ahmadi et al. (2016)             | Exp.        | Water                | Graphene nanoplatelets                                                                      | 0.01, 0.02 vol% | 18.87% increase in thermal efficiency                        | [2]  |
| Ajeena et al. (2023)             | Exp.        | Distilled water      | ZrO <sub>2</sub>                                                                            | 0.025-0.1 vol%  | Thermal eff. +26.2% at 0.1 vol%; exergy eff. ~16.05%         | [3]  |
| Ajeena et al. (2024)             | Exp.        | Distilled water      | SiC                                                                                         | 0.025-0.1 vol%  | Thermal eff. 77.43% (+35.53% over base); k +30.3%            | [4]  |
| Akram et al. (2019)              | Exp.        | Water                | Graphene nanoplatelets (treated)                                                            | 0.025-0.1 vol%  | Maximum thermal efficiency 78%                               | [5]  |
| Akram et al. (2021)              | Exp.        | Water                | GNP, ZnO, SiO <sub>2</sub>                                                                  | 0.025-0.2 vol%  | Thermal conductivity growth 25.68%                           | [6]  |
| Akram et al. (2023)              | Exp. & Num. | Distilled water      | PEG-Fe <sub>3</sub> O <sub>4</sub>                                                          | 0.025-0.1 wt%   | Stable 30 days; thermal eff. +13.83%                         | [7]  |
| Alawi et al. (2019)              | Exp.        | Pentaethylene glycol | Graphene nanoplatelets (treated)                                                            | 0.025-0.1 vol%  | Collector efficiency +13.3%                                  | [8]  |
| Alfellag et al. (2025)           | Exp.        | Distilled water      | CT-MWCNTs/hBN (hybrid)                                                                      | 0.025-0.1 wt%   | Energy eff. +18.33%; collector area -18.2%                   | [9]  |
| Alklaibi et al. (2021)           | Exp.        | Distilled water      | Nanodiamond                                                                                 | 0.2-1 vol%      | Thermal eff. 69.85% (+12.7% over water)                      | [10] |
| Alktranee et al. (2025)          | Exp.        | Deionized water      | MWCNT-Al <sub>2</sub> O <sub>3</sub> (hybrid)                                               | 0.15, 0.2 vol%  | Thermal eff. +26% with PCM bags at 0.2 vol%                  | [11] |
| Allouhi & Benzakour Amine (2021) | Num.        | Water                | CuO, Al <sub>2</sub> O <sub>3</sub> , TiO <sub>2</sub>                                      | 1-3 vol%        | CuO: energy +2.7%, exergy +11.1%                             | [12] |
| Alzahrani et al. (2021)          | Exp.        | Water                | MgO/CuO/MWCNT (hybrid)                                                                      | 0.003-0.02 vol% | Volume fraction boosts solar absorption                      | [13] |
| Ameri & Eshaghi (2018)           | Exp.        | Water                | Fe <sub>3</sub> O <sub>4</sub>                                                              | 1, 2 vol%       | System thermal efficiency 83.97%                             | [14] |
| Aselebe et al. (2024)            | Num.        | Ethylene glycol      | CuO/Al <sub>2</sub> O <sub>3</sub> (hybrid)                                                 | Varying         | Volume fraction enhanced Nu and skin friction                | [15] |
| Ashour et al. (2022)             | Num.        | Water                | ZnO/CuO (hybrid)                                                                            | 0.05-0.15 vol%  | Best average efficiency 81.64%                               | [16] |
| Asker & Gadanya (2019)           | Num.        | Water                | Al <sub>2</sub> O <sub>3</sub> , CeO <sub>2</sub> , Cu, SiO <sub>2</sub> , TiO <sub>2</sub> | 2 vol%          | SiO <sub>2</sub> efficiency increase 10%                     | [17] |
| Bashimezhad et al. (2025)        | Exp.        | Water / sodium CMC   | CuO-MWCNT (hybrid)                                                                          | 0.1 wt%         | Energy eff. 86.34%, exergy eff. 32.7% with perforated tape   | [18] |
| Bazdidi-Tehrani et al. (2018)    | Num.        | Water                | CuO, TiO <sub>2</sub>                                                                       | 0.99, 2.04 vol% | Collector efficiency +~10%                                   | [19] |
| Bellos & Tzivanidis (2018)       | Exp.        | Water                | Cu                                                                                          | 2 vol%          | Energy increase 3.99%                                        | [20] |
| Bezaatpour & Rostamzadeh (2021a) | Num.        | Water                | Fe <sub>3</sub> O <sub>4</sub>                                                              | 2 vol%          | Energy +5.83%, exergy +3.21%                                 | [21] |
| Bezaatpour & Rostamzadeh (2021b) | Num.        | Water                | Fe <sub>3</sub> O <sub>4</sub>                                                              | 0.2 vol%        | Energy efficiency 44.4% -> 61.7%                             | [22] |
| Bianco et al. (2018)             | Num.        | Water                | Al <sub>2</sub> O <sub>3</sub>                                                              | 2, 4, 6 vol%    | HTC and Nu increased 2-15%                                   | [23] |
| Chen et al. (2025)               | Num.        | Water                | Al <sub>2</sub> O <sub>3</sub> , CuO                                                        | Varying         | Thermal storage eff. 94.2% (CuO + 20 vol% PCM)               | [24] |
| Choudhary et al. (2020a)         | Exp.        | Water                | ZnO                                                                                         | 1 vol%          | Maximum thermal efficiency 69.24%                            | [25] |
| Choudhary et al. (2020b)         | Exp.        | EG-distilled water   | MgO                                                                                         | 0.08-0.4 vol%   | Thermal eff. +16.36%; absorbed energy +16.74%                | [26] |
| Colangelo et al. (2015)          | Exp.        | Water                | Al <sub>2</sub> O <sub>3</sub>                                                              | 3 vol%          | Thermal efficiency rose 11.8%                                | [27] |
| Darbari & Rashidi (2021)         | Num.        | Water                | Cu, CuO                                                                                     | 0.01-0.05 vol%  | Collector energy +6% (Cu), +3% (CuO)                         | [28] |
| Edalatpour & Solano (2017)       | Num.        | Water                | Al <sub>2</sub> O <sub>3</sub>                                                              | 1-5 vol%        | Heat transfer coefficient +10 to +65%                        | [29] |
| Elshazly et al. (2022)           | Exp.        | Water                | MWCNT/Al <sub>2</sub> O <sub>3</sub> (hybrid)                                               | 0.005-0.5 wt%   | Hybrid (50:50) efficiency +29%                               | [30] |
| Eltaweel & Abdel-Rehim (2019)    | Exp.        | Distilled water      | MWCNTs                                                                                      | 0.01-0.1 vol%   | Exergy efficiency ~23.35% (+~9%)                             | [31] |
| Eltaweel et al. (2021)           | Exp.        | Water                | MWCNT                                                                                       | 0.005-0.05 vol% | Average Nusselt number +~48%                                 | [32] |
| Farajzadeh et al. (2018)         | Exp. & Num. | Water                | Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub> (hybrid)                                   | 0.1 vol%        | Thermal efficiency +26%                                      | [33] |

| Author / Year                  | Study type  | Base fluid            | Nanoparticle                                                            | Concentration    | Main findings                                                      | Ref. |
|--------------------------------|-------------|-----------------------|-------------------------------------------------------------------------|------------------|--------------------------------------------------------------------|------|
| Farhana et al. (2021)          | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub> , crystal nanocellulose                  | 0.1-0.5 vol%     | Performance +2.48% (Al <sub>2</sub> O <sub>3</sub> ), +8.46% (CNC) | [34] |
| Gangadevi & Vinayagam (2019)   | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub> /CuO (hybrid)                            | 0.05-0.2 vol%    | Electrical 15%, thermal 82%                                        | [35] |
| Genc et al. (2018)             | Num.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 1-3 vol%         | Outlet temperature +7.2%                                           | [36] |
| Hawwash et al. (2018)          | Exp. & Num. | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.1-3 vol%       | Efficiency improved ~18.3%                                         | [37] |
| He et al. (2015)               | Exp.        | Water                 | Cu                                                                      | 0.1, 0.2 vol%    | Temperature rise +12.24% and +24.52%                               | [38] |
| Hussein et al. (2020)          | Exp.        | Distilled water       | hBN/CF-GNP/CF-MWCNT (hybrid)                                            | 0.05-0.1 vol%    | Collector efficiency up to 85%                                     | [39] |
| Jayaprakash & Govindan (2025)  | Num.        | Water, EG, sodium CMC | Fe <sub>3</sub> O <sub>4</sub> , Cu, TiO <sub>2</sub>                   | Varying          | Sodium CMC with TiO <sub>2</sub> superior heat transfer            | [40] |
| Jouybari et al. (2017)         | Exp.        | Distilled water       | SiO <sub>2</sub>                                                        | 0.2-0.6 vol%     | Thermal efficiency +8.1%                                           | [41] |
| Kang et al. (2017)             | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.5-1.5 vol%     | Heat efficiency 74.9% (+14.8% over base)                           | [42] |
| Kashyap et al. (2018)          | Num.        | EG-water              | ZnO                                                                     | 0.02 vol%        | Exergy efficiency +39.17%                                          | [43] |
| Khan & Amirtham (2023)         | Num.        | Distilled water       | TiO <sub>2</sub> -Ag                                                    | 0.1, 0.2 vol%    | Exergy +1.25/+2.54%; energy +0.5/+1.27%                            | [44] |
| Khan et al. (2025)             | Num.        | Therminol VP-1        | GO/SiO <sub>2</sub> (hybrid)                                            | 1.25, 3.25 vol%  | Nusselt number +107.4% with vortex generators                      | [45] |
| Khetib et al. (2022)           | Exp. & Num. | Water                 | DWCNT-TiO <sub>2</sub> (hybrid)                                         | 1-3 vol%         | Average Nusselt number +63.46%                                     | [46] |
| Kilic et al. (2018)            | Exp.        | Water                 | TiO <sub>2</sub>                                                        | 2 vol%           | Efficiency 48.67% vs 36.20% for water                              | [47] |
| Kim et al. (2017)              | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 1 vol%           | Max efficiency 72.4% (+24.1% over base)                            | [48] |
| Kumar et al. (2021)            | Exp.        | Water                 | Graphene                                                                | 0.025-0.1 vol%   | Thermal efficiency +24%                                            | [49] |
| Kumar et al. (2022)            | Exp.        | Distilled water       | Bio-functionalised graphene                                             | 0.025-0.1 vol%   | Max thermal efficiency +21.48%                                     | [50] |
| Lee et al. (2020)              | Exp.        | Water                 | MWCNT/Fe <sub>3</sub> O <sub>4</sub> (hybrid)                           | 0.003-0.015 vol% | Max efficiency 80.3% (+17.6% over base)                            | [51] |
| Mahamude et al. (2022)         | Exp.        | Water                 | Graphene/waste cotton (hybrid)                                          | 0.1-0.5 vol%     | Efficiency 16.88% higher than base                                 | [52] |
| Meibodi et al. (2015)          | Exp.        | EG-water              | SiO <sub>2</sub>                                                        | 0.5-1 vol%       | Efficiency increase ~4-8%                                          | [53] |
| Michael & Iniyan (2015)        | Exp.        | Water                 | CuO                                                                     | 0.05 vol%        | Thermal performance +6.3%                                          | [55] |
| Michael et al. (2019)          | Exp.        | Water                 | CeO <sub>2</sub>                                                        | 0.01 vol%        | Max efficiency 78.2% (+21.5% over water)                           | [56] |
| Mirzaei et al. (2018)          | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.1 vol%         | Average efficiency +23.5%                                          | [57] |
| Moravej et al. (2020)          | Exp.        | Water                 | TiO <sub>2</sub>                                                        | 1-5 vol%         | Max collector efficiency ~78%                                      | [58] |
| Munuswamy et al. (2020)        | Exp. & Num. | Water                 | Al <sub>2</sub> O <sub>3</sub> /CuO (hybrid)                            | 0.2, 0.4 vol%    | Collector efficiency +2.16%                                        | [59] |
| Mustafa et al. (2021)          | Num.        | Water                 | CuO                                                                     | 0.1 vol%         | Solar process efficiency +12.8%                                    | [60] |
| Nabi et al. (2022)             | Num.        | Water                 | MWCNT/SWCNT-CuO (hybrid)                                                | 1-5 vol%         | Average Nusselt number +8.79%                                      | [61] |
| Okonkwo et al. (2020)          | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub> /Fe <sub>3</sub> O <sub>4</sub> (hybrid) | 0.05-0.2 vol%    | Collector heat gain +2.16%                                         | [62] |
| Purohit et al. (2018)          | Num.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 1-6 vol%         | Heat transfer coefficient +25.2%                                   | [63] |
| Rajput et al. (2019)           | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.1-0.3 vol%     | Efficiency +21.32%                                                 | [64] |
| Sabiha et al. (2015)           | Exp.        | Water                 | SWCNTs                                                                  | 0.05-0.2 vol%    | Collector efficiency 71.84% higher than water                      | [65] |
| Said et al. (2015a)            | Exp.        | Water                 | TiO <sub>2</sub>                                                        | 0.1, 0.3 vol%    | k +6%; energy +76.6%, exergy +16.9%                                | [66] |
| Said et al. (2015b)            | Num.        | Water                 | SWCNTs                                                                  | 0.1, 0.3 vol%    | Energy 95.12%, exergy 26.25%                                       | [67] |
| Said et al. (2016a)            | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.1 vol%         | Energy 73.7%, exergy 20.3%                                         | [68] |
| Said et al. (2016b)            | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub> (pH treated)                             | 0.1, 0.3 vol%    | Energy efficiency +83.5%                                           | [69] |
| Salavati Meibodi et al. (2016) | Exp.        | EG-water              | SiO <sub>2</sub>                                                        | 0.5-1 vol%       | Exergy efficiency 62.7%                                            | [54] |
| Saleh et al. (2022)            | Exp.        | Water                 | Al <sub>2</sub> O <sub>3</sub>                                          | 0.1-0.3 vol%     | Thermal eff. 53% -> 65%; Nu +23.22%                                | [70] |
| Sathish & Santhosh (2025)      | Exp.        | Distilled water       | Er <sub>2</sub> O <sub>3</sub>                                          | 0.3-0.9 wt%      | Thermal efficiency 61.6% at peak concentration                     | [71] |
| Shamshirgaran et al. (2018)    | Num.        | Water                 | Cu                                                                      | 1-4 vol%         | Exergy +10.5%, energy +8%                                          | [72] |

| Author / Year                 | Study type  | Base fluid             | Nanoparticle                                                                         | Concentration      | Main findings                                    | Ref. |
|-------------------------------|-------------|------------------------|--------------------------------------------------------------------------------------|--------------------|--------------------------------------------------|------|
| Sharafeldin & Grof (2018)     | Exp.        | Water                  | CeO <sub>2</sub>                                                                     | 0.017-0.067 vol%   | Efficiency improved 10.74%                       | [73] |
| Sharafeldin et al. (2017)     | Exp.        | Water                  | WO <sub>3</sub>                                                                      | 0.016-0.067 vol%   | Collector efficiency +13.48%                     | [74] |
| Sharma et al. (2020)          | Exp.        | Water                  | CeO <sub>2</sub>                                                                     | 0.25-2 vol%        | Max collector efficiency 57.1%                   | [75] |
| Shojaeizadeh et al. (2015)    | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub>                                                       | 0.0906-0.1423 vol% | Optimal inlet temp -2%, mass flow -68%           | [76] |
| Sint et al. (2017)            | Exp.        | Water                  | CuO                                                                                  | 0.1-2 vol%         | Collector efficiency up to +5%                   | [77] |
| Stalin et al. (2020)          | Exp.        | Water                  | CeO <sub>2</sub>                                                                     | 0.01-0.1 vol%      | Efficiency 28.07% higher than water              | [78] |
| Sundar et al. (2018a)         | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub>                                                       | 0.5-1.5 vol%       | Collector performance +24.1%; thermal eff. +18%  | [79] |
| Sundar et al. (2018b)         | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub>                                                       | 0.1, 0.3 vol%      | Collector efficiency increased to 58%            | [80] |
| Sundar et al. (2020b)         | Exp.        | Water                  | Nanodiamond                                                                          | 0.2-1 vol%         | Heat transfer +52.33%, Nu +32.31%                | [82] |
| Sundar et al. (2020a)         | Exp.        | Water                  | Cu                                                                                   | 0.1, 0.3 vol%      | Efficiency 52% → 58%                             | [81] |
| Sundar et al. (2021)          | Exp.        | Water                  | Cu                                                                                   | 0.1, 0.3 vol%      | Thermal conductivity +23.56%                     | [83] |
| Sundar & Chandra Mouli (2023) | Exp. & Num. | Water                  | MgO                                                                                  | 0.1-1.0 vol%       | Nusselt number +37.28% at 1.0 vol%               | [84] |
| Sundar et al. (2025)          | Exp. & Num. | Glycerol-water (30:70) | SiO <sub>2</sub>                                                                     | 0.25-1.0 vol%      | k +25.87% at 100 C; exergy eff. x4.332 at midday | [85] |
| Suthahar et al. (2022)        | Num.        | Water                  | Al <sub>2</sub> O <sub>3</sub>                                                       | 0.1-0.5 vol%       | Average instantaneous thermal efficiency 84.85%  | [86] |
| Tahat & Benim (2017)          | Exp.        | EG-water               | Al <sub>2</sub> O <sub>3</sub> /CuO (hybrid)                                         | 0.5-2 vol%         | Collector efficiency improved up to 45%          | [87] |
| Tang et al. (2010)            | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub> /CuO (hybrid)                                         | 0.5, 1 vol%        | Thermal efficiency +16%                          | [88] |
| Verma et al. (2016)           | Exp.        | Water                  | MgO                                                                                  | 0.25-1.5 vol%      | Thermal eff. +9.34%; exergetic eff. +32.23%      | [89] |
| Verma et al. (2017)           | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub> , SiO <sub>2</sub> , TiO <sub>2</sub> , CuO, graphene | 0.75 vol%          | CNT: exergy 29.32%, energy 23.47%                | [90] |
| Verma et al. (2018)           | Num.        | Water                  | CuO/MgO/MWCNT (hybrid)                                                               | 0.25-2 vol%        | Energy eff. +25.1%; collector energy +16.28%     | [91] |
| Vincely & Natarajan (2016)    | Exp.        | Water                  | Graphene oxide                                                                       | 0.02 vol%          | Max collector efficiency +11.5%                  | [92] |
| Xiong et al. (2021)           | Num.        | Water                  | Ag-Al <sub>2</sub> O <sub>3</sub> (hybrid)                                           | 0.1 vol%           | Hybrid nanofluid increased collector performance | [93] |
| Ziyadanogullari et al. (2018) | Exp.        | Water                  | Al <sub>2</sub> O <sub>3</sub> , CuO, TiO <sub>2</sub>                               | 0.2-0.8 vol%       | Max collector performance +63.71%                | [94] |

## VIII. BASE FLUID AS AN UNCONTROLLED VARIABLE

Sections 5 and 6 show that the great majority of studies in this study attribute their reported performance gains to the nanoparticle additive, while the underlying base fluid — overwhelmingly water in some form (88.3%, Section 6.2) — is treated as a fixed and largely interchangeable carrier. This section argues that the assumption is unsafe, that it compromises the comparability of enhancement percentages across the literature, and that base fluid should be reported and controlled as an experimental variable.

### 8.1 The comparability problem

An enhancement percentage is a ratio, and its value depends as much on the denominator as on the numerator. When a study reports that a nanofluid improved collector efficiency by 26%, that figure is meaningful only relative to the specific base fluid, collector, circulation mode and ambient conditions against which it was measured. Three features of the present study make such figures difficult to compare.

First, the baseline fluid itself varies. Although water dominates, the study includes plain water, distilled water, deionised water, ethylene-glycol–water blends at unstated ratios, a glycerol–water blend, pentaethylene glycol and Therminol VP-1. These fluids differ substantially in thermal conductivity, specific heat capacity and viscosity, so a given nanoparticle loading does not represent the same perturbation in each. An enhancement expressed against a high-viscosity organic baseline is not equivalent to the same percentage expressed against distilled water.

Second, the circulation mode varies and interacts with base-fluid properties. In a pumped collector the flow rate is imposed, and base-fluid viscosity affects pumping power but not circulation rate. In a natural-circulation thermosyphon the flow rate is itself set by the buoyancy balance, so viscosity and density differences between base fluids alter the circulation rate directly, and therefore alter both the useful heat gain and the plate-to-cover temperature difference that governs top loss. A nanoparticle loading that raises viscosity will consequently have qualitatively different consequences in the two configurations. Several thermosyphon studies in this study — including work with Cu/H<sub>2</sub>O [83], MgO/water [84] and SiO<sub>2</sub>/glycerol–water nanofluids [85] — report enhancement relative to a single base fluid without a matched alternative-base-fluid control, so the reader cannot separate the nanoparticle contribution from the contribution of the carrier.

Third, the baseline is frequently not measured. Item Q6 of the quality appraisal (Section 6.6) records whether the baseline was measured on the same rig under the same conditions. Where it was not — where it was taken instead from a correlation, a

manufacturer datasheet or an earlier publication — the reported enhancement conflates the nanoparticle effect with differences in rig, instrumentation and ambient conditions between the two sources.

## 8.2 Implications for the interpretation of reported gains

The consequence is that the distribution of enhancement percentages reported in Section 6.5 — roughly 44% of studies in the 0–15% band and 37% in the 15–30% band — should be understood as a distribution of heterogeneously defined ratios rather than as a distribution of a single physical quantity. It remains informative about the general scale of reported benefit, and about the fact that the typical benefit is considerably smaller than headline figures suggest, but it cannot support fine-grained comparison between nanoparticle chemistries drawn from different studies.

This has a direct bearing on how the field's most-cited comparisons should be read. Where two studies report, say, a 26% gain with an  $\text{Al}_2\text{O}_3/\text{TiO}_2$  hybrid [33] and a 29% gain with an MWCNT/ $\text{Al}_2\text{O}_3$  hybrid [30], the difference between those figures is smaller than the plausible variation introduced by baseline and configuration differences between the two experiments. Ranking chemistries on such differences is not defensible on the present evidence.

It also bears on the economic case for nanofluid adoption. Nanoparticle synthesis, dispersion, stabilisation and replacement all carry cost, and the case for incurring that cost rests on the magnitude of the enhancement relative to the cheapest available alternative. Where a change of base fluid, or a change of circulation configuration, could deliver a comparable improvement at lower cost, that alternative forms part of the correct comparator set. The present study does not permit that comparison to be made, because base fluid is almost never varied within a study.

## 8.3 Reporting requirements

The following reporting practices would make future FPSC nanofluid studies mutually comparable, and are proposed here as a minimum standard for the field:

- (1) Report the baseline explicitly: which fluid, at what composition and, for mixtures, at what volumetric or mass ratio.
- (2) Measure the baseline on the same rig, under the same irradiance and ambient conditions, and within the same test campaign as the nanofluid case. Where this is not possible, say so and quantify the difference in conditions.
- (3) Report absolute performance alongside percentage enhancement, so that a reader can recompute the ratio against a baseline of their own choosing.
- (4) Report a propagated measurement uncertainty for every derived quantity, particularly efficiency and heat-transfer coefficient, both of which depend on a small difference between two larger temperatures and are correspondingly sensitive to instrument resolution at low irradiance.
- (5) Report suspension stability over a duration at least as long as the test campaign, with the assessment method stated.
- (6) State the circulation mode and, for forced circulation, the flow rate and the pumping power penalty relative to the baseline fluid.
- (7) Where freeze protection or corrosion inhibition motivates the choice of base fluid, state this, since it constitutes a benefit that a thermal-performance comparison alone will not capture.

# IX. RESEARCH GAPS AND FUTURE DIRECTIONS

## 9.1 Controlled base-fluid studies

The most direct gap following from Section 8 is the near-absence of studies that vary base fluid and nanoparticle loading within a single experimental campaign on one rig. A factorial design crossing two or three base fluids with two or three loadings, conducted on a single collector under matched conditions, would separate the carrier contribution from the nanoparticle contribution and would establish whether the enhancement percentages reported across the literature are robust to a change of carrier. Such a design would be of particular value in natural-circulation configurations, where the coupling between fluid properties and circulation rate is strongest.

## 9.2 Uncertainty and repeatability

The quality appraisal identifies propagated uncertainty analysis as the weakest reporting item in the study. Efficiency and convective heat-transfer coefficient are both computed from a small temperature difference and are therefore noisy, particularly at low irradiance where the temperature rise may be only a few tenths of a degree. Studies reporting single-point efficiency values at low irradiance without an uncertainty band should be treated with caution, and future work should report replicate counts, standard deviations and confidence intervals at each operating condition as a matter of course.

## 9.3 Durability, cost and life-cycle assessment

Long-term stability remains the principal barrier to field deployment, and stability durations reported in the study are typically measured in days [7] rather than the years a collector installation must survive. Comparable gaps exist in cost accounting and in life-cycle assessment: few studies quantify the pumping-power penalty against the thermal gain, and fewer still report an energy payback or a life-cycle environmental balance for the nanoparticle inventory itself. Green synthesis routes [9] address part of this concern but have not yet been assessed over a full life cycle.

## 9.4 Limitations of this review

Four limitations should be borne in mind. First, the protocol was not pre-registered, so the possibility of post-hoc adjustment to the eligibility criteria cannot be excluded. Second, the search was restricted to English-language, peer-reviewed journal articles, which may under-represent work published in other languages or in the grey literature. Third, no formal publication-bias assessment was undertaken; given that the corpus reports overwhelmingly positive enhancements, the possibility that null or negative results are under-published is real and cannot be quantified from the available data. Fourth, the quality-appraisal instrument was developed for this review and has not been independently validated; it should be treated as a structured description of reporting completeness rather than as a validated risk-of-bias score.

## X. CONCLUSION

This systematic review examined 94 studies on the application of nanofluids in flat-plate solar collectors, published between 2015 and 2025 and identified through a documented and reproducible search protocol. The principal findings are as follows.

- (1) Water in some form is the base fluid in 88.3% of included studies (74.5% plain water, 12.8% distilled or deionised), with ethylene-glycol–water blends the principal alternative at 8.5%.  $\text{Al}_2\text{O}_3$  is the most studied nanoparticle, accounting for 24.6% of the 134 nanoparticle–study pairings recorded, ahead of CuO at 14.2% and  $\text{TiO}_2$  at 9.0%.
- (2) Experimental work accounts for 67.0% of the study, numerical work for 25.5% and combined approaches for 7.4%, with the numerical and combined share growing markedly after 2020 through the adoption of CFD and artificial neural network methods.
- (3) Most work operates at low loading: 55.3% of studies test no higher than 0.5 vol%, and 29.8% no higher than 0.1 vol%, confirming that appreciable thermal enhancement is attainable without incurring severe viscosity penalties.
- (4) Hybrid formulations appear in 22.3% of studies and are the fastest-growing category, with 16 of the 21 hybrid studies published in 2020 or later. Integration with passive enhancement devices and with phase-change materials is now a prominent trend, and the highest combined performance reported in the study — 86.34% energy efficiency with a hybrid CuO–MWCNT nanofluid and perforated twisted-tape inserts [18] — arises from precisely such a combination.
- (5) Reporting quality is uneven, and is weakest on the items that determine whether a reported enhancement can be trusted: propagated uncertainty and explicit baseline identification are both reported by a minority of studies.
- (6) Enhancement percentages across the study are expressed against heterogeneous and often unstated baselines, and are consequently not directly comparable between studies. Base fluid should be treated as a controlled variable rather than a fixed background choice, and Section 8.3 sets out seven reporting requirements that would render future studies mutually comparable.

The field has matured considerably over the review period, moving from single-component characterisation toward hybrid formulations, system integration, green synthesis and machine-learning-assisted optimisation. Its principal methodological weakness is no longer the absence of data but the difficulty of comparing the data that exist. Addressing that weakness — through controlled base-fluid studies, routine uncertainty reporting and explicit baseline specification — is the most valuable contribution the next generation of studies could make.

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## AUTHORS' CONTRIBUTIONS

Both authors made substantial contributions to all aspects of the preparation and drafting of this paper. Study screening and selection were performed independently by both authors; data extraction was performed by the first author and independently verified by the second on a randomly selected subset of the study.

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## AVAILABILITY OF DATA AND MATERIALS

The complete extracted dataset supporting the findings of this review, including all screening decisions, extraction fields, quality-appraisal scores and the formulae underlying every reported statistic, is provided as supplementary material and deposited in a public repository.

## DECLARATIONS

Ethics approval and consent to participate: not applicable; this review involved no human or animal participants. Competing interests: the authors declare that they have no competing interests.

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