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Review

Nanofluids as next-generation geothermal working fluids: Benchmarking against water-based systems, phase change materials (PCMs), and supercritical CO_2 (SC-CO_2)

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ABSTRACT

Geothermal energy is a promising clean energy source because of its ample reserves and minimal carbon footprint. However, its effective extraction relies on the stimulated reservoir's size and the thermophysical properties of the working fluid. Mainly water and, in some cases, SC-CO_2 are used as a working fluid, but PCMs and nanofluids could be an alternative. Most existing reviews treat these candidate fluids separately, making it difficult to compare options using consistent criteria that account for thermal performance, hydraulic penalties, operational risks, and deployment feasibility. Therefore, this review evaluates thermophysical properties of geothermal fluids, including water/brine, SC-CO_2, PCMs, and nanofluids, across various reservoir and wellbore configurations, using a framework that clarifies tradeoffs and readiness barriers to help identify the most suitable fluid for each geothermal application. Water/brines have high specific heat and conductivity but face corrosion and scaling problems. SC-CO_2's low viscosity and high expansivity boost heat extraction by about 50% in moderate-temperature reservoirs, but its low thermal conductivity can limit heat uptake and reduce delivered temperature in practice. PCMs store latent heat for thermal management, yet phase segregation and cycling degradation limit their use in geothermal systems. Nanofluids can boost thermal conductivity by up to 40%, improving heat transfer, but face high viscosity and pumping power costs. Nevertheless, with suitable nanoparticle type and concentration, nanofluids can greatly improve heat extraction, showing promise as next-generation geothermal fluids. Accordingly, this review discusses feasible solutions to key challenges of nanofluids and identifies research gaps and future directions to support their ongoing development.

1. Introduction

The population increase and the rise in energy demand have a linear relationship with energy harvesting and quality of life (Pasten and Santamarina, 2012). However, the rising global population and industrialization raise concerns about global warming due to the increasing amounts of CO_2 emissions, with the energy sector being responsible for the significant portion of these emissions and risks (Hajiyev et al., 2025). Increasing air pollution leads to a reduction in life expectancy and an increase in human health issues, particularly related to the respiratory system, resulting in approximately 2 million deaths annually (Nkinyam et al., 2025). According to BP Energy Outloook (2024), global oil demand is projected to peak at around 102 million barrels per day (BPD) in 2025 and steadily decline to 75 million BPD by 2050, as renewables are expected to supply 25% of global energy demand (50% in an ideal Net Zero scenario). To achieve these goals, world nations need to focus on renewable and clean energy sources to reduce their reliance on fossil fuels (Fentaw et al., 2024). One of the clean energy sources with a minimal carbon footprint is geothermal energy, which can provide continuous baseload power (Osario Acosta et al., 2025).

Geothermal energy is a versatile resource that can be utilized to generate hot water for our homes, maintain comfortable temperatures in our living spaces, support plant growth in greenhouses, and even produce electricity (Allahverdiyev et al., 2025). Geothermal heat reserves worldwide are abundant, estimated at around 42 million MW, which is sufficient to provide sustainable energy for billions of years (US DOE, 2025). As reported by the IEA as of 2024 (IEA, 2024), geothermal energy accounts for less than 1% of the world's energy demand, primarily

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concentrated in a few countries, including the United States, Iceland, Indonesia, Türkiye, Kenya, and Italy. In contrast, by 2050, geothermal energy has the potential to meet 15% of the global electricity demand (IEA, 2024).

The first ever geothermal power plant was built in Larderello, Italy, in 1904 (Parri et al., 2016). Since that time, geothermal power plants have begun to operate worldwide, both for electricity generation and district heating. Currently, the US leads the way in geothermal energy R&D investment, at $122.47 million, which is four times higher than Germany's $30.82 million (Statista, 2025a). Fig. 1 represents the number of geothermal power plants in the US by state, with California and Nevada leading the way with 31 and 26 plants, respectively, and global geothermal electricity capacity steadily increased from 2009, when it was 9791 MW, to 15427 MW in 2024 (Statista, 2025b). Despite the tangible improvements to date, geothermal heat extraction is still not fully utilized around the world, and research is advancing heat extraction strategies to improve its efficiency.

Historically, water and various brines have been used as working fluids in geothermal systems, where the working fluid refers to the circulating heat-transfer medium in the subsurface loop. This practice was later extended to binary geothermal systems utilizing Organic Rankine Cycles (ORC) with organic fluids to recover heat from moderate-temperature reservoirs (Alekseenko et al., 2024). However, other working fluids have also been proposed for geothermal applications over time. Brown was the first to suggest utilizing Supercritical CO_2 (SC-CO_2) as a working fluid for hot dry rock reservoirs (Brown, 2000), due to its high density-viscosity ratio and high thermal expansivity (Okoroafor et al., 2021). Similarly, Choi was the first to investigate nanofluids as a means to enhance the thermal conductivity of the working fluid (Choi, 1998). After Choi, nanofluids were further investigated as a working fluid for geothermal energy extraction for several years (Cui et al., 2024; Kaggwa and Carson, 2019; Mahian et al., 2021). Similar to nanofluids, Phase Change Materials (PCMs) have also recently gained attention in enhancing thermal properties of fluids (Kaggwa and Carson, 2019). While a diverse range of geothermal working fluids has been studied to date, their suitability for many geothermal applications depends on how their thermophysical properties interact with reservoir characteristics to govern heat transfer efficiency, fluid circulation, and overall performance.

Given their critical role in governing heat transport and fluid flow in geothermal reservoirs, research efforts commonly emphasize several key thermophysical parameters of working fluids, such as thermal conductivity (k), specific heat capacity (C_p), viscosity (μ), and density (ρ). For instance, a higher k value improves conductive and convective heat transfer, enabling more efficient heat transfer from the reservoir rock to the circulating working fluid. Subsequently, larger C_p and ρ values increase the volumetric heat capacity (ρC_p) of the fluid, allowing more thermal energy to be transported per unit volume and thereby directly improving the fluid's volumetric heat extraction rate. In contrast, higher viscosity increases pumping power requirements due to elevated pressure losses and promotes thermal channeling, potentially leading to early thermal breakthrough and increased operational costs (Ji et al., 2025). Despite their critical role in governing working-fluid feasibility, to date no single working fluid exhibits all desirable thermophysical properties (Cong et al., 2024). Additionally, thermophysical properties alone are insufficient for field-scale deployability. Economic viability, environmental impacts, downhole chemistry, and in-situ pressure and temperature conditions further complicate optimal working-fluid selection for geothermal applications.

These constraints are evident across the major classes of geothermal working fluids. For instance, high-salinity brines, which are commonly encountered in geothermal reservoirs, exhibit reduced thermophysical performance compared to freshwater. In general, brines with higher salt concentrations can have 15% lower specific heat capacity than freshwater at 80°C, resulting in 10% reduction in volumetric heat capacity (ρC_p) (GeoModel, 2025). Increasing salinity also reduces thermal conductivity while, simultaneously exacerbating scaling and corrosion risks. While fresh water exhibits favorable thermophysical properties, its applicability in moderate-temperature geothermal reservoirs is limited by its low power-cycle efficiency and the need for phase-change to steam, which is often not achievable at these temperatures without binary (ORC) conversion and additional heat-exchange infrastructure. SC-CO_2 has been proposed as an alternative working fluid, particularly in enhanced geothermal systems (EGS), where partial CO_2 sequestration provides an added environmental benefit. However, its relatively low thermal conductivity under supercritical conditions raises concerns regarding long-term heat extraction efficiency and limits its broader applicability as a primary working fluid. PCMs can significantly increase effective heat storage capacity through latent heat mechanisms (Alavy et al., 2024), but their practical deployment is fundamentally constrained by the low thermal conductivity of pure PCMs, which restricts heat transfer rates and necessitates additional enhancement strategies. Nanofluids are promising alternatives to enhance thermal conductivity (Sui et al., 2017). However, they also face persistent challenges related to long-term stability, nanoparticle agglomeration, erosion and corrosion, environmental impacts, and production costs, which collectively hinder immediate field-scale implementation.

Collectively, these findings highlight the need for more innovative working fluids. However, most existing reviews still treat these candidate fluids separately, focusing on nanofluids, SC-CO_2, or PCMs in isolation or discussing alternatives mainly at a descriptive level. This makes it difficult for readers to compare options using a consistent set of criteria that accounts for thermal performance, hydraulic penalties, operational risks, and deployment feasibility. Additionally, due to their promise to improve thermal conductivity, nanofluids in particular warrant more thorough, solution-oriented examination to identify feasible mitigation strategies that enable efficient translation of their benefits to field-scale geothermal applications.

Therefore, this review provides a detailed comparison of water/brine, SC-CO_2, PCMs, and nanofluids (including hybrid nanofluids) to

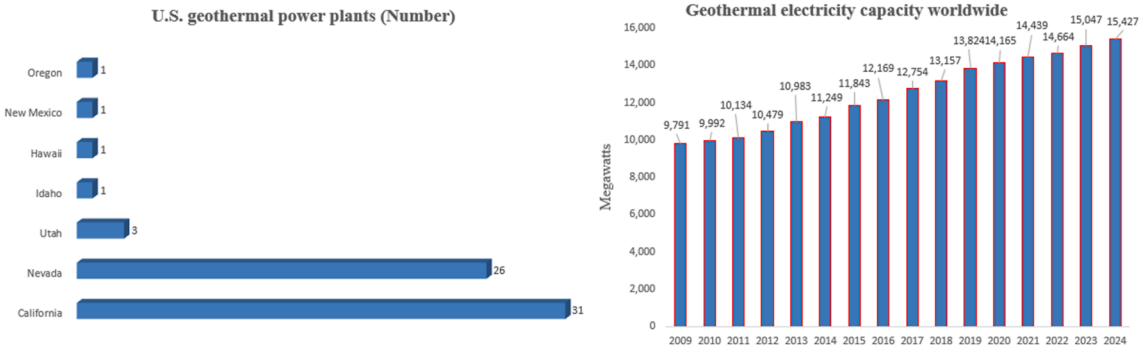


Fig. 1. The current state of geothermal energy in the US (Statista, 2025b).

support decision-making in geothermal applications. Additionally, nanofluids are critically examined, and feasible strategies for mitigating their limitations as geothermal working fluids are synthesized. Working-fluid options are examined across two primary geothermal settings: (i) deep, high-temperature systems which include enhanced geothermal systems (EGS) and hydrothermal reservoirs and (ii) moderate-temperature closed-loop wellbore heat exchangers (e.g., coaxial and U-tube designs). Additionally, the role of key thermophysical properties such as thermal conductivity, specific heat, viscosity, and density, in system-level outcomes such as heat extraction potential, pressure losses, pumping requirements, and operational integrity under geothermal-relevant temperature-pressure conditions is discussed. Within this scope, PCMs are discussed as thermal-buffering/thermal-storage enhancements, implemented through slurries, encapsulated PCM dispersions, or PCM-integrated borehole configurations, rather than as standalone circulating fluids in all cases. Subsequently, in line with pragmatic reviews, the manuscript translates existing evidence into decision pathways and connects fluid properties to practical constraints in geothermal clean-energy systems.

The novelty of this review lies in three key contributions. First, it provides cross-system benchmarking of the key thermophysical drivers that govern geothermal performance across fundamentally different reservoir and wellbore configurations. Second, it introduces a comparative evaluation framework that makes the main tradeoffs and readiness barriers among working fluids explicit, enabling more transparent comparison across fluid types and deployment contexts. Third, it synthesizes existing experimental and modeling evidence to identify the current challenges and suggest deployment-relevant design pathways and constraint-aware strategies for the practical use of nanofluids in geothermal applications.

To deliver and support these goals contextually, this review aims to achieve the following objectives.

- Compare the thermophysical properties of water/brine, SC-CO_2, PCM formulations, and nanofluids for geothermal conditions, and explain how they affect heat transfer and flow in subsurface systems.
- Summarize geothermal performance data (outlet temperature, heat extraction rate, COP/efficiency, pressure drop, pumping power) from experimental, numerical, and field studies, highlighting agreements and differences.
- Assess feasibility by linking thermal gains to key real-world challenges: scaling, corrosion, phase behavior, stability, clogging risks, reservoir heterogeneity, manufacturing, environmental impact, and cost.
- Map optimal fluids for various geothermal contexts, highlighting their most defensible operating windows.
- Highlight remaining research gaps hindering the transition from lab or modeling to field deployment and suggest targeted priorities to advance practical readiness and decision-making for clean-technology implementation.

The review begins by providing readers with the review methodology which discusses how the review was initiated, the databases that were chosen, screening, filtering, and inclusion criteria. The third chapter provides a general overview of the thermophysical properties of working fluids that are referenced throughout the article. The fourth chapter gives a brief overview of the four studied working fluids. The fifth chapter discusses water and its brine solutions, comparing their thermal performance and highlighting the challenges and limitations faced in geothermal systems. The sixth chapter is dedicated to SC-CO_2, providing insights into its benefits and drawbacks. The seventh chapter provides a review of PCMs used in geothermal heat extraction, including a systematic literature review. The eighth chapter provides a comprehensive literature review of nanofluids and hybrid nanofluids in geothermal heat extraction, highlighting the tradeoffs associated with their use in this context and feasible solutions to the existing challenges. The last three chapters summarize the entire literature review, enabling readers to compare all types of working fluids, present a critical synthesis and a scoring matrix, identify current research gaps, future prospects, and conclude the literature review and comparative analysis across the reviewed geothermal working fluids.

2. Review methodology

This review was designed to support geothermal working-fluid selection across two application classes: deep, high-temperature systems (EGS and hydrothermal) and moderate-temperature closed-loop wellbore heat exchangers. To ensure the review is comprehensive, the synthesis explicitly compares fluids using a consistent set of criteria: heat-extraction benefit (thermophysical properties), hydraulic penalty, operational integrity risks, environmental/safety considerations, cost/deployability, and technology readiness. The literature identification, screening, eligibility assessment, and inclusion steps were adjusted in accordance with the PRISMA; Page et al. (2021) reporting guidance, as outlined in the workflow presented in Fig. 2.

Identification: The search was initiated using Google Scholar, ScienceDirect, and Springer/Springer Nature. The search terms combined "geothermal" with "working fluid", "heat extraction", "heat exchanger", "nanofluid", "nanoparticle", "hybrid nanofluid", "supercritical CO_2", "SC-CO_2", "phase change material", "PCM slurry", "encapsulated PCM", "brine", and "salinity". This stage identified approximately 1594 records.

Screening: Duplicate records were removed, followed by title/abstract screening and full-text relevance checking. Records that were not directly related to geothermal working fluids or did not support the review scope were excluded. A total of 1164 records were excluded, leaving 430 records for the next stage.

Eligibility: The remaining records were assessed using the inclusion criteria. Studies were retained if they focused on a geothermal system, evaluated at least one target fluid class, and reported extractable data such as system geometry, temperature/pressure or flow conditions, fluid formulation, performance metrics, or operational issues. After applying these criteria, 274 studies were excluded.

Inclusion: A total of 156 studies were included in the technical synthesis. These included 75 records from ScienceDirect, 16 from Springer/Springer Nature, and 65 from Google Scholar, including studies from individual platforms such as MDPI, ASME, ACS, and Taylor & Francis. An additional 29 references were used only for background, historical context, or methodological support.

Initiate the search process: A structured search was designed to capture geothermal working-fluid research for deep high-temperature systems (EGS/hydrothermal) and moderate-temperature closed-loop wellbore heat exchangers, focusing on water/brine, SC-CO_2, PCMs, and nanofluids. The process was initiated utilizing the Google Scholar search engine.

Evidence was synthesized beyond description by (i) constructing a comparative matrix that evaluates each fluid class across constraints defined during the literature review process; (ii) performing cross-system comparison; and (iii) creating a synthesis that outlines tradeoffs and differing perspectives in geothermal literature while addressing decision-relevant pathways.

3. Thermophysical property fundamentals

Efficient thermal energy exchange in geothermal energy extraction relies heavily on the selection and performance of working fluids. Four thermophysical properties are vital to this performance: thermal conductivity (k), specific heat capacity (C_p), viscosity (μ), and density (ρ). These parameters influence heat transfer, fluid flow, and heat exchange processes under various geological conditions.

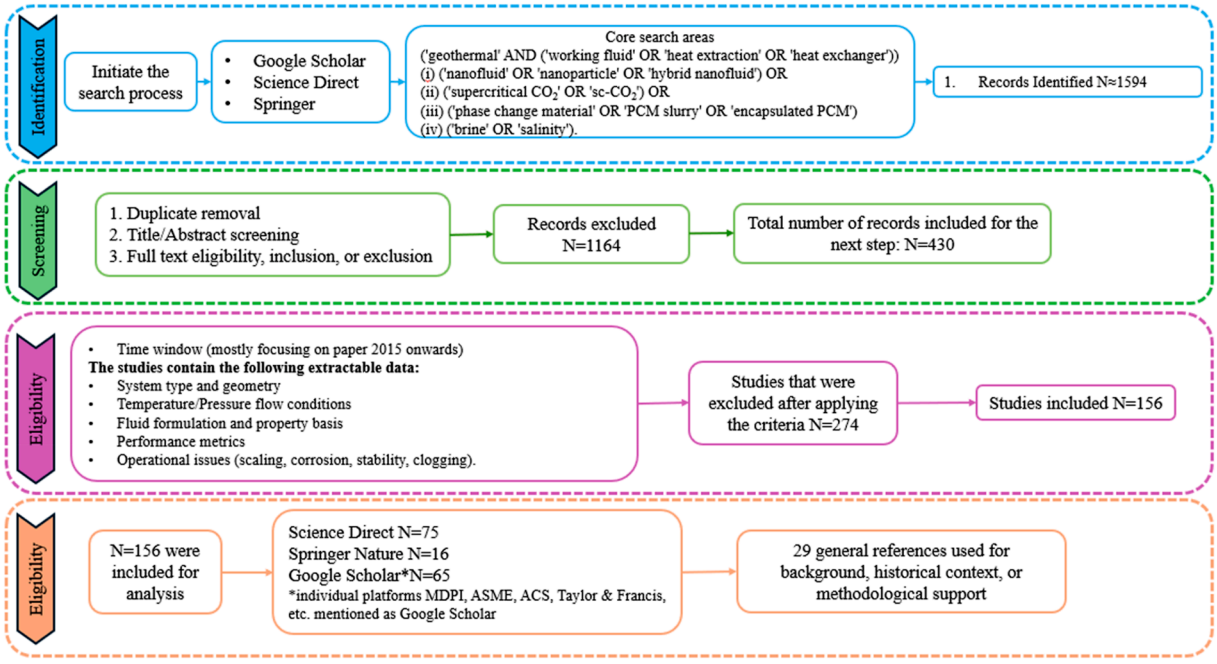


Fig. 2. Review methodology and synthesis workflow.

- Thermal Conductivity is a fluid's ability to conduct heat, measured in W/(m·K). This parameter is crucial for heat transfer between the fluid and the surrounding rocks; higher thermal conductivity facilitates greater heat transfer. For example, the thermal conductivity of water is about 0.6 W/(m·K), while the SC-CO_2 value ranges between 0.1 and 0.2 W/(m·K)—a lower value that can sometimes hinder its heat exchange ability. However, this can be compensated for by other advantages such as low viscosity, buoyancy effect, etc. (Cong et al., 2024).
- Specific Heat Capacity (measured in J/(kg·K)) is defined as the amount of energy required to increase the temperature of a kilogram of a substance by 1 K. Higher values of Cp mean that the fluid can store more thermal energy, thus allowing heat to be transported over long distances. For instance, water has a high value of C_p (4180 J/(kg·K)). However, nanofluids (suspensions of fluid and nanoparticles) generally enhance C_p and k but may increase viscosity as a result (Mahian et al., 2013).
- Viscosity (μ in Pa·s) is the fluid's resistance to flow, which strongly affects the pumping power and pressure drop in subsurface systems. Low-viscosity fluids can dramatically improve energy efficiency during circulation. In some cases, higher-viscosity fluids can help increase heat retention, reduce flow rate, but raise total costs (Gagne-Boisvert and Bernier, 2017).
- Fluid density (ρ, in kg/m^3) influences natural convection currents and hydrostatic pressure variations within subsurface systems. SC-CO_2 (with a density ranging between 600 and 800 kg/m^3) is more sensitive to buoyancy effects in vertical boreholes than water (1000 kg/m^3), which is beneficial in closed-loop geothermal systems (Pan et al., 2018).

Temperature and pressure changes with depth significantly influence the thermophysical properties. In deep boreholes, increasing temperatures significantly decrease the viscosity and improve the thermal conductivity of water. At the same time, shifts in pressure may cause phase changes in supercritical CO_2, resulting in markedly different transport properties. Tracking changes in these thermophysical characteristics with depth allows for improved modeling of deep underground thermal processes (Randolph and Saar, 2011). As a result, accurate thermal modeling for closed-loop boreholes operating at such depths may require correction factors or specialized empirical models for brines and CO_2 due to their markedly different properties compared to surface conditions (McSpadden et al., 2025).

4. Brief overview of fluid categories

This paper focuses on the range of working fluids including water, brines, supercritical CO_2, phase change materials (PCMs), nanofluids, and hybrid fluids that could be used in subsurface heat transfer systems. Below is a brief descriptive overview of the working fluids. Each fluid is discussed in detail in the next sections.

- *Water and Brines* are well-known fluids due to their availability and enhanced thermophysical properties. Brines are generally denser than pure water and exhibit modified k and μ depending on salt concentration (Cong et al., 2024).
- *Supercritical CO_2* is advantageous over traditional fluids due to its low viscosity, moderate density, and buoyancy properties in deep geothermal conditions. However, its lower C_p and k cause design challenges that could be optimized via system configuration (Avanthi Isaka et al., 2019).
- *Phase Change Materials (PCMs)* have the property of enhancing thermal energy capacity, particularly within borehole systems. PCMs operate on the latent heat storage principle, i.e., adsorb or release heat while changing from a liquid to a solid phase and vice versa (Wikipedia, 2025).
- *Nanofluids* consist of a primary fluid (usually water or ethylene glycol) suspended with nanoparticles like Al_2O_3 or CuO. Although k and C_p of nanofluids exhibit enhancement, higher viscosity and stability issues at high depth are the primary areas of investigation (Sui et al., 2017).
- *Hybrid nanofluids*, formed by dispersing several nanoparticles in a base fluid, have been proven to increase their thermal conductivity more than mono-nanofluids (Babar and Ali, 2019). For instance, an investigation of TiO_2-Al_2O_3 nanofluids in 40% ethylene glycol demonstrated enhanced thermal conductivity, rendering the fluids functional for heat transfer purposes (Urmi et al., 2024).

5. Water-based fluids: pure and saline solutions

The distinct thermophysical properties of brines (e.g., NaCl and $CaCl_2$) and pure water make water-based fluids necessary for geothermal energy extraction. Since salts can significantly change specific heat capacity, thermal conductivity, viscosity, and density, they ultimately shape how thermal systems operate with these fluids. Knowledge of these engineering changes benefits geothermal energy extraction processes.

6. Water and brine properties (NaCl, $CaCl_2$ solutions)

As shown in Fig. 3, water exhibits a thermal conductivity of 0.606 W/(m·K) at 30°C, increasing to 0.6768 W/(m·K) at 100°C (Ramires et al., 1995). However, aqueous NaCl and $CaCl_2$ vary with changing concentration of salinity and pressure. For example, the thermal conductivity of aqueous $CaCl_2$ increases with increasing temperature. However, with increasing concentration, the thermal conductivity slightly decreases (from 0.599 W/(m·K) at 5% concentration at 20°C to 0.581 W/(m·K) at 20% concentration at 20°C). As pressure increases, the thermal conductivity of aqueous $CaCl_2$ also rises, regardless of the increase in concentration (Akhmedova-Azizova and Abdulagatov, 2014). The solution of NaCl demonstrates a similar trend: the thermal conductivity of NaCl solutions increases with temperature and pressure (Nagasaka et al., 1983), whereas $CaCl_2$ solutions have higher thermal conductivity than NaCl solutions at the same concentrations, due to the presence of divalent calcium ions, which play a more significant role in energy transfer (Assael et al., 1989). Absolute measurements indicate that the thermal conductivity of aqueous chloride salt solutions (e.g., NaCl and $CaCl_2$) decreases with salt concentration (Assael et al., 1989), a trend that is also reflected in widely used saline-water property correlations summarized in the literature (Qasem et al., 2021).

As salt concentration increases, the specific heat capacity of saline solutions typically decreases. The specific heat capacity of NaCl solutions decreases linearly as the salt concentration increases. This occurs because NaCl reduces the amount of water molecules available to absorb thermal energy, resulting in a lower specific heat capacity than pure water. Also, the specific heat capacity of saline solutions varies at different temperatures. However, the trend of a decrease in specific heat capacity with increasing salt concentration remains the same (Carvalho et al., 2015).

6.1. Salinity and depth effects

Salinity and depth significantly alter the density, viscosity, and thermal conductivity of NaCl and $CaCl_2$ solutions. Many applications, such as geothermal energy and desalination, depend on these properties. Generally, increased salinity leads to a higher density of solutions, with the density variations across different concentrations and temperatures (Hoffert et al., 2024). An increase in salinity leads to higher dynamic viscosity, which is essential for fluid flow in geothermal systems (Qasem et al., 2021). As depth increases, temperature generally rises, subsequently influencing the thermophysical properties. For example, both density and thermal conductivity depend on temperature, with specific correlations established at different depths (Sharqawy et al., 2010). Higher pressure at greater depths can change the behavior of saline solutions, affecting their thermophysical properties (Qasem et al., 2021). While the changes in the thermophysical properties of single solutions are well-known, they must be considered when dealing with mixtures of saline solutions (Saluja et al., 1995). Furthermore, the interaction of a mixture of saline solutions with formation rocks and its effect on thermophysical properties at varying depths, concentrations, temperatures, and salinities remains unexplored mainly, representing a gap in our understanding that warrants further research.

6.2. Limitations in harsh geological environments

Using water and saline solutions for geothermal energy extraction presents several challenges in harsh geologic environments, which limit its implementation. High temperatures, corrosive fluids, and complex mineral interactions that geothermal formations encounter lead to limitations. Water and saline solutions can interact with minerals in geothermal formations, causing the dissolution or precipitation of salts like halite and anhydrite (Khan et al., 2026), which may clog wells and decrease efficiency (Moore and Holländer, 2021). The primary limitations include high reactivity of saline solutions with undersaturated water, potential well clogging, formation dissolution, and thermal short-circuiting, which necessitate careful monitoring and management of heat exchange fluid compositions in highly saline environments.

Additives in saline solutions frequently exhibit inadequate thermal stability, leading to fluid loss and diminished performance in extreme geologic conditions (Olivares, 2024). The main limitations include unwanted mineral precipitation, fluid-material interactions, scaling, and corrosion, which result from the diverse compositions and conditions of

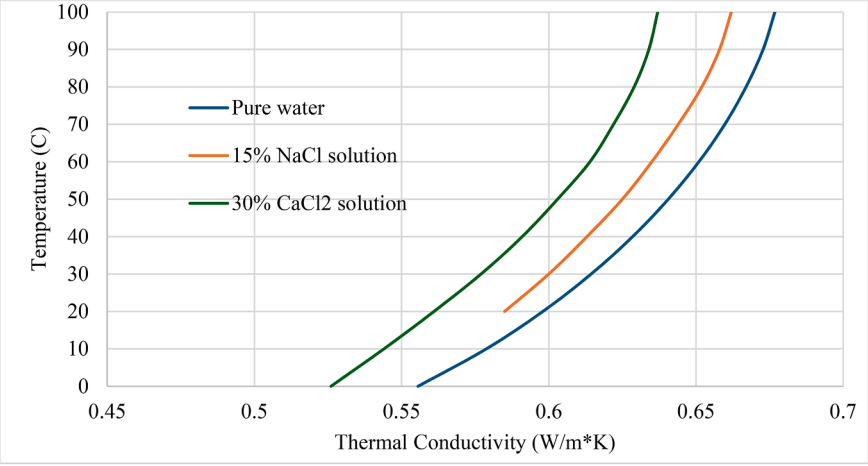


Fig. 3. Thermal conductivity of aqueous 15% NaCl (Sodium chloride) and 30% $CaCl_2$ (Calcium chloride) solution with changing temperature (Ozbek and Phillips, 1980; Ramires et al., 1995).

geothermal fluids. These factors complicate both the design and operation of geothermal power plants in challenging geological settings (Frick et al., 2011).

Table 1 presents an overview of the challenges and limitations associated with water and brine geothermal systems, as reported in recent literature.

Table 1
Summary of primary challenges of the use of water and saline solutions.

Refs	Fluid/solution	Challenge/ limitation	Summary and results
Moore and Holländer (2021)	NaCl and $MgCl_2$ solutions	Reactivity with Geological Formations	Can interact with halite formations, resulting in issues of dissolution and precipitation. $MgCl_2$-brine lessens halite dissolution and precipitation when compared to NaCl-brine.
Carter and Cramer (1992)	Saline solutions	Corrosive Nature	High-salinity working fluids are corrosive, leading to corrosion and failure of construction materials. Studies indicate that high-chromium ferritic stainless steels may be the solution. Inconels, Hastelloy, and titanium alloys also show acceptable corrosion resistance.
Frick et al. (2011)	Saline solution + gases	Mineral precipitation, fluid-material interactions, scaling	Due to the diverse properties of brines and gases, mineral precipitation, fluid-rock interactions, scaling, and corrosion pose challenges. Also, two-phase flow and pressure differentials complicate the design process. The study investigated the Groβe Schönebeck site for research, focusing on geochemical and process-engineering challenges.
Weis et al. (2014)	Saline fluids	Fluid Dynamics	Under high temperatures and pressures, saline fluids may undergo phase separation, forming solid halite.
Flores et al. (2017)	Saline solutions	Salt precipitation	A study highlights the precipitation of salt as salinity saturation increases, resulting in a reduction in reservoir permeability and well productivity.
Loschetter et al. (2024)	Water	Biogeochemical perturbations, corrosion, and scaling	The study investigates the effect of water quality on geothermal energy storage. Poor quality, leading to biogeochemical perturbations, corrosion, and scaling, can result in clogging, loss of injectivity, and environmental impacts.

Overall, the reviewed water/brine studies indicate a consistent tradeoff between strong thermal capacity and operational chemistry. Water remains an effective geothermal working fluid because its high specific heat allows efficient sensible heat transport, making it suitable for systems where heat uptake and outlet temperature are the main performance targets. However, in real geothermal reservoirs, dissolved salts and reactive minerals can reduce this advantage by changing thermophysical properties, promoting scaling, accelerating corrosion, and increasing treatment requirements. Therefore, water/brine performance should not be interpreted only from heat capacity or thermal conductivity. Its practical value depends on the balance between heat-carrying capacity, injectivity, scaling tendency, corrosion risk, water availability, and brine management costs. This explains why water/brine remains the dominant near-term option, but not necessarily the optimal fluid under every reservoir condition.

7. Supercritical CO_2: thermosiphon and beyond

If the fluid is above critical temperature and pressure, it will be in a supercritical state. For CO_2, the critical temperature and pressure are 304.25 K and 7.39 MPa, respectively, representing the qualities of the gas (high compressibility) and the liquid (due to its density) (Fentaw et al., 2026). These qualities of CO_2 make it an ideal candidate for use in thermosiphons within geothermal rocks (Brown, 2000). First, at the bottom, it absorbs heat from the hot rocks, becoming less dense as a result. Later, due to its buoyancy, it rises through the risers without requiring pumping power. At the surface, a heat exchange process occurs, resulting in a reduction in its density, which later enables it to sink back down to the geothermal rocks through the injection well, thereby completing the closed-loop heat exchange process (Adams et al., 2014). Adams et al. (2014) highlighted the advantages of SC-CO_2, including reduced pressure losses, a significant flow rate induced by thermosiphon, a high heat extraction rate at shallow depths, and lower pumping power requirements as compared to brine.

A numerical study by Hu et al. (2020) also indicated an increased heat extraction rate of CO_2, with a flow velocity of CO_2 1.3-1.5 times higher than that of water, while indicating the lower temperature output as the main drawback of CO_2 over water.

Among other drawbacks, authors indicate that increased pressure in the reservoir by CO_2 was not beneficial in increasing the heat extraction rate, concluding that for geothermal heat extraction in closed-loop systems, a working fluid with high specific heat capacity is required (Hu et al., 2020). Al-Alawi et al. (2025) indicate that CO_2 was unable to reach the full geothermal potential of a real-world heterogeneous reservoir, which negatively impacted heat sweeping. Khankishiyev et al. (2024) indicate that the potential of CO_2 in heat extraction is high in multilateral closed-loop systems, particularly in high-temperature environments of up to 350°C, but the project's cost significantly exceeds economic limits with an increase in the number of laterals. Yang et al. (2024) observed that the CO_2 heat extraction rate is 1.4–2.2 times that of water, and CO_2 is efficient in low-permeability, high-pressure, and high-temperature reservoirs. However, CO_2 is less efficient in high-permeability reservoirs, and thermal breakthrough is observed in formations with high porosity and pressure, limiting its applicability in actual geological formations with complexities (Yang et al., 2024).

As indicated in the literature review, SC-CO_2 offers several benefits, including low viscosity, high density, and enhanced energy extraction efficiency through high extraction rates (Saar, 2025). Additionally, lower pressure drops occur, and at turbulent flows, higher Nusselt numbers (indicating improved heat transfer) are observed (Manda et al., 2021). Also, by utilizing SC-CO_2 in Enhanced Geothermal Systems (EGS), a high portion of CO_2 is sequestered within geologic formations, contributing to a reduction in greenhouse gas emissions (Horne et al., 2025).

Numerical simulations of closed-loop geothermal systems using CO_2 show that heat-extraction performance can be constrained under certain

operating conditions, limiting the achievable outlet-temperature gain and extracted heat rate compared with idealized expectations (Hu et al., 2020). In coupled CO_2-storage–geothermal evaluations of depleted gas fields, the predicted geothermal recovery is strongly influenced by reservoir architecture and sweep behavior, so heterogeneous formations can reduce the uniformity of heat mining (Yang et al., 2024).

The apparent disagreement among SC-CO_2 studies reflects differences in system configuration and limiting mechanisms rather than inconsistency in the fluid behavior. Adams et al. (2014) emphasized the advantage of SC-CO_2 in thermosiphon circulation, where low viscosity and buoyancy reduce pumping demand. In contrast, Hu et al. (2020) showed that even though CO_2 can achieve higher flow velocity than water, its lower outlet temperature may limit heat delivery when specific heat capacity controls performance. Similarly, Yang et al. (2024) reported higher CO_2 heat-extraction rates than water under low-permeability, high-pressure, and high-temperature conditions, but also noted reduced efficiency in high-permeability reservoirs due to thermal breakthrough. Al-Alawi et al. (2025) further showed that reservoir heterogeneity can prevent CO_2 from fully sweeping the available geothermal heat. These differences suggest a consensus trend: SC-CO_2 is most favorable when hydraulic mobility, reduced pressure loss, and buoyancy-driven circulation dominate, whereas water/brine remains competitive when heat capacity, outlet temperature, and stable thermal sweep control the system response.

A comparative EGS study further reports that SC-CO_2 does not consistently outperform water, and that the relative heat-extraction rate depends on reservoir properties and extraction conditions (Al-Alawi et al., 2025). Most importantly, the thermal conductivity of the SC-CO_2 is lower than that of water and brines, as shown in Fig. 4(a), and it reduces with increasing temperature. Additionally, Fig. 4(b) indicates that high-temperature and high-pressure environments cause a reduction in thermal conductivity, which mimics reservoir conditions.

Additionally (Saar, 2025), notes that SC-CO_2 geothermal circulation can be accompanied by flow-path clogging driven by geochemical/mineral deposition, whereas (Wang et al., 2019) show that the heat-extraction increment diminishes over time as the adjacent hot rock cools during continued operation. Future studies should address this limitation by accounting for variations in permeability, porosity, and structural factors, such as faults and fractures, to improve prediction accuracy. Additionally, they should address challenges in compressibility, phase boundaries, and system control optimization.

The reviewed SC-CO_2 studies indicate that its performance relative to water depends strongly on the system objective and reservoir conditions. SC-CO_2 can outperform water when low viscosity, high expansivity, and buoyancy-driven circulation reduce pumping requirements and improve circulation efficiency. This advantage is particularly relevant in low-permeability, high-temperature, or closed-loop/EGS configurations where hydraulic losses strongly affect performance. However, SC-CO_2 does not always provide higher outlet temperature or more stable long-term heat delivery. Its lower heat capacity and lower thermal conductivity compared with water can limit heat uptake, especially in systems where thermal sweep and fluid heat-storage capacity dominate performance. Therefore, the apparent conflict in the literature is mainly caused by differences in permeability, flow-path

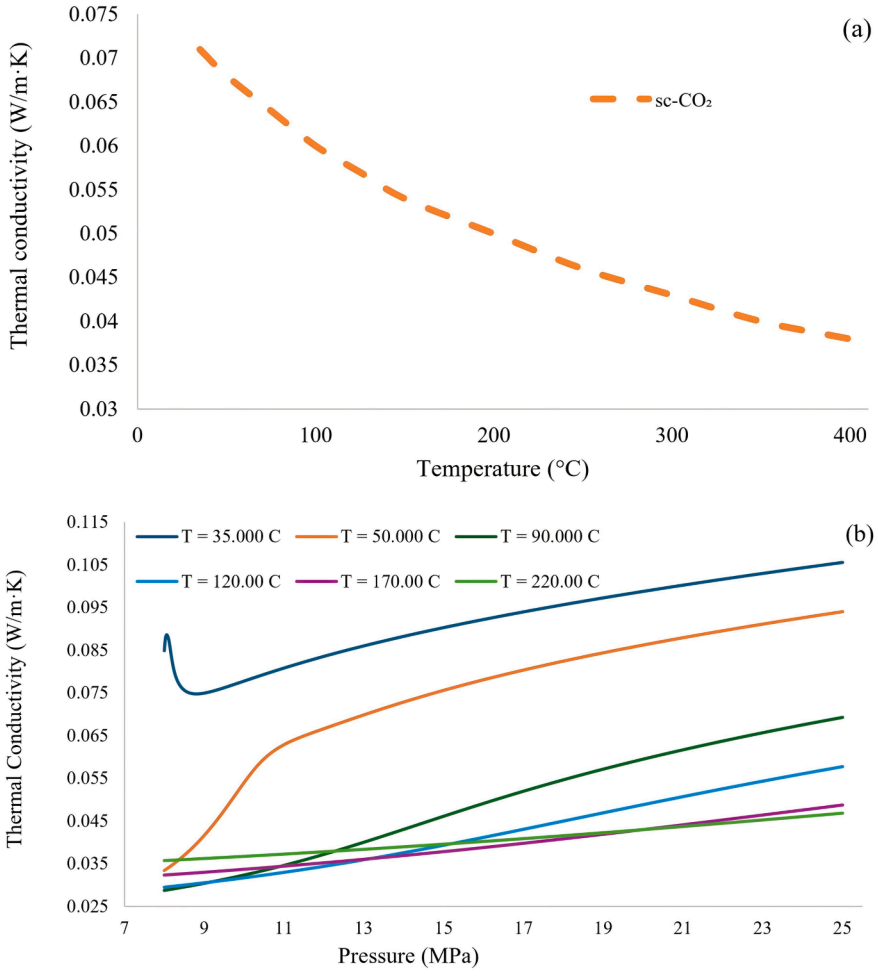


Fig. 4. (a)Change of thermal conductivity of SC-CO_2 at 8 MPa with increasing temperature (from (Lemmon et al., 2018)); (b) Thermal conductivity of SC-CO_2 with increasing temperature at different temperatures (from (NIST Chemistry WebBookS. 69, 2025); correlation for thermal conductivity from (Huber et al., 2016)).

geometry, pressure-temperature conditions, and whether performance is evaluated using heat-extraction rate, outlet temperature, pumping power, or long-term thermal decline. SC-CO_2 should therefore be considered a context-dependent option rather than a universally superior working fluid.

8. Phase change materials (PCMs) in geothermal energy

During the geothermal heat extraction process from the hot rocks, the soil initially loses energy to the working fluid, as its thermal energy is limited. In the second phase, the rocks undergo a cooling process, during which they begin to absorb heat for the next cycle (Shu et al., 2025). This phenomenon limits the extraction of geothermal energy through ground-source heat exchangers (Emmi et al., 2015). Recent literature suggests utilizing Phase Change Materials (PCMs) to address this issue by stabilizing underground heat exchange processes (Emmi et al., 2015; Shu et al., 2025). Fig. 5 shows an increasing interest in the application of PCMs in geothermal, with research articles comprising the highest portion of publications, indicating high research activity.

PCMs provide a built-in thermal buffering effect, storing heat when available and releasing it when temperatures drop. Generally, the PCMs are classified by their ability to store latent heat (Alavy et al., 2024), as shown in Fig. 6. The most commercially available and used PCMs are solid-liquid, exhibiting high thermal conductivity and wide energy storage capability (Dehghan et al., 2023). Alavy et al. (2024) conducted a review on PCMs in geothermal, pointing out that the main parameters used to define the effectiveness of PCMs are the Coefficient of Performance (COP) and thermal conductivity. A review of the literature indicates that the COP is high for slurries with higher thermal conductivity (Alavy et al., 2024), while highly depending on the type of PCMs as well (Fig. 7). The standard expression of COP is defined as:

$$\mathrm{COP} = \frac{\mathrm{Q_{delivered}}\ (heat\ delivered)}{\mathrm{W_{electric}}\ (input\ power)}$$

Whereas COP in percentage is quantified utilizing the following formula:

$$\Delta\mathrm{COP}\ \% = \frac{\mathrm{COP_{PCM}} - \mathrm{COP_{ref}}}{\mathrm{COP_{ref}}}$$

For instance, as reported in a numerical investigation by Hajaj and Saghir (Al Hajaj and Ziad Saghir, 2023) incorporating PCMs in geothermal system energy storage increased by up to 46.23%, while energy extraction improved by up to 59.55%. Soni et al. (2023) modeled the performance of PCMs in a geothermal closed-loop system and indicated that the use of Phase Change Slurries (PCSs) enhances thermal output by 12.5% compared to fluids like water. It should also be noted that PCMs initially exhibit low thermal conductivities; some literature suggests increasing them by adding ethylene glycol, graphene platelets, etc. (Alavy et al., 2024) but its applicability in geothermal systems has not been adequately studied yet. Moreover, as indicated by Chen et al. (2023), it would complicate the composition and would not fully resolve the limitation of low thermal conductivity. Recent NEPCM literature (Rasool et al., 2025) further supports the need to treat PCM performance as a coupled material–system problem. Nanoparticle addition, fin insertion, metallic foam embedding, and encapsulation can improve PCM thermal conductivity, reduce leakage, and accelerate charging/-discharging rates; however, these gains introduce tradeoffs related to cost, recyclability, nanoparticle toxicity, cycling durability, and system integration. Therefore, nano-enhanced PCMs should be viewed as promising thermal-buffering and storage enhancers, but not as automatically superior alternatives unless their thermal benefit is validated together with stability, compatibility, and lifecycle performance (Rasool et al., 2024).

Fig. 7 indicates that PCM system performance does not increase linearly with thermal conductivity. Although PureTemp29 (PCM 4) shows the highest COP improvement of approximately 81%, its thermal conductivity remains relatively low, below 1.5 W/(m·K). This suggests that the observed COP improvement is governed not only by thermal conductivity, but also by phase-change temperature matching, latent heat utilization, charging/discharging behavior, and system configuration. In contrast, decanoic–lauric acid composition (PCM 7) shows the highest thermal conductivity, but its COP improvement is much lower, indicating that higher conductivity alone does not guarantee better system-level efficiency. Therefore, PCM selection for geothermal applications should consider both material-level properties and system-level heat-transfer behavior. The figure also highlights the need for conductivity-enhancement strategies, such as encapsulation design, expanded graphite, metal foams, fins, or nano-enhanced PCMs, particularly when low-conductivity PCMs are used.

As can be seen from Table 2, PCMs present several issues in geothermal applications, including stability, safety, long-term effectiveness due to degradation issues, and, most importantly, scaling issues, which several researchers have reported.

Moreover, varying changes in properties depending on the type of PCM are one of the limitations that highlight the importance of selecting a suitable PCM. For instance, paraffins are stable but expensive and have lower conductivity, whereas hydrated salts have high storage capacity but exhibit phase segregation and cooling issues.

PCM implementation in geothermal energy. In Enhanced Geothermal Systems (EGS), including closed-loop geothermal systems, phase PCMs are mainly studied for their roles in thermal energy storage and improving heat transfer. One method uses micro-encapsulated PCM slurries as working fluids that absorb and release latent heat, thereby enhancing energy transport with a lower temperature drop than water alone (Zargartalebi et al., 2025). Typically, PCMs buffer and store geothermal heat for steadier output, such as through a surface PCM storage tank providing consistent temperature to the power cycle (Mucciardi et al., 2014). Overall, PCMs improve heat extraction efficiency and enable latent heat storage, either within the working fluid or

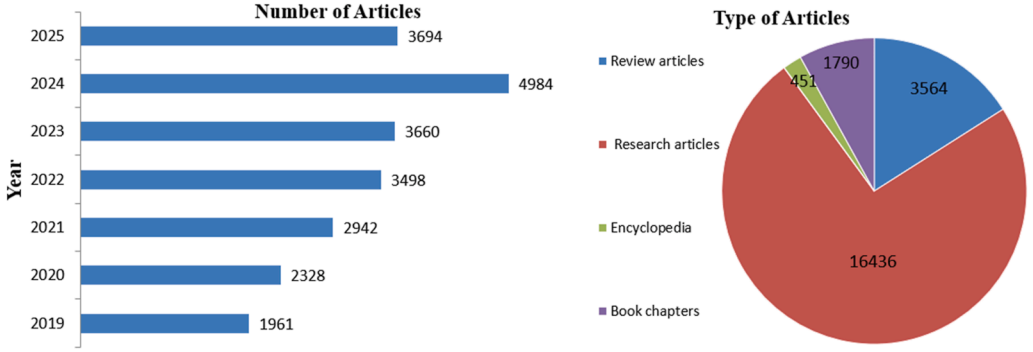


Fig. 5. "Number of Articles" and "Type of Articles" published from 2019 to 2025 (June) with keywords "Phase Change Materials" and "geothermal" from the ScienceDirect database.

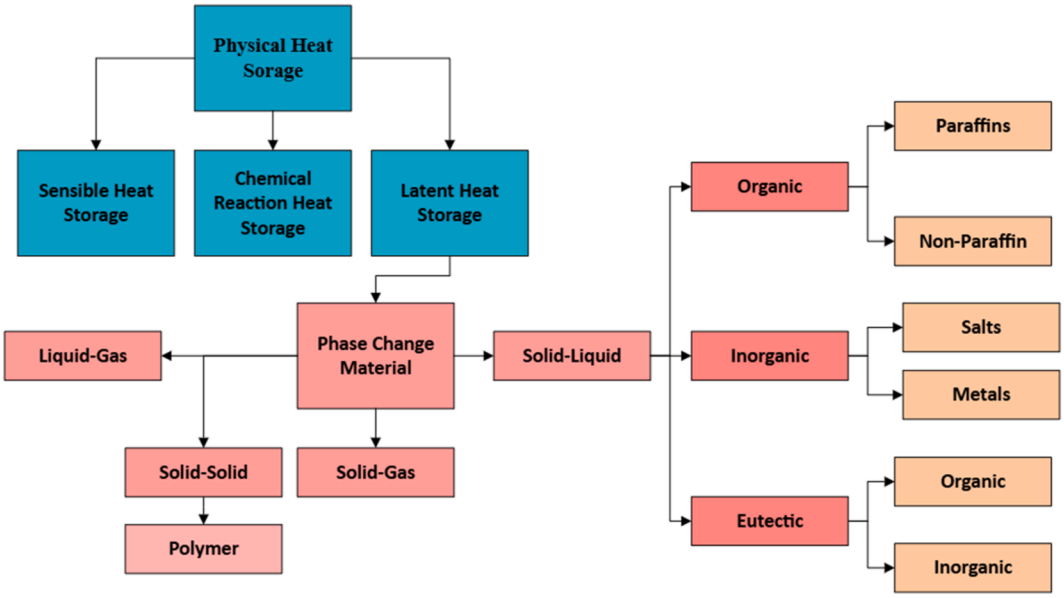


Fig. 6. The classification of physical heat storage and PCMs based on different phase change processes, including liquid-gas, solid-gas, solid-solid, and solid-liquid transitions (Alavy et al., 2024).

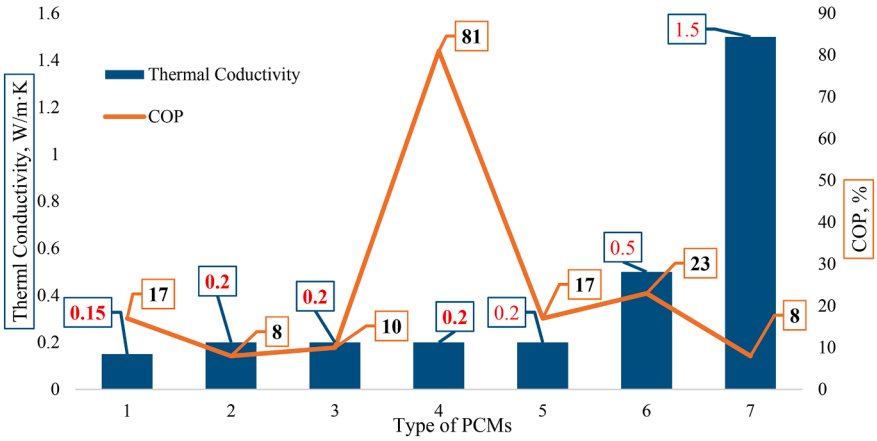


Fig. 7. Comparison of Thermal Conductivity and COP of different PCMs reported in the literature. Type of PCMs: 1–RT-6 PCM (Bonamente and Aquino, 2019); 2–Paraffin A8, A24 (Bottarelli and González Gallero, 2020); 3–Paraffin wax (Wang et al., 2019); 4–PureTemp29 (Lyne et al., 2019); 5–Microencapsulated paraffin wax (Dehdezi et al., 2011); 6–Hydrated salt PCM^3 (Alkhwildi et al., 2020); 7–Decanoic and lauric composition (Chen et al., 2018).

as separate storage, stabilizing and enhancing geothermal system performance. In Ground Source Heat Pumps (GSHP) systems, PCMs are added to borehole grouts or backfills to enhance ground heat exchangers by serving as underground thermal batteries (Dong et al., 2025). They absorb and release excess heat or cold during heat pump operation, smoothing out soil temperature fluctuations and preventing extreme seasonal changes. This stabilizes fluid temperatures and increases heat pump efficiency, with PCM-enhanced backfill shown to improve COP by about 17% (Zargartalebi et al., 2025). PCMs do not add extra energy but provide latent heat storage that buffers peaks in demand while protecting the ground's thermal reservoir. Their use is focused on the geothermal side, often in encapsulated forms, to boost performance without contaminating groundwater. Fig. 8 demonstrates the main applications of PCMs in geothermal energy systems.

For PCM-based systems, the reviewed studies generally agree that PCMs are more suitable as thermal-buffering or thermal-storage enhancements than as universal primary circulating fluids. Their main advantage is latent heat storage, which can stabilize temperature fluctuations and improve short-term thermal performance. However, low intrinsic thermal conductivity, phase segregation, cycling degradation, encapsulation requirements, and slurry stability limit their broader deployment. Therefore, PCM-based systems are most defensible when the objective is thermal storage or outlet-temperature stabilization rather than continuous high-rate heat extraction.

9. Nanofluids in heat transfer applications

Nanotechnology refers to the part of science where the size of particles or working elements is measured in nanometers. Nanoparticles significantly change the properties of base fluids, particularly thermophysical properties. The literature of the last decade has focused on the application of nanofluids in Enhanced Oil Recovery (EOR), primarily increasing oil recovery by mobilizing trapped oil in reservoirs (Davoodi et al., 2022). However, the use of nanofluids as working fluids for heat extraction in geothermal wells has become increasingly popular over the past years (Fig. 9). Compared to traditional working fluids, nanofluids exhibit enhanced transfer of energy, momentum, and mass. Nanofluids also have the potential to mitigate some of the challenges associated

Table 2
Challenges and Limitations of PCM reported in the literature.

Refs	Objective	Challenge/Limitation
Anand et al. (2021)	Stability and corrosion study of PCMs	PCMs **degrade** after prolonged exposure to heat and undergo melt/freeze cycles. Corrosion in PCM containers reduces life and functionality.
Al Hajaj and Ziad Saghir (2023)	Impact of PCMs on the Energy Storage Capability of Geothermal Energy Pile.	Insufficient **Long-term Performance** Data for PCMs
Matuszek et al. (2023)	Energy Storage of PCMs at Moderate Temperatures	Numerous PCMs face practical challenges related to **stability and safety**. Foundational literature is deficient in providing a clear perspective on the viability of these materials.A
Martelo et al. (2024)	Scaling study of PCMs in geothermal brine	**Scaling** issues were observed among the investigated PCMs, restricting reinjection. **Corrosion** risks were low due to the presence of chloride content.
Akbarzadeh et al. (2024)	Heat transfer in PCMs	**Low thermal** conductivity reduces PCM efficiency and slows heat transfer.
Guo et al. (2024)	PCM performance by microfluidic encapsulation	Phase change materials exhibit **low thermal conductivity**, which can lead to challenges such as **leakage and corrosion**.
Pássaro et al. (2022)	Geothermal borehole heat exchange improvement through PCM	The study revealed that thermal performance problems persisted, resulting in only a 0.15% increase in heat pump efficiency, while the PCM used only 30% of its stored energy under ideal conditions.
Soni et al. (2023)	Performance of PCMs in closed-loop geothermal systems.	Unstable PCS may precipitate, form agglomerates, and ultimately block the heat-exchange process. Potentially to **degrade** after a couple of charging and discharging cycles.
Sun et al. (2025)	Heat-transfer mechanisms and PCM-assisted thermal management under high thermal-stress conditions	PCMs can provide thermal buffering, but their low thermal conductivity can delay heat dissipation and create uneven melting/solidification zones. Under high heat generation or transient thermal loading, PCM-only systems may require conductivity enhancers such as graphite, fins, foams, or composite structures to avoid localized temperature buildup and performance loss.

with geothermal heat extraction that were previously discussed in Table 1 (primary challenges of the use of water and saline solutions), including reduced erosion, lower pumping power, and controlled geochemical interactions within the formation (Sui et al., 2017).

A comprehensive review of the literature presented in Appendix A, reveals that nanofluids are a promising fluid for heat extraction in geothermal wells. Table 3 summarizes geothermal-specific nanofluid studies.

Table 3 shows that geothermal nanofluid performance is strongly system-dependent. Several studies reported improved heat extraction, outlet temperature, or reduced borehole thermal resistance; however, the magnitude of improvement varied with heat-exchanger geometry, nanoparticle type, concentration, flow rate, and operating temperature. The main design implication is that nanofluids are more defensible in controlled closed-loop geothermal systems than in open reservoir circulation, where long-term stability, clogging, and pumping-power penalties remain more difficult to manage.

Table 4 summarizes the role of nanoparticle type, morphology, concentration, and stability using representative studies from the reviewed literature. Because this table is interpretive, the references are listed as representative supporting sources rather than as an exhaustive record of all studies.

Table 4 shows that nanoparticle selection should not be based only on thermal conductivity. Cu, Ag, CNT, and graphene-based nanofluids can provide stronger thermal enhancement, but they often introduce higher costs, greater dispersion difficulty, sedimentation, or concerns about pumping power. In contrast, Al_2O_3 and SiO_2-based nanofluids may provide more moderate thermal gains but are generally more practical due to availability, stability, and lower environmental risk. Therefore, nanoparticle selection should not be based only on intrinsic thermal conductivity; particle morphology, concentration, aggregation tendency, pH sensitivity, and stabilization method must also be considered because these factors control both thermal enhancement and viscosity penalty (Razzaq et al., 2025).

The main limitation of many nanofluid studies is that thermal enhancement is sometimes reported without equal attention to viscosity, pressure drop, and pumping-power demand. Therefore, Table 5 isolates studies where heat-transfer gains can be compared with hydraulic penalties. This comparison is important because improved thermal conductivity or heat-transfer coefficient does not necessarily translate into better geothermal system efficiency.

Table 5 shows that the main contradiction in nanofluid studies is not whether nanoparticles can improve heat transfer, but whether the improvement persists after accounting for viscosity, pressure drop, and pumping power. For example, some studies reported strong heat-transfer enhancement, while others showed that the associated pressure drop or pumping power increase can reduce the practical benefit. This supports the conclusion that low-concentration, stable nanofluids are more realistic for geothermal applications than high-concentration formulations that maximize thermal conductivity but increase hydraulic resistance.

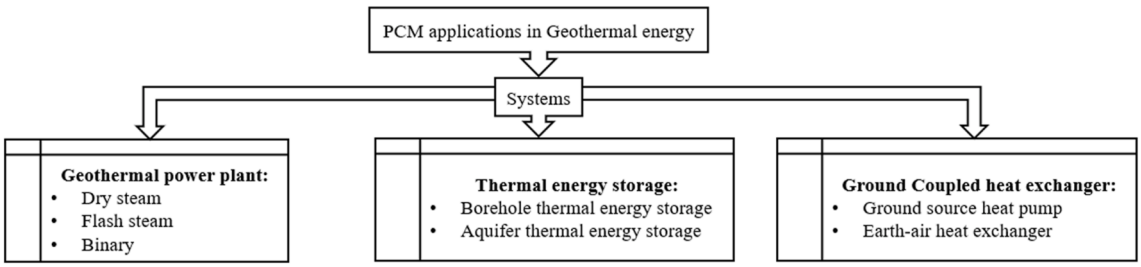


Fig. 8. PCM application in geothermal energy (adjusted after (Mahmoud et al., 2022)).

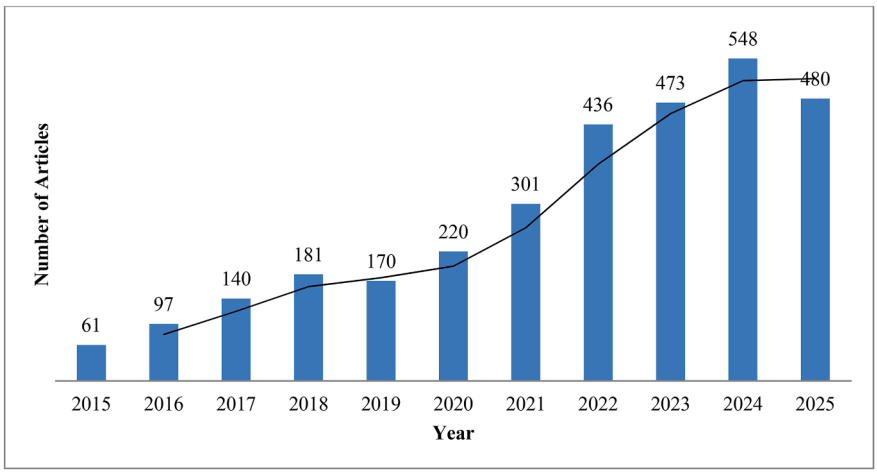


Fig. 9. Number of papers changes over the years (2015-mid 2025) of papers containing the title words "geothermal" and "nanofluids" (from Science Direct).

Table 3
Geothermal-specific nanofluid studies.

Refs	Nanofluid	Geothermal system	Concentration	Main thermal improvement	Hydraulic/stability penalty	Design implication
Sui et al. (2017)	Al_2O_3/water	Double-pipe geothermal heat exchanger	Noted in study	11.24% higher heat extraction than water	Viscosity must remain below ~0.05 Pa s	Thermal gain is useful only if viscosity remains controlled
Narei et al. (2016a)	Al_2O_3/water	Vertical U-tube GSHP	5vol%	1.3% borehole-length reduction	Limited system-level improvement	Nanofluid benefit may be diluted by borehole thermal resistance
Daneshipour and Rafee (2017)	Al_2O_3/water; CuO/water	200-m coaxial BHE	2vol%–6vol%	0.4%–1.0% higher heat extraction; CuO > Al_2O_3	Pressure drop increased with concentration	Higher concentration does not guarantee practical benefit
Du et al. (2020b)	CuO/water	Double U-shaped geothermal heat exchanger	3wt%	39.84% heat-transfer-rate increase	Pumping power increased by 16.75%	Strong thermal gain but must be judged against pumping cost
Jahanbin et al. (2022)	Ag/water; Cu/water; SiO_2; TiO_2; Al_2O_3; Fe_2O_3; CuO	200-m single U-tube BHE	2vol% for Ag/water	2.55% borehole thermal-resistance reduction	Ag/water required 31% more pumping power; Cu/water 26% more	High-conductivity particles can create hydraulic penalties
Chappidi et al. (2023)	Cu/water; Al_2O_3-Cu/water; CuO-Al_2O_3/water	3861-m abandoned oil well coaxial heat exchanger	4vol%	25% outlet-temperature increase; COP 1.83× water	Field-scale validation still needed	Promising for closed-loop repurposed wells
Q. Liu et al. (2023)	CuO/water	Horizontal spiral BHE	1%	9.4% higher heat-exchange rate	Performance coefficient below 1	Thermal improvement alone is insufficient
Sun et al. (2018)	Al_2O_3/water; Fe_3O_4/water	Geothermal heat exchanger	0.01vol%	Evaluated nanoparticle suspension behavior	Static precipitation; sedimentation increases with particle size	Flow velocity is important for stability

9.1. Effect of concentration, temperature, and type of nanoparticle on thermal conductivity and specific heat of nanofluids

The thermal conductivity of nanofluids is much higher than that of regular fluids, which helps speed up heat transfer (Adarsh Varma et al., 2024; Mohite et al., 2024). Nanoparticles enhance heat transfer through both conductive and convective mechanisms, enabling heat exchangers to operate efficiently. However, this process presents challenges such as nanoparticle dispersion and cost-effectiveness (Waware et al., 2024). Various factors, including nanoparticle type, concentration, and temperature, influence the enhancement of thermal conductivity of nanofluids. Different types of nanoparticles conduct heat at different rates.

For instance, copper oxide (CuO) and magnesium oxide (MgO) stand out, as they improve thermal conductivity by 13.1% to 20.9% at higher temperatures and greater concentrations (Theegala and Rachamalla, 2025). Experimental studies by Patel et al. (2024) and Theegala and Rachamalla (2025) show that the increase of volume percentage (0.5% to 2%) and temperature (30 to 60°C) increases the thermal conductivity of nanofluids. Similarly, Vicki et al. (2021) showed that nanofluid temperature and volume concentration increase the thermal conductivity of both mono and hybrid Al_2O_3–TiO_2 nanofluids.

Although nanoparticles like Al_2O_3 and TiO_2 enhance the thermal conductivity of water-based nanofluids with the increase of concentration, Masuda et al. (1993) concluded that water-based nanofluids containing SiO_2 would not impact thermal conductivity. However, studies by (Esfahani and Toghraie, 2017) on SiO_2 water and ethylene glycol indicated that the 5% volume fraction at 50°C increases the thermal conductivity by 50.9% as compared to the thermal conductivity of the base fluid at 25°C. Earlier studies by Eastman et al. (1996) also revealed that adding a 5% concentration of Al_2O_3 and CuO to the oil-based fluids increased the thermal conductivity of the working fluid by up to 60%, and up to 40% with ethylene-glycol-based CuO nanofluids (Eastman et al., 2001), thereby increasing interest in nanofluids. Another study on ethylene glycol-based 5% of MgO, TiO_2, ZnO, Al_2O_3, and SiO_2 by (Xie et al., 2010) revealed that MgO nanoparticles showed the highest thermal conductivity increase (almost 40.6%) at the experimental temperature range 10–60°C among other nanoparticle studies.

On the other hand, Begum Elcioglu (Begum Elcioglu, 2025) states that the thermal conductivity of a nanofluid may also decrease if the

Table 4
Nanoparticle type, morphology, concentration, and stability effects in nanofluids.

Nanoparticle class	Examples from reviewed studies	Main advantage	Main limitation	Practical geothermal implication
Metal oxides	Al_2O_3, CuO, TiO_2, ZnO, Fe_2O_3	Widely available; commonly studied; moderate-to-high heat-transfer enhancement	Viscosity and pressure drop can increase with concentration; stability depends on the dispersion method	Suitable for closed-loop geothermal systems if the concentration is optimized
High-conductivity metals	Cu, Ag	Strong thermal conductivity and heat-transfer potential	Higher cost, density, sedimentation risk, and pumping-power penalty	Useful only when thermal gain offsets hydraulic and economic penalties
Carbon-based particles	CNT, MWCNT, graphene, rGO	Very high thermal conductivity at low loading; good potential for advanced heat exchangers	Dispersion difficulty, high cost, environmental uncertainty, and possible agglomeration	Promising for high-performance closed-loop systems, but long-term stability must be proven
Hybrid nanofluids	Ag-MgO/water, TiO_2-Cu/water, Al_2O_3-CuO/water, Fe_3O_4-MWCNT/water	Tunable thermal and rheological behavior; possible synergy between particles	More complex formulation, stability control, and cost	Useful where an optimized thermal-hydraulic tradeoff is needed
Low-risk/stable oxides	SiO_2, Al_2O_3, TiO_2	Better stability and lower environmental concern than metals/carbon materials	Lower thermal enhancement than Cu, Ag, CNT, or graphene systems	More suitable for environmentally sensitive geothermal sites
Particle size and shape effects	Spherical, rod-shaped, cubic, plate-like particles	Shape and size can improve thermal conductivity, Nusselt number, and heat-transfer coefficient	Smaller or irregular particles may increase viscosity or agglomeration; larger particles may sediment faster	Particle morphology should be optimized together with concentration and flow rate
Concentration and stability effects	Low-loading vs. high-loading nanofluids	Higher concentration can increase thermal conductivity and heat-transfer coefficient	Excess concentration increases viscosity, pressure drop, sedimentation, and pumping power	Low-concentration stable nanofluids are more practical than high-concentration formulations

Table 5
Thermal-hydraulic tradeoff reported in nanofluid studies.

Refs	Thermal gain	Hydraulic penalty	Net interpretation
Du et al. (2020a)	39.84% higher heat-transfer rate	16.75% higher pumping power	Strong net potential, but pumping penalty must be included
Jahanbin et al. (2022)	2.55% lower borehole thermal resistance	31% higher pumping power for Ag/water; 26% for Cu/water	Thermal improvement may be offset by pumping demand
Mokhtari Moghari et al. (2015)	Improved thermal behavior	Pressure drop increased 22% at 1% and 195% at 5%	High concentration becomes hydraulically unfavorable
Kabeel et al. (2013)	13% higher heat-transfer coefficient	45% pressure-drop increase and 95% power-consumption increase at 4%	Heat-transfer gain can be outweighed by pumping cost
Kwon et al. (2011)	30% higher heat-transfer coefficient at 6vol% Al_2O_3	40% pressure-drop increase	High loading improves heat transfer but reduces hydraulic feasibility
Fotukian and Nasr Esfahany (2010)	25% heat-transfer increase	20% pressure-drop increase	Even dilute nanofluids may increase flow resistance
Mansoury et al. (2020)	33%–46% heat-transfer-coefficient increase	Pressure drop increased from 8% to 83% depending on concentration	An optimum concentration is required
Duangthongsuk and Wongwises (2009)	6%–11% heat-transfer increase	No major pressure-drop increase at 0.2vol%	Low concentration may provide a safer thermal-hydraulic balance

nanoparticle's thermal conductivity is initially low such as in the case of fullerene nanoparticles (Hwang et al., 2006). A separate survey by (Hwang et al., 2006) on fullerene, oil-based multi-walled carbon nanotube (MWCNT), and CuO and SiO_2 indicate that with the increase in concentration of fullerene nanoparticles in base fluid, the thermal conductivity of nanofluid decreased because fullerene's initial thermal conductivity is low. These observations highlight the importance of nanoparticle selection when incorporating nanofluids for energy extraction.

Apart from concentration, the size of nanoparticles has a direct effect on thermophysical properties. For instance, Darvanjooghi and Esfahany (2016) observed that increasing SiO_2 particle size from 10.6 to 62 nm enhanced thermal conductivity in ethanol-based nanofluids, with a more pronounced effect for particles <20 nm. Conversely, Maheshwary et al. (2017) reported higher thermal conductivity for smaller TiO_2 nanoparticles (16.3–31.3 nm) in water-based nanofluids, while Ali et al. (2013) found that the thermal conductivity of Al_2O_3-water nanofluids increased with particle size (11–63 nm) in the presence of CTAB surfactant. Darvanjooghi and Esfahany (2016) experimentally isolated nanoparticle size effects by preparing in-situ silica–ethanol nanofluids and showing that thermal conductivity is sensitive to particle size in a non-aqueous base fluid. Maheshwary et al. (2017) then provided a broader parametric dataset for TiO_2/water, demonstrating that thermal conductivity enhancement is jointly controlled by concentration, particle size, and particle shape, while Ali et al. (2013) similarly reported that Al_2O_3 nanofluid conductivity (and thermal diffusivity) varies systematically with particle size and volume fraction.

Additionally, several studies emphasize that the apparent "concentration/temperature" trend is strongly mediated by dispersion controls. Das et al. (2016) quantified surfactant effects on Al_2O_3–water thermophysical properties. Asadi et al. (2017) linked conductivity changes to surfactant selection and sonication time via stability, and Das et al. (2017) reported comparable surfactant-dependent behavior for TiO_2–water. Finally, Agarwal et al. (2017) framed thermal conductivity outcomes through sensitivity analysis for Al_2O_3 nanofluids, and Fan and Zhong (2022) extended the evidence base to kerosene-based nanofluids, confirming that conductivity enhancement trends have also been measured in hydrocarbon-based fluids.

Fig. 10 below compares the effect of nanoparticle size (in nanometers, nm) in ethylene glycol (EG) as the base fluid used while, Fig. 11 illustrates the variation in thermal conductivity of different nanofluids relative to changes in temperature, as measured by thermal conductivity from publicly available data.

Fig. 10 shows that thermal conductivity increases with nanoparticle concentration for Al_2O_3 + EG nanofluids, with concentration being a stronger factor than particle size within the range. The difference between 28 nm and 15 nm particles is small, and larger particles slightly outperform smaller ones across most concentrations. While smaller particles are usually expected to offer better thermal performance due to larger surface area, the observed trend suggests particle-size effects depend on other factors like dispersion, interactions, clustering, and fluid properties. Thus, reducing particle size alone doesn't guarantee

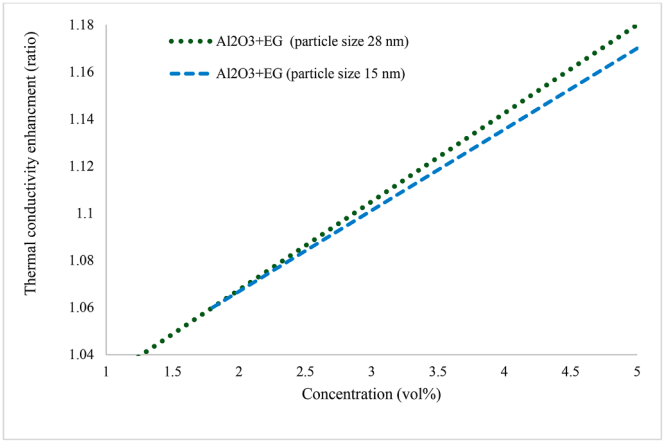


Fig. 10. Effect of particle size on thermal conductivity (Das et al., 2003; Lee et al., 1999; Yu et al., 2008).

better thermal conductivity. Concentration is the key, and particle size should be optimized with stability and rheology in mind.

Fig. 11 shows that thermal-conductivity enhancement generally increases with nanoparticle concentration, although the magnitude of improvement differs among nanofluid types and temperatures. CuO/water and Al_2O_3/water show stronger enhancement than SiO_2/water and TiO_2/water, indicating that nanoparticle material strongly affects heat-transfer potential. However, concentration increase should not be viewed as a universal design solution. Higher nanoparticle loading may improve thermal conductivity, but it can also reduce specific heat capacity and increase viscosity, pressure drop, and stability problems. Temperature can further modify these properties, often improving thermal conductivity and specific heat behavior, but the trend is not uniform for all nanofluids. Therefore, nanofluid performance depends on the combined effects of particle type, concentration, temperature, base-fluid interaction, and dispersion quality rather than concentration alone.

Experimental work by Akilu et al. (2017) revealed that increasing nanoparticle concentration (1.0%–4.0%) leads to a decrease in specific heat capacity, as observed in SiO_2-based nanofluids while, increase in temperature increases specific heat capacity. Thakur et al., (2017) also concluded that higher temperatures generally result in increased specific heat (Thakur et al., 2017). Shahrul et al. (2014) conclude that the specific heat of nanofluids decreases with increased nanoparticle volume concentration, and specific heat varies with the type and size of nanoparticles used. Shahrul et al., (2014) also noted that while certain studies indicate that specific heat may decrease with rising temperature, several other studies suggest the opposite, warranting the need for more studies to clarify these results (Shahrul et al., 2014).

9.2. *Hybrid nanofluids*

Hybrid fluids are represented by a mixture of two or more fluids in the base fluid, enhancing the thermophysical properties of the end product. The primary goal of creating hybrid nanofluids is to leverage the unique properties of their components. In general, hybrid fluids could be comprised of supercritical CO_2 plus brine mixtures and water. Similarly, hybrid nanofluids comprise of a composite blend of nano-sized metallic, polymeric, or non-metallic particles combined with a base fluid to enhance heat transfer rates in various applications (Abbas et al., 2020).

Typically, a single material cannot offer all the desirable traits needed for a specific application; it might excel in either thermal properties or rheological properties, but not both (Sarkar et al., 2015). Chappidi et al. (2023) investigated the use of Al_2O_3–Cu/water hybrid nanofluid in abandoned oil and gas wells, which demonstrated an improvement in outlet temperature by 25% with 4% nanoparticle concentration. Additionally, Javadi et al. (2021) evaluated hybrid nanofluids as the circulating fluid in a borehole heat exchanger and reported that enhancing the fluid's effective thermophysical properties can translate into improved BHE thermal performance (e.g., higher outlet temperature and/or reduced required exchanger length relative to water). Che Sidik et al. (2017) provided a methods-and-stability focused review of hybrid nanofluids, showing that reported thermal-property gains are tightly coupled to how the hybrids are prepared and stabilized, and emphasizing stability as a key barrier to practical deployment. Gokul et al. (2021) developed a ZnO–multi-walled carbon nanotube hybrid nanofluid and used a thermal-lens approach to characterize its heat-transfer-relevant response, supporting its potential for energy-efficient heat transfer applications compared with the base fluid. At the same time, Javadi et al. (2021) concluded that the pressure drops caused by the hybrid nanofluid are not economically beneficial.

9.3. *Realistic deployment challenges and limitations of nanofluids in geothermal systems*

Although nanofluids can improve heat-transfer performance in geothermal applications, their field deployment remains limited by

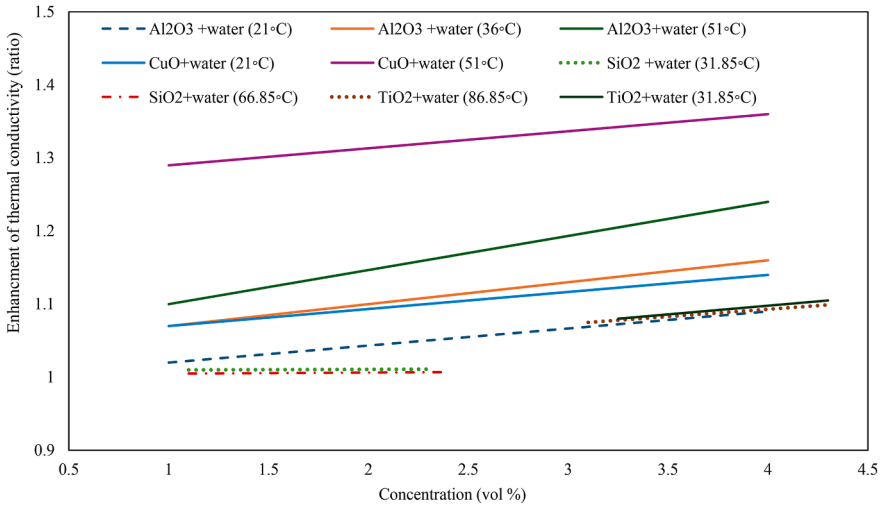


Fig. 11. Change of thermal conductivity of different nanofluids with changing temperature and concentration (Das et al., 2003; Lee et al., 1999; Masuda et al., 1993; Wang et al., 1999; Yu et al., 2008).

several coupled constraints. These constraints can be analyzed through four connected dimensions: thermodynamic limits, hydraulic penalties, environmental risks, and economic constraints. This structure is important because a nanofluid that performs well thermally may still be unsuitable for geothermal deployment if it causes excessive pressure drop, instability, clogging, environmental uncertainty, or cost escalation. Most geothermal nanofluid studies remain at the laboratory, numerical, or component scale, while long-duration field-scale validation remains limited.

From a thermodynamic perspective, nanofluids effectively enhance the overall system's thermal performance, but the impact of turbulent flow on thermal conductivity and other thermophysical parameters under reservoir conditions remains unclear and requires further investigation (Aglawe et al., 2021). This limitation is critical because geothermal systems operate under coupled temperature, pressure, salinity, and flow conditions that may differ significantly from controlled laboratory heat-transfer experiments. As a result, thermal-conductivity enhancement measured under simplified conditions may not directly translate into sustained reservoir-scale heat extraction. Another challenge is the manufacturing of nanofluids at the reservoir scale, as the process requires high-cost advanced equipment and technology. Stability is also a paramount factor to consider (Sukarno, 2017). Although the thermophysical properties of nanofluids may improve with increasing nanoparticle concentration, it is essential to maintain fluid stability under both static and dynamic conditions. Konate et al. (2025) highlighted that instability issues may affect heat-transfer efficiency. Research on nanofluid stability in EOR applications has been conducted, but there is almost no laboratory or field-scale validation of long-term stability under geothermal operating conditions. Therefore, the thermodynamic benefit of nanofluids should be interpreted as conditional: it depends on whether enhanced thermal conductivity can be maintained without loss of suspension stability, reduction in heat capacity, or an unfavorable increase in viscosity during long-term circulation.

Soltani et al. (2022) revealed that low-diameter nanoparticles may increase heat transfer and efficiency in closed-loop geothermal wells, as illustrated in Fig. 12(a), although this may also reduce heat capacity at high flow rates. ZrO_2 nanofluids in a closed-loop geothermal well may increase convective heat-transfer coefficients by up to 123% in laminar flow and 8.8% in turbulent flow, leading to higher energy output in geothermal systems (Calviño et al., 2024). In a separate coaxial heat-exchanger study, shown conceptually in Fig. 12(b), Pisarevsky et al. (2024) reported that an 8wt% Al_2O_3 nanofluid increased geothermal heat extraction by approximately 23%. These studies confirm that nanofluids can improve heat transfer in controlled geothermal-relevant geometries. However, they also show that the current evidence is mainly component-scale rather than field-scale. Therefore, the key limitation is not the absence of thermal enhancement, but the lack of evidence that this enhancement can be maintained under long-duration geothermal circulation, reservoir heterogeneity, salinity, and operational cycling.

The second limitation dimension is hydraulic penalty and flow assurance. Some studies indicate an increase in pressure drop when nanofluids are used in heat exchangers (Sidik et al., 2014). A similar limitation may be observed in geothermal reservoir conditions, where pumping power is already a major operating constraint. Kanaris et al. (2009) observed a 40% increase in pumping power when using nanofluids compared with water. This hydraulic penalty is important because geothermal systems require continuous circulation over long periods; even a moderate increase in viscosity or pressure drop can reduce the net energy gain if the additional heat extraction is offset by higher pumping demand. Faizal et al. (2013) quantified the energy, economic, and environmental tradeoffs of using metal-oxide nanofluids, showing that performance gains can come with cost penalties that lengthen the payback period. Said et al. (2018) synthesized evidence across thermal-photovoltaic studies and highlighted that life-cycle and material-handling considerations can limit large-scale adoption of nanofluids despite reported efficiency improvements; however, their analysis also showed lower environmental damage costs due to lower CO_2 emissions. This highlights the need for more affordable technologies to produce nanoparticles.

Table 5 shows that pressure-drop penalties are a recurring outcome when nanofluids are circulated through heat-exchanger passages, as demonstrated for TiO_2–water in a double-tube counterflow exchanger by Duangthongsuk and Wongwises (Duangthongsuk and Wongwises, 2009). Similar hydraulic penalties were observed in corrugated plate heat exchangers when nanoparticles were introduced, indicating that heat-transfer gains can come at the expense of higher frictional losses.

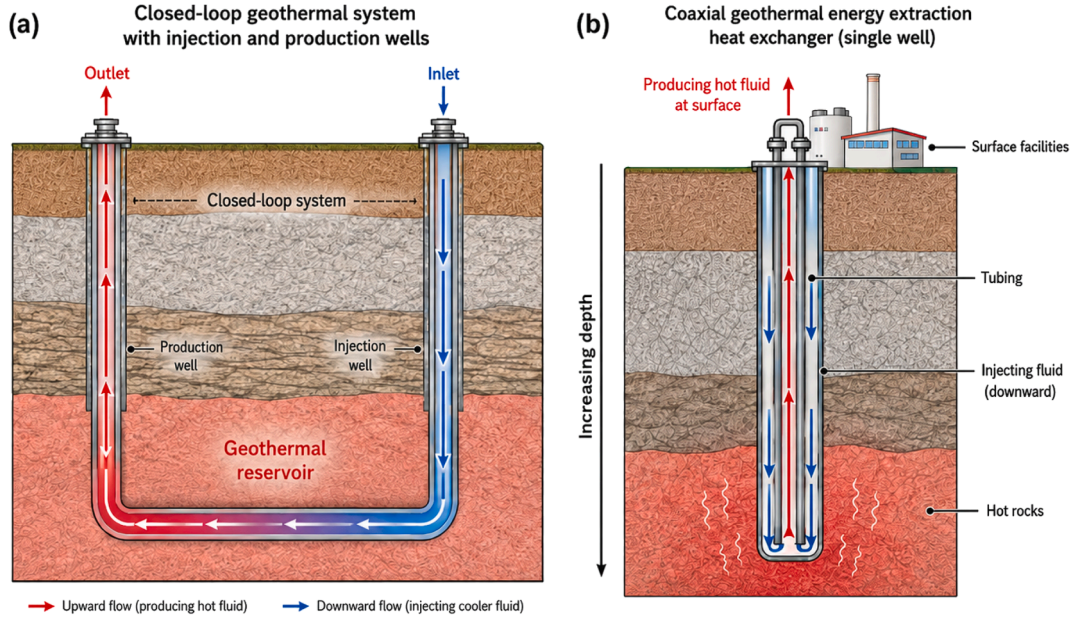


Fig. 12. (a) Closed-loop geothermal system: heat is extracted through circulating working fluid between separate injection and production wells within a geothermal reservoir; (b) Single well coaxial heat exchanger: heat is extracted within one well using a coaxial tube, cooler fluid is injected down the annulus, and hot fluid returns from the inner tubing.

Across multiple exchanger configurations, Mansoury et al. (2020) further showed that nanofluid-based heat-transfer enhancement is commonly accompanied by increased flow resistance, which must be treated as a design trade-off rather than an afterthought. Consistent with these observations, Mokhtari Moghari et al. (2015) numerically quantified how nanofluid pressure drop increases with nanoparticle loading for Al_2O_3–water flow in horizontal annuli.

For geothermal-relevant geometries, Liu et al. (2023) experimentally evaluated CuO/water nanofluid in a spiral-coil ground heat exchanger and reported measurable hydraulic resistance effects alongside thermal-performance changes. In a borehole context, Jahanbin et al. (2022) showed that the resulting increase in ΔP translates directly into higher pumping-power requirements for U-tube borehole heat exchangers when nanofluids are used as the carrier fluid. From a mechanistic perspective, Wang and Mujumdar (2008) highlighted that increasing particle volume fraction raises effective viscosity and therefore wall shear stress and frictional losses, which is why stable dispersion is central to performance claims. This practical constraint is echoed in broader renewable-energy nanotechnology assessments that emphasize aggregation control as an operational requirement, not a laboratory detail (Hussein, 2015). Because density and rheological properties also shift with nanoparticle loading, property datasets such as those reported for Al_2O_3–water nanofluids provide the basis for estimating pressure-loss penalties under realistic operating conditions. A geothermal-focused synthesis of nanofluid applications argues that these coupled thermal–hydraulic tradeoffs are a main reason why optimized nanoparticle selection, including type, size, loading, and formulation strategy, remains critical for scalable geothermal deployment (Soltani et al., 2022).

Flow assurance is also directly connected to clogging, scaling interaction, and corrosion/material compatibility. Clogging is the most direct nanofluid-related concern because nanoparticle agglomeration, sedimentation, and surface deposition can restrict flow paths, increase hydraulic resistance, and reduce heat-transfer efficiency. Scaling and corrosion are not always caused directly by nanoparticles, but they become important when nanofluids are prepared in saline geothermal brines or circulated through high-temperature geothermal equipment. Under these conditions, nanoparticle deposition may interact with mineral precipitation, while surfactants, stabilizers, and particle–wall interactions may influence erosion, corrosion, or material compatibility. Therefore, geothermal nanofluid deployment should evaluate clogging, scaling, corrosion, and erosion together as field-scale integrity risks rather than treating them as isolated issues.

The third dimension is environmental risk. Although many nanofluid studies assume closed-loop circulation, environmental concerns remain relevant because leakage, fluid replacement, disposal, or accidental release could introduce engineered nanoparticles, surfactants, or stabilizers into soil or groundwater. The environmental risk depends on nanoparticle composition, particle size, toxicity, persistence, recovery efficiency, and end-of-life handling. Therefore, environmental assessment should not focus only on lower CO_2 emissions or improved efficiency; it should also include nanoparticle recovery, toxicity screening, disposal pathways, and life-cycle impacts. This is particularly important because geothermal nanofluids would require larger fluid volumes and longer circulation times than many laboratory heat-transfer studies.

The fourth dimension is economic constraint. The economic limitation is not only the purchase price of nanoparticles. Large-scale geothermal deployment would require nanoparticle production, dispersion equipment, stabilizers, quality control, filtration, monitoring, fluid replacement, and possible recovery or disposal systems. These costs are added to the pumping-power penalty caused by higher viscosity or pressure drop. Therefore, even when nanofluids increase heat extraction, the technology may not be economically favorable unless the additional thermal output exceeds the combined cost of fluid preparation, pumping, maintenance, environmental management, and replacement.

This concern is supported by the limited real-world geothermal nanofluid evidence. The field-relevant studies by (Kapicioglu, 2022; Kapıcıoğlu and Esen, 2024) in Türkiye demonstrate that nanofluids can be operated in integrated GSHP/GHE prototype systems, but the reported system-level benefits remain modest. For example, the slinky-GHE heating study increased COP only from 4.30 for the base fluid to 4.38 with 0.1vol% Al_2O_3/EG-water, while 0.2vol% reduced the benefit to 4.34. A simple screening calculation illustrates the economic limitation: for a 2.207 kW heating load operated for 1500 full-load hours/year, the electricity saving from COP 4.30 to 4.38 is only about 14 kW h/year, or approximately $2.1/year at $0.15/kWh. This implies that the acceptable nanofluid premium for a 10-year payback would be only about $21 for this small prototype, before accounting for nanoparticle preparation, stability management, replacement, or disposal. The long-term follow-up study further weakens the economic case because the same nanofluid-assisted system showed up to 3% loss in GHE performance and 2.5% drop in COP after three years, indicating that sedimentation or standby degradation can convert short-term gains into operational penalties.

Based on the DOE/EERE TRL scale, these real-world GSHP studies are best interpreted as approximately TRL 6, because they demonstrate integrated prototype systems in a relevant environment. However, they do not reach TRL 7 because there is no replicated pilot-scale or near-commercial geothermal deployment with long-duration reliability, cost tracking, environmental assessment, and maintenance validation. Therefore, the current field evidence suggests that geothermal nanofluids are technically promising but economically immature. Future studies should report not only COP or heat-transfer improvement, but also nanofluid inventory, preparation cost, pumping energy, replacement frequency, filtration/maintenance needs, disposal cost, and long-term stability under real operating cycles.

9.4. Potential solutions to challenges in nanofluid deployment for geothermal systems

This section presents feasible solutions to the challenges identified in prior sections that hinder the deployment of nanofluids in geothermal content.

- Nanoparticle stability and agglomeration:
  1. *Use of charged or polymeric surfactants:* Charged or polymeric surfactants (SDS, SDBS, CTAB, PVP, etc.) tailored to the particle type (metal oxide vs. carbon) prevents coagulation. Adjusting pH and ionic strength (e.g., pH 4–9) can maximize zeta potential. For example, optimal nanofluid stability was observed at volume fractions below 2% and at pH 4–9 (Razzaq et al., 2025). Continuous agitation or ultrasonication, along with high-shear mixing during preparation, also disrupts incipient clusters and extends the dispersion time (Razzaq et al., 2025). Mousavi et al. (2025a) assessed SDS, APTES, and Span 80 as surface modifiers to stabilize aluminum-based nanofluids under closed-loop geothermal conditions (50–100°C and 100–300 bar). Surfactant functionalization increased surface charge relative to the unmodified nanofluid (−18.0 mV), with SDS (−42.7 mV) and APTES (−36.5 mV) providing stronger electrostatic stabilization than Span 80 (−26.2 mV). DLVO analysis showed higher energy barriers after modification (4.5 zJ for SDS, 6.0 zJ for Span 80, and 8.5 zJ for APTES), indicating improved resistance to aggregation compared with bare aluminum (1.7 zJ). Long-term monitoring (DLS/CT/Cryo-SEM) demonstrated that SDS-coated nanofluids exhibited the smallest increase in hydrodynamic diameter and the most uniform dispersion, while Span 80 showed the greatest structural instability and APTES showed intermediate behavior, with divergence becoming evident beyond 90–100 days. In four-month thermal aging at 80–100°C, stability indicators stayed above 95% for the first two months, but degradation became

pronounced after month 3 (notably at 100°C), supporting the practical use of SDS- and APTES-stabilized nanofluids for 3 months before reconditioning in geothermal loops (Mousavi et al., 2025a). Despite promising stabilization, the study remains constrained by ≤ 100°C fluid validation and 3-month durability, leaving key geothermal uncertainties unresolved—particularly long-term thermal cycling and high-salinity brine interactions (ionic screening, scaling/corrosion, and rock–fluid effects) required for field deployment.

2. *Choosing naturally stable nanoparticles and geometries:* Oxide nanoparticles such as SiO_2 and Al_2O_3, particularly when surface-modified, are often reported to remain well-dispersed for months under controlled conditions. High–surface area materials (e.g., MXenes and graphene) can also be chemically functionalized (for example, by introducing oxygen-containing groups) to strengthen interparticle repulsion and reduce clumping. Likewise, anisotropic nanomaterials such as CNT and graphene nanoflakes may preferentially orient under flow, which can help limit sedimentation relative to spherical particles. A further option is to use hybrid nanofluids that blend two nanoparticle types, as some combinations exhibit improved dispersion and greater stability. Across these strategies, selecting sub-50 nm particles and applying steric stabilization remains a practical way to promote stabilization and delay aggregation (Razzaq et al., 2025).
3. *Consistent, well-documented dispersion protocols:* A key step is to adopt consistent, well-documented dispersion protocols (Kotadia and Shah, 2021). Extended ultrasonication (with temperature control) can reduce early-stage clustering, and filtration or centrifugation can remove residual aggregates before use. More broadly, coordinated industry–academic guidelines for preparation and characterization would improve reproducibility, supported by agreed stability metrics (e.g., Turbiscan-based indices and zeta-potential acceptance thresholds) (Kotadia and Shah, 2021).
4. *Invest in R&D of novel stabilizers:* Investing in R&D of novel stabilizers (e.g. thermally stable polymers, ionic liquids) that survive >300°C and implementing quality standards that require stability testing under reservoir conditions is another potential solution. Policy incentives (e.g. grants, tax credits) for developing durable nanofluid formulations can also accelerate commercialization. Overall, a combination of chemical design (surface modifiers, optimal pH) and robust preparation methods can overcome agglomeration issues (Kotadia and Shah, 2021; Mousavi et al., 2025a).

- Pumping Power and Pressure Drop:
  1. *Use the lowest effective particle loading to achieve heat-transfer goals:* High-conductivity additives like graphene or carbon nanotubes can allow sub-percent volume fractions, limiting viscosity rise. Surface treatments again help: SDS- or silane-modified nanofluids showed 6%–8% lower viscosity and 7%–10% lower friction factor than unmodified cases (Mousavi et al., 2025b). Any reduction in effective viscosity directly cuts pumping power.
  2. *Shape optimization of nanoparticles:* High-aspect-ratio particles (nanorods, nanotubes) can align with the flow and cause less drag than spheres. Studies of ZnO nanofluids found that increasing particle aspect ratio decreased the friction factor in turbulent pipe flow (Lin et al., 2022). In practice, using fiber-like or platelet nanoparticles (e.g. CNTs, graphene) may mitigate pressure-drop penalties while delivering excellent thermal conductivity.
  3. *Enlarge pipe diameters or smooth inner surfaces:* Enlarging pipe diameters or smoothing inner surfaces (with ceramic or Teflon coatings) in circulation loops can help reduce head losses. Preferring straight pipelines with gentle curves and refraining from unnecessary fittings or sudden contractions, when possible, can further improve circulation and reduce pumping costs. Multiple flow paths, where space permits, can trade higher flowrate for lower pressure drop. Insulating piping to ensure the nanofluid carries more energy per pumping work and using heat exchangers with fins or microchannels can help further lower flowrates for a given thermal duty.
  4. *Control injection velocity:* Moderate flow rates (order 0.03–0.05 m/s) often maximize heat uptake while keeping power use reasonable (Mousavi et al., 2025b). Operating in a turbulent regime just sufficient for mixing – excessive turbulence raises friction, while fully laminar flow sacrifices heat transfer. Furthermore, periodically pulsing or flushing the flow can avoid clogging and minimize large pressure surges.
  5. *Policy and Economics:* Incorporating full life-cycle pumping costs in project planning is necessary to evaluate economic viability. Government subsidies or low-interest loans for high-efficiency pumps can be justified by the performance gains they deliver. Furthermore, regulations can mandate energy-efficiency ratings for geothermal equipment. Combining nanofluids with renewable incentives can offsets higher pump energy with greater geothermal output, improving economics.
- ***Cost and Scalability of Nanofluid Production:***
  1 *Prioritize inexpensive, abundant nanoparticles*: Oxides like SiO_2 or Al_2O_3 cost only a few dollars per kilogram (versus $5/g for specialty particles), and can be sourced from industrial byproducts or natural clays (Kotadia and Shah, 2021). Even magnetic iron oxide or carbon black (soot) is orders of magnitude cheaper. Using waste streams (e.g., slag and fly ash) as nanoparticle feedstock could dramatically reduce material costs.
  2. Nanofluid manufacturing in large mixing vessels with recirculation loops makes fluid prep easy for large volumes. Integrated filtration minimizes waste, allowing recovery and reuse of nanofluid. Modular on-site “mixing stations”, such as ready-mix concrete plants, could improve efficiency and lower costs.
  3. *Design geothermal plants to recover and reuse nanoparticles*: For example, settling tanks or magnetic separators can reclaim particles at the end of life. Regenerating nanofluid reduces the need for fresh nanoparticles. Patentable “closed-loop” systems promising zero nanoparticle loss would appeal to regulators.
  4. *Policy and standardization:* Provide R&D tax credits or grants for nanomaterial manufacturing scale-up. Classify nanofluid-enhanced geothermal as clean-energy subsidies or carbon credits to boost ROI. Use public procurements like geothermal plants as launch customers to generate volume. Develop industry standards for nanofluid fabrication and quality, including particle size and purity. Certified nanofluid types (e.g., Al_2O_3@SDS nanofluid, pH 7) would ease procurement and encourage competition through bulk pricing.
- ***Environmental and Regulatory Concerns:***
  1. *LCA (Life-Cycle Assessment) studies:* LCA studies that include accounting for nanoparticle production, transport, and end-of-life can ensure that nanofluid use reduces net CO_2 emissions (e.g., via smaller drilling footprint or higher efficiency).
  2. *“Green” nanoparticles:* Silicon dioxide, cellulose nanofibers, zeolites or clays, and certain metal oxides have minimal ecological risk compared to heavy metals or engineered carbon. Whenever feasible, opt for biodegradable or water-soluble coatings. For instance, using an Al_2O_3 nanofluid stabilized with eco-friendly, plant-based surfactants could help minimize long-lasting pollution.
  3. *Encourage using technologies to recover nanomaterials*: Technologies that recover nanomaterials from brines or geothermal fluids, like magnetic separation or sorbents for concentrating particles can lead to reuse or neutralization of nanoparticles, reducing their operational costs and environmental impact. Regulations can require geothermal operators to plan for nanofluid disposal, including filtration in plant design.

4. *Provide incentives for low-impact nanofluid choices:* Incentives such as bonuses and credits can promote low-impact nanofluid choices, while taxes or restrictions can discourage toxic nanomaterials. Certifications such as EPA Safer Choice or the EU Ecolabel can further support green nanofluids. Finally, engaging stakeholders by highlighting CO_2 reductions and communicating safety transparently can help build social license.

10. Modeling framework for geothermal working fluids

The performance of geothermal working fluids is controlled by coupled thermal, hydraulic, and porous-media transport processes. Therefore, the evaluation of water/brine, supercritical CO_2, phase-change materials, and nanofluids should not be limited to individual thermophysical properties alone. Instead, properties such as density (ρ), viscosity (μ), specific heat capacity (C_p), thermal conductivity (k), and thermal expansion coefficient (β) should be linked to the governing equations and dimensionless groups describing heat extraction, fluid mobility, convective heat transfer, and buoyancy-driven circulation.

A basic expression for geothermal heat extraction is:

$$Q = \dot{m} C_p \Delta T$$

where Q is the heat extraction rate, $\dot{m}$ is the mass flow rate, C_p is the specific heat capacity of the working fluid, and ΔT is the temperature difference between production and injection conditions. This equation shows that a working fluid with higher heat capacity can transport more heat for the same mass flow rate and temperature change. However, heat extraction also depends on how easily the fluid flows through the reservoir and how efficiently heat is transferred from the rock to the fluid.

For flow through geothermal reservoirs, mass conservation in porous media can be expressed as:

$$\frac{\partial(\phi\rho_f)}{\partial t} + \nabla \cdot (\rho_f \mathbf{u}) = q_m$$

where ϕ is porosity, ρ_f is fluid density, u is Darcy velocity, and q_m is a mass source or sink term. In low-velocity porous-media flow, Darcy's law is commonly used:

$$u = -\frac{K}{\mu}(\nabla p - \rho_f \mathrm{g})$$

where K is permeability, μ is dynamic viscosity, p is the pressure gradient, and g is gravitational acceleration. This relation directly links the viscosity of the working fluid to injectivity and circulation rate. Lower-viscosity fluids generally require less pressure gradient to achieve the same flow rate, while higher-viscosity fluids may increase pumping power and reduce reservoir sweep efficiency. For fractured or high-permeability geothermal systems, Darcy's law may be insufficient because viscous shear and inertial effects can become important. In such cases, the Darcy–Brinkman equation provides a more general momentum formulation:

$$0 = -\nabla p + \mu_{\mathrm{eff}} \nabla^2 \mathrm{u} - \frac{\mu}{K}\mathrm{u} + \rho_f \mathrm{g}$$

where $\mu_{\mathrm{eff}}\nabla^2\mathrm{u}$ represents viscous diffusion or boundary-layer shear effects. If inertial effects are significant, a Forchheimer correction can also be included:

$$0 = -\nabla p + \mu_{\mathrm{eff}} \nabla^2 \mathrm{u} - \frac{\mu}{K}\mathrm{u} - \frac{C_F \rho_f}{\sqrt{K}}|\mathrm{u}|\mathrm{u} + \rho_f \mathrm{g}$$

where C_F is the Forchheimer coefficient. This form is particularly relevant for enhanced geothermal systems, where flow may occur through rough fractures or stimulated fracture networks.

The energy balance in a geothermal porous medium can be written as:

$$\left[(1-\phi)\rho_s C_{ps} + \phi\rho_f C_{pf}\right]\frac{\partial T}{\partial t} + \rho_f C_{pf}\mathbf{u}\cdot\nabla T = \nabla\cdot\left(k_{\mathrm{eff}}\nabla T\right) + Q_T$$

where ρ_s and C_{ps} are the density and heat capacity of the rock, C_{pf} is the fluid heat capacity, T is temperature, k_{eff} is the effective thermal conductivity of the saturated porous medium, and Q_T is a heat source or sink term. This equation reflects geothermal conditions because heat is stored in both the rock and the fluid, while heat transport occurs by conduction through the rock–fluid system and advection by the moving working fluid.

If the rock and fluid are not at the same temperature, a local thermal non-equilibrium model can be used. In this case, separate energy equations are written for the fluid and solid phases:

$$\begin{aligned}\phi\rho_f C_{pf}\frac{\partial T_f}{\partial t} + \rho_f C_{pf}\mathrm{u}\cdot\nabla T_f &= \nabla\cdot\left(\phi k_f \nabla T_f\right) + h_{sf}a_{sf}\left(T_s - T_f\right)(1-\phi)\rho_s C_{ps}\frac{\partial T_s}{\partial t} \\ &= \nabla\cdot\left((1-\phi)k_s\nabla T_s\right) + h_{sf}a_{sf}\left(T_f - T_s\right)\end{aligned}$$

where T_f and T_s are the fluid and solid temperatures, h_{sf} is the solid–fluid heat-transfer coefficient, and a_{sf} is the interfacial area per unit volume. This approach is important in geothermal reservoirs where rapid fluid flow through fractures prevents the rock and fluid from reaching local thermal equilibrium.

The convective heat-transfer coefficient is commonly evaluated using the Nusselt number:

$$Nu = \frac{hD}{k_f}$$

where Nu is the Nusselt number, h is the convective heat-transfer coefficient, D is a characteristic length such as pipe diameter or fracture aperture, and k_f is the fluid thermal conductivity. Rearranging this equation gives:

$$h = \frac{Nu\ k_f}{D}$$

This relationship shows that increasing the effective thermal conductivity of a working fluid can increase the convective heat-transfer coefficient, provided that the Nusselt number does not decrease due to unfavorable changes in viscosity or flow regime. Therefore, for nanofluids, the enhancement is not solely determined by the higher effective thermal conductivity but also by the combined effects of viscosity, density, and heat capacity on convective transport.

The Reynolds number describes the flow regime:

$$Re = \frac{\rho_f v D}{\mu}$$

where v is the average fluid velocity. In geothermal wells and fractures, Re indicates whether the flow is laminar, transitional, or turbulent. A lower viscosity or higher density can increase Re, which may enhance convective heat transfer. However, increased viscosity, which may occur in some nanofluids or concentrated brines, can reduce Re, increase pressure losses, and reduce the net benefit of thermal enhancement.

The Prandtl number links momentum diffusivity and thermal diffusivity:

$$Pr = \frac{\mu C_p}{k_f}$$

or equivalently,

$$Pr = \frac{\nu}{\alpha}$$

where $\nu = \mu/\rho_f$ is kinematic viscosity and $\alpha = k_f/(\rho_f C_p)$ is thermal diffusivity. A high Pr indicates that momentum diffuses more rapidly

than heat, while a low *Pr* indicates stronger thermal diffusion. This is important when comparing water, brine, supercritical CO_2, and nanofluids because each fluid occupies a different range of *Pr*, affecting thermal boundary-layer development.

For buoyancy-driven geothermal circulation, the Rayleigh number is important:

$$Ra = \frac{g\beta\Delta TL^3}{\nu\alpha}$$

where g is gravitational acceleration, β is the thermal expansion coefficient, ΔT is the temperature difference, and L is a characteristic length. In porous geothermal reservoirs, the Darcy–Rayleigh number is more appropriate:

$$Ra_D = \frac{\rho_f g\beta\Delta TKL}{\mu\alpha}$$

This form includes permeability K, showing that buoyancy-driven circulation depends not only on the fluid properties but also on the ability of the reservoir to transmit flow. A higher Ra_D indicates stronger natural convection, while a lower value suggests conduction-dominated heat transfer.

The main property–performance relationships can therefore be summarized as follows:

$$C_p \uparrow \Rightarrow Q = \dot{m}C_p\Delta T\uparrow$$

$$k_f \uparrow \Rightarrow Nu = \frac{hD}{k_f}, h = \frac{Nuk_f}{D}$$

$$\mu \uparrow \Rightarrow Re\downarrow, \mathrm{u}\downarrow, \text{pumping power}\uparrow$$

$$K \uparrow \Rightarrow \mathrm{u}\uparrow, Ra_D\uparrow\beta\uparrow\Rightarrow Ra\uparrow, Ra_D\uparrow$$

Thus, geothermal working-fluid performance is governed by the balance between thermal benefits and hydraulic penalties. For example, nanofluids may improve heat transfer by increasing effective thermal conductivity:

$$k_{\mathrm{eff}} > k_f$$

which can increase the convective heat-transfer coefficient:

$$h_{\mathrm{eff}} = \frac{Nu\ k_{\mathrm{eff}}}{D}$$

However, nanoparticle addition may also increase viscosity:

$$\mu_{\mathrm{eff}} > \mu_f$$

which can reduce Reynolds number:

$$Re_{\mathrm{eff}} = \frac{\rho_{\mathrm{eff}} vD}{\mu_{\mathrm{eff}}}$$

and increase the pressure drop. Therefore, the net geothermal benefit of nanofluids should be evaluated using both heat-transfer and flow-resistance criteria, rather than thermal conductivity alone.

Heat-transfer scaling laws are useful for comparing working fluids and geothermal systems under different operating conditions. For forced convection in wells, pipes, or heat exchangers, the Nusselt number is commonly expressed as a function of Reynolds and Prandtl numbers:

$$Nu = CRe^m Pr^n$$

where C, m, and n depend on geometry and flow regime. This relation shows that changes in density, viscosity, heat capacity, and thermal conductivity influence heat transfer through their effects on *Re* and *Pr*.

For buoyancy-driven porous-media convection, heat transfer is commonly scaled as:

$$Nu = aRa_D^b$$

where a and b are empirical or system-dependent constants. This scaling indicates that stronger buoyancy and higher permeability increase convective heat transfer relative to conduction.

The conductive reference heat flux can be written as:

$$q_{\mathrm{cond}} = -k_{\mathrm{eff}}\nabla T$$

while the advective heat flux is:

$$q_{\mathrm{adv}} = \rho_f C_{pf}\mathbf{u}T$$

The relative importance of advective and conductive heat transport can be represented by the Peclet number:

$$Pe = Re\ Pr$$

or, in porous media:

$$Pe = \frac{vL}{\alpha}$$

A high *Pe* means heat transport is mainly controlled by fluid advection, while a low *Pe* indicates conduction-dominated behavior. This is highly relevant in geothermal reservoirs because high flow rates may improve heat extraction initially but can also accelerate thermal breakthrough.

Overall, this governing equation and dimensionless analysis approach provide a stronger basis for reviewing geothermal working fluids. It shows that performance depends on the coupled influence of C_p, k, ρ, μ, β, K, and ϕ on heat extraction rate, convective heat transfer, buoyancy circulation, and pumping requirements. Therefore, the enhancement observed in nanofluids should be described as a combined thermo-hydraulic effect: increased effective thermal conductivity can improve the Nusselt number and heat-transfer coefficient, but increased viscosity may reduce Reynolds number, decrease mobility, and increase pumping power. This balanced interpretation is more suitable for geothermal systems, where both heat transfer and fluid circulation control the practical efficiency of working fluids.

11. Critical synthesis and comparative assessment of geothermal working fluids

This section compares water/brine, SC-CO_2, PCM-based systems, and nanofluids using a normalized benchmarking approach and a Multi-Criteria Decision Analysis (MCDA) framework. Because the reviewed studies differ in system geometry, reservoir assumptions, flow rate, temperature, pressure, fluid formulation, and reported performance metric, a formal statistical meta-analysis was not appropriate. Instead, a range-based quantitative synthesis and MCDA framework were used to compare fluids under consistent decision criteria.

Normalized Benchmarking of Working Fluids: Table 6 summarizes the main thermal benefits, hydraulic or operational penalties, and system-level interpretation of each working-fluid class. Water/brine is treated as the practical baseline because it remains the most widely used geothermal working fluid.

The normalized comparison shows that no working fluid is universally superior. Water/brine remains the most mature option; SC-CO_2 is attractive where hydraulic mobility and thermosiphon effects dominate; PCM-based systems are most useful for thermal buffering; and nanofluids are promising only when enhanced heat transfer outweighs viscosity, pressure drop, and stability penalties.

MCDA Criteria and Weighting: To reduce subjectivity in the comparison, the original 1–5 scoring matrix was revised into an MCDA framework. Six criteria were selected based on the main deployment constraints identified in the review. Each fluid was scored from **1** to **5**,

Table 6
Normalized benchmarking of geothermal working fluids relative to water/brine.

Fluid class	Main thermal benefit	Main hydraulic/operational penalty	Representative quantitative indicators	System-level interpretation
Water/brine	High heat capacity and proven sensible heat extraction. Water has high C_p of about 4180 J/(kg·K)	Scaling, corrosion, salinity-related property degradation, and water-management issues.	Dissolved salts such as NaCl can reduce thermal performance by lowering thermal conductivity (Aleksandrov et al., 2013)	Most mature and deployable baseline fluid, but chemically constrained in high-salinity and reactive formations.
SC-CO_2	Low viscosity, high expansivity, strong buoyancy response, and thermosiphon potential.	Lower thermal conductivity and heat capacity than water; performance depends strongly on reservoir and flow conditions.	SC-CO_2 thermal conductivity can be much lower than water, with values around 0.038 W/(m·K) under relevant conditions (Huber et al., 2016)	Favorable when mobility, low pressure loss, and buoyancy-driven circulation dominate; not universally superior to water.
PCM-based systems	Latent heat storage and thermal buffering, useful for reducing temperature fluctuations.	Low intrinsic thermal conductivity, phase segregation, cycling degradation, encapsulation issues, and slurry stability limitations.	PCM slurries can increase thermal output by about 12.5% compared with water in closed-loop systems (Soni et al., 2023)	More suitable as a thermal-storage or buffering enhancement than as a universal circulating fluid.
Nanofluids	Increased viscosity, pressure drop, pumping power, agglomeration, sedimentation, clogging risk, cost, and environmental uncertainty.	Increased effective thermal conductivity and convective heat-transfer coefficient.	CuO/water nanofluid increased heat-transfer rate by 39.84% and improved the heat-load-to-pumping-power ratio by 20%. Cu-based nanofluid reduced borehole thermal resistance by 3.5%–3.8% at 0.1vol%–1vol% (Diglio et al., 2018)	Promising mainly in controlled closed-loop systems when thermal gains exceed hydraulic and stability penalties.

where **1** represents very unfavorable performance and **5** represents highly favorable performance (Table 7).

The final MCDA score for each fluid was calculated as:

$$S_i = \sum_{j=1}^{n} w_j x_{ij}$$

where S_i is the final score for fluid i, w_j is the weight assigned to criterion j, and x_{ij} is the normalized score of fluid i under criterion j (Table 8).

Water/brine receives the highest overall score because it has the greatest technical maturity, broad availability, and proven field performance. However, its operational-integrity score is reduced because geothermal brines can cause scaling, corrosion, and mineral precipitation, especially under high-temperature and high-salinity conditions (Penot et al., 2023). SC-CO_2 scores highest in hydraulic performance because of its low viscosity, high expansivity, and thermosiphon potential. It remains attractive in systems where reduced pressure loss and buoyancy-driven circulation are important. However, its thermal score is lower than water/brine because SC-CO_2 has lower heat capacity and thermal conductivity, which can limit heat uptake under some conditions (Lei, 2022). Its economic score is also reduced because CO_2-based systems may require compression, transport, storage infrastructure, and CO_2-compatible materials (Baig et al., 2025; Fentaw et al., 2026). PCM-based systems receive the lowest overall score because they are better suited for thermal storage and buffering than for use as universal circulating fluids. Although PCMs can improve thermal stability through latent heat storage, their low thermal conductivity, cycling degradation, phase segregation, encapsulation requirements, and limited field readiness remain major constraints (Zargartalebi et al., 2025; Zhao et al., 2020). Nanofluids receive the highest thermal-performance score because they can improve effective thermal conductivity and convective heat transfer. However, their overall score is reduced by hydraulic and operational penalties. Increased nanoparticle loading can increase viscosity, pressure drop, and pumping-power demand, while stability loss, agglomeration, sedimentation, and clogging remain important concerns (Soltani et al., 2022). Therefore, nanofluids are most defensible in controlled closed-loop systems where particle type, concentration, and stabilization strategy can be optimized.

Geothermal Fluid Selection Map: The MCDA results do not indicate a universally superior working fluid. Instead, they show that fluid selection should depend on geothermal setting, design objective, and operating constraints (Table 9).

Overall, the MCDA framework supports a context-dependent interpretation of geothermal working-fluid selection. Water/brine remains the most reliable near-term baseline. SC-CO_2 is most favorable where hydraulic mobility and buoyancy-driven circulation dominate. PCM-based systems are best interpreted as thermal-buffering or storage enhancements. Nanofluids are particularly promising in closed-loop systems, where heat transfer improvements can be achieved without excessive viscosity, pumping power, or stability penalties, and without environmental or cost penalties.

Table 7
MCDA criteria and weighting factors.

Criterion	Meaning	Weight
Thermal performance	Heat-transfer coefficient, heat extraction, outlet temperature, heat capacity, and thermal conductivity	0.25
Hydraulic performance	Pressure drop, viscosity, pumping-power demand, and circulation efficiency	0.2
Operational integrity	Scaling, corrosion, clogging, stability, agglomeration, and material compatibility	0.2
Environmental/ safety risk	Toxicity, emissions, leakage, disposal, water demand, and environmental exposure	0.15
Economic feasibility	Fluid cost, infrastructure, treatment, reuse, and field-scale preparation	0.1
Technical maturity/ TRL	Field use, pilot studies, commercial readiness, and operational experience	0.1

12. Research gaps and future prospects

While nanofluids have demonstrated improved thermal properties of the working fluid, issues related to system erosion, corrosion, stability, nanoparticle agglomeration, environmental aspects, and production costs limit their immediate real-world implementation. Although oxide nanofluids in geothermal applications have been well studied experimentally, analytically, and economically, there is limited work on CNTs and MWCNTs. As some literature indicates, the increase in thermal conductivity in MWCNT is up to 150%. The thermophysical properties of nanofluids are well-studied, but the effects on pressure drop and friction factor also need to be thoroughly investigated, as these are among the governing variables in geothermal system effectiveness.

As indicated by Chakraborty and Panigrahi (2020), proper stability design is crucial for reducing resistance in the heat exchange system. Raei et al. (2018) reported that adding a drag-reducing Al_2O_3 nanofluid decreased flow resistance by 4.8% in heat-exchanger tests, while Da et al. (2022) showed that an activated-silica nanofluid can reduce flow resistance by 30.36% (up to 95.43%) based on combined microfluidic experiments and CFD modeling. However, the economic feasibility of

Table 8
MCDA scoring matrix for geothermal working fluids.

Fluid class	Thermal performance	Hydraulic performance	Operational integrity	Environmental/safety risk	Economic feasibility	Technical maturity/ TRL	Final weighted score
Water/brine	4	3	2	4	4	5	3.50
SC-CO_2	3	5	3	3	2	3	3.30
PCM-based systems	3	2	2	3	2	2	2.40
Nanofluids	5	2	3	3	3	3	3.30

Table 9
Geothermal fluid selection map.

Geothermal setting or design objective	Most defensible fluid option	Reason
Mature hydrothermal system	Water/brine	Highest technical maturity, established infrastructure, and proven field use.
High-temperature, low-permeability EGS	SC-CO_2 or engineered water/ brine	SC-CO_2 offers lower viscosity and buoyancy advantages, while water/brine offers higher heat capacity.
High-temperature, high-permeability reservoir	Water/brine	Higher heat capacity and more stable thermal sweep; SC-CO_2 may experience preferential flow or early thermal breakthrough.
Moderate-temperature closed-loop wellbore heat exchanger	Water/brine or optimized nanofluid	Nanofluids may improve heat transfer if viscosity and stability penalties are controlled.
Thermal-storage-dominated system	PCM-integrated system	PCMs provide latent heat buffering and can stabilize outlet temperature.
Environmentally sensitive site	Water/brine or low-risk SiO_2-based nanofluid	Lower toxicity and simpler environmental management.
High-performance closed-loop system	Low-loading CNT, graphene, or hybrid nanofluid	High thermal conductivity at low concentration may reduce viscosity penalty, but field validation is still needed.

deploying these drag-reducing nanofluids at geothermal field scale has not yet been established, warranting further investigation.

Additionally, erosion and corrosion are issues that require further attention in future research. According to reports, Al_2O_3 increases the erosion and corrosion rate of pipes by 237% compared to seawater in turbulent flows (Pisarevsky et al., 2024). Fotowat et al. (2017) experimentally showed that a water-based nanofluid can exhibit ~2× higher corrosion rates under acidic conditions, and Saidina et al. (2020) similarly emphasize in their review that acidic environments intensify corrosion risks for metal-oxide nanofluid systems. Additionally, to the above-mentioned limitations, future research should focus on sedimentation issues in heat exchange systems, namely, the correlation between nanoparticle type, concentration, and their impact on pumping power and pressure drop.

Above all, there are some environmental concerns associated with the use of nanofluids, as they can easily disperse into the environment, contaminating air, water, and soil, resulting in ecological impacts (Bhattacharjee et al., 2023). Certain nanoparticles, like boron-containing ones (water-rock interactions), may be harmful to plants and animals if released in high concentrations from geothermal source systems (Mott et al., 2022), reinforcing the need for mitigation strategies alongside performance goals. Soltani et al. (2022) highlight that moving nanofluid concepts toward geothermal deployment requires attention to environmental compatibility and safer formulations as part of overall feasibility, while Bhattacharjee et al. (2023) synthesize evidence that nanomaterials can pose human-health and ecological risks depending on composition and exposure pathways. From an economic sustainability standpoint, Mukherjee et al. (2024) argue that future research should prioritize safer, environmentally responsible alternatives that reduce adverse impacts without undermining practicality. Therefore, a practical next step is to prioritize fluid formulations and operational strategies that measurably reduce toxicity and environmental risk, but still meet field requirements for thermal delivery, stability, and manageable pumping power, so safety improvements do not come at the expense of deployability.

Regarding PCMs, the main issue is the low thermal conductivity of pure PCMs. However, as reported in (Qiao et al., 2021), adding an expanded graphite (EG) of around 20wt% would increase the thermal conductivity of organic PCMs by up to 250%. The economic feasibility and realistic deployment opportunities of such combinations still need to be addressed in future research.

Water is suitable for geothermal energy, but in moderate-temperature reservoirs, low power-cycle efficiency and the need for phase-change to steam limit its use without binary (ORC) conversion and extra heat-exchange infrastructure. Moreover, brines have lower thermal conductivities than pure water. For instance, 1 mol/kg of NaCl reduces the thermal conductivity by 1%-3%, which can also lead to scaling and corrosion problems. Given their technical maturity, the main remaining research directions for water and brines are largely incremental and cost-driven, such as focusing on cheaper, more durable scaling and corrosion control approaches that preserve heat-exchanger performance and long-term operability without adding major complexity or operating costs.

Even though SC-CO_2 can offer operational advantages, such as lower pressure losses and potentially higher circulation rates than water, multiple studies also report that this does not consistently translate into higher delivered temperature or sustained heat output. Additionally, while SC-CO_2, as a geothermal working fluid, is particularly beneficial in EGS systems where some part of CO_2 is sequestered in the ground, addressing global environmental issues, its long-term applicability, given its low thermal conductivity in supercritical environments, raises concerns about its further use. In particular, the low thermal conductivity can manifest as a practical heat-transfer penalty, where high circulation rates still yield lower outlet temperatures and weaker heat sweeping in heterogeneous formations, making outcomes strongly dependent on reservoir permeability, porosity, pressure, and temperature rather than uniformly favorable. These limitations reinforce the need to frame SC-CO_2 as a context-dependent option. Therefore, running standardized SC-CO_2 pilots in several contrasting reservoirs and reporting consistently defined temperature-decline, net-heat-delivery, and circulation/compression-energy metrics would enable direct cross-site comparison and define an evidence-based applicability window for SC-CO_2.

13. Conclusion

A synthesis of the reviewed studies shows that no geothermal working fluid is universally superior. Optimal fluid selection depends on reservoir temperature and pressure, permeability, system configuration, operational risk tolerance, environmental constraints, and economic feasibility. Therefore, this review compares water/brine, supercritical CO_2, PCM-based systems, and nanofluids through a feasibility lens that

links thermophysical advantages to hydraulic penalties, operational integrity, cost, and environmental risk.

For nanofluids, the reviewed evidence shows that nanoparticle concentration, particle characteristics, and flow regime strongly control thermal gains. Increasing nanoparticle loading can improve thermal conductivity, with one representative dataset showing a 22% conductivity enhancement at 1.5× baseline concentration. However, nanofluids are not automatically superior because thermal enhancement is only useful when stability is preserved and hydraulic penalties remain acceptable. The evidence supports nanofluid deployment mainly in closed wellbore systems such as U-tube, coaxial, and closed-loop concepts, while open-hole geothermal circulation remains premature because of unresolved clogging, wellbore damage, nanoparticle migration, and long-term stability risks. Low-loading formulations using high-conductivity additives such as graphene or carbon nanotubes, or more stable and lower-cost oxides such as SiO_2 and Al_2O_3, appear more practical than high-concentration formulations that increase viscosity and pumping requirements.

For PCM-based approaches, the reviewed studies support their use as thermal buffers or thermal-storage enhancers rather than direct replacements for circulating working fluids. Representative PCM-integrated configurations report an average COP increase of approximately 26%, but long-duration operation may reduce effectiveness because of cycling degradation, high-temperature instability, and material compatibility issues. Improving PCM thermal conductivity remains necessary; for example, adding ethylene glycol at 10% concentration has been reported to increase PCM thermal conductivity by up to 250%. However, these material-level improvements still require techno-economic validation under geothermal operating conditions. In cost-oriented comparisons, nanofluids may reduce borehole length by approximately 1.3%–3%, whereas PCM-enabled designs may achieve up to 8% under favorable assumptions.

For supercritical CO_2, reported heat recovery relative to water spans approximately 0.8–1.9×, showing that its performance is strongly context-dependent. SC-CO_2 is most defensible where low viscosity, thermosiphon circulation, and reduced pumping demand dominate system behavior. However, it should not be treated as a universal replacement for water because its performance is sensitive to permeability, injection pressure, temperature, preferential flow, and thermal breakthrough. In systems where heat capacity, outlet temperature, and stable thermal sweep dominate, water/brine can remain more favorable.

Water/brine remains the most deployable near-term baseline because it is mature, operationally familiar, and compatible with existing geothermal infrastructure. However, scaling, corrosion, salinity effects, and brine-management requirements continue to limit performance and increase operating costs. Therefore, alternative fluids should be viewed as targeted solutions for specific operating windows rather than universal replacements.

Overall, the main contribution of this review is to show that geothermal working-fluid selection must be based on net system performance, not isolated property enhancement. Thermal benefits must be evaluated together with pumping power, clogging and scaling risks, long-term stability, materials compatibility, environmental impacts, cost, and technology readiness. The comparative scoring matrix supports the conclusion that nanofluids are promising for controlled closed-loop geothermal systems but are not yet field-ready for broad reservoir-scale deployment. Future progress should prioritize long-duration stability testing, standardized performance protocols, techno-economic analysis, life-cycle assessment, and pilot-scale validation under realistic geothermal operating conditions.

14. Declaration of generative AI and AI-assisted technologies

During manuscript preparation, the authors used ChatGPT for language editing and organization support; all content was reviewed and verified by the authors.

Nomenclature

NaCl	Sodium chloride	Ag	Silver
$CaCl_2$	Calcium chloride	MgO	Magnesium oxide
$MgCl_2$	Magnesium chloride	TiO_2	Titanium dioxide
Al_2O_3	Aluminum oxide	Fe_3O_4	Magnetite (iron (II,III) oxide)
CuO	Copper (II) oxide	SiO_2	Silicon dioxide (silica)
Cu	Copper	ZnO	Zinc oxide
CeO_2	Cerium (IV) oxide (ceria)	CNTs	Carbon nanotubes
ZrO_2	Zirconium dioxide (zirconia)	MWCNT	Multi-walled carbon nanotube
rGO	reduced graphene oxide	CTAB	Cetyltrimethylammonium bromide
SDS	Sodium dodecyl sulfate	SDBS	Sodium dodecylbenzenesulfonate
PVP	Polyvinylpyrrolidone	Span 80	Sorbitan monooleate
APTES	(3-Aminopropyl) triethoxysilane	DLVO	Derjaguin–Landau–Verwey–Overbeek (DLVO) theory-based stability analysis
CFD	Computational fluid dynamics	NEPCM	Nano-enhanced PCM

CRediT authorship contribution statement

Elvin Hajiyev: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft. **Jemal Fentaw:** Data curation, Formal analysis, Writing – review & editing. **Yildirim Kocoglu:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Abdul Rehman Baig:** Methodology, Writing – review & editing. **Hossein Emadi:** Resources, Supervision. **Marshall Watson:** Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The full list of nanofluid studies reviewed, including geothermal-specific studies and broader heat-exchanger or thermal-property studies, is provided in Appendix Table A1.

Table A1
A review of nanofluids used in geothermal energy extraction in heat exchangers.

Refs	Nanofluid	Purpose of the study conducted	Results obtained from the analysis
Sui et al. (2017)	Al_2O_3/water	Investigation of geothermal energy extraction from a double pipe heat exchanger	**11.24%** more heat energy is extracted when applying nanofluid than when using water at high flow rates. In geothermal energy extraction, the viscosity of the nanofluid must remain below a threshold of approximately 0.05 Pa s, as any further increase has little effect on the outlet temperature and heat capacity.
Narei et al. (2016a)	Al_2O_3/water	Reduction of Borehole Length for Vertical U-Tube Heat Exchangers in Ground Source Heat Pumps (GSHP)	A **5%** volume-concentrated Al_2O_3/water nanofluid required **1.3%** less borehole length to extract equivalent thermal power than water.
Daneshipour and Rafee (2017)	Al_2O_3/water CuO/water	The viability of Al_2O_3/water and CuO/water nanofluids as circulating fluids in the 200-m deep coaxial wellbore heat exchanger (CWHE) for ground source heat pumps	Adding **2vol%–6vol%** CuO or Al_2O_3 nanofluids to a coaxial geothermal borehole heat exchanger increased heat extraction by **0.4%–1.0%** (CuO > Al_2O_3), while pressure drop increased with concentration.
Peng et al. (2018)	Cu/water	U-tube heat exchanger with a 50 m length for geothermal heat pumps.	A **1.5%** volume concentrated Cu/water nanofluid needed about **3%** less borehole length than water to extract equivalent thermal power in both summer and winter.
Diglio et al. (2018)	Cu/water	The heat extraction capability of a 250 m long U-tube WHE (Wellbore Heat Exchanger)	Incorporating **1%** silver (Ag) nanoparticles resulted in a **27%** enhancement of the heat transfer coefficient. The cost of GSHP rises by **12%** when employing a Cu-based nanofluid with a **1%** concentration of Cu.
Du et al. (2020b)	CuO/water	The experimental investigation of the thermal performance of a double U-shaped Geothermal heat exchanger	**39.84%** rise in heat transfer rate by incorporating **3%** weight of CuO nanoparticles. Adding nanoparticles increases the pump's power consumption by **16.75%.**
Du et al. (2020a)	CuO/water	Numerical investigation of the effect of nanoparticle diameter and particle shape on the thermal performance of the Geothermal heating system	Spherical CuO particles provide **8.55%** greater energy efficiency than rod-shaped nanoparticles. As the performance efficiency of 5 nm and 50 nm diameter nanoparticles was less than 1, their application in geothermal heat extraction is not recommended. Utilizing optimally sized and shaped nanoparticles can significantly enhance geothermal heat extraction.
Javadi et al. (2021)	Ag-MgO/water, TiO_2-Cu/water, Al_2O_3-CuO/water, Fe_3O_4-MWCNT/ water	The effect of employing hybrid nanofluids in a U-tube heat exchanger of 2 m length on thermal performance in geothermal.	The **15%** volume of Ag-MgO/water hybrid nanofluid achieved a **67%** increase in the coefficient of performance as compared to water. Ag-MgO/water was chosen as the best working fluid due to its minimal pressure drop, optimal effectiveness, and thermal resistance.
Jahanbin et al. (2022)	Ag, Cu, and water SiO_2; TiO_2; Al_2O_3; Fe_2O_3; CuO and water	Evaluation of thermal performance by employing nanofluids in a single U-tube length of 200 m. Borehole heat exchangers (BHEs)	Ag/water with a **2%** volume fraction showed a peak reduction of **2.55%** in borehole thermal resistance when compared to pure water. The Ag/water required approximately **31%** more pumping power, and Cu/water required **26%** more pumping power, compared to water. SiO_2- and TiO_2-water nanofluids exhibit poor thermal performance, yet they demonstrate the lowest pressure drop.
Jahanbin et al. (2021)	Cu/water	Heat-carrying effect of nanofluid on a 100 m long U-tube as a BHE	A **0.5%** concentration of Cu/water nanofluids can reduce the thermal resistance of the borehole by around **2.25%** compared to water. **0.5%** and **2%** concentrations of nanoparticles have the optimal percentage of thermal resistance.
Chappidi et al. (2023)	Cu/water Al_2O_3-Cu/water CuO-Al_2O_3/water	Numerical investigation of extracting heat from a 3861 m deep abandoned oil well with the use of nanofluids in coaxial heat exchangers.	A **4%** volume fraction of Cu/water nanofluid increased the outlet temperature by **25%.** The coefficient of performance of nanofluids is **1.83** times higher than that of water in CWHE. Cu/water nanofluid extracts more heat energy than the Al_2O_3-Cu and CuO-Al_2O_3 hybrid nanofluids.
Jamshidi and Mosaffa (2018)	Al_2O_3/water	Thermal performance of a conical helical geothermal heat exchanger 3 m below the ground	A **0.5%** volume fraction of nanofluid increases thermal performance by **18%.** A decrease in nanoparticle diameter increases the heat transfer.
Liu et al. (2023)	Al_2O_3-CuO/water	Evaluation of the performance of a geothermal heat exchanger at a depth of 3 m with a diameter of 36 mm employing a hybrid nanofluid.	**2%** Al_2O_3 nanoparticles and a spiral pipe in BHE provide better thermal performance than a **2%** CuO nanofluid. Additionally, Al_2O_3 nanofluids have a performance coefficient of **4.6**, whereas CuO has a coefficient of **4.4.**
Q. Liu et al. (2023)	CuO/water	Experimental investigation of CuO/water nanofluid performance with spiral tube in the sandbox 4.1 × 1 × 1 m size	A 1% CuO/water nanofluid enhanced the heat exchange rate within a horizontal BHE by **9.4%** compared to that of water. However, it was not recommended to use this **1%** of the nanofluid as the performance coefficient was below 1. Elevating the concentration of CuO nanofluid enhances heat exchange efficiency and minimizes the pressure drop in the geothermal heat exchanger.
Sun et al. (2018)	Al_2O_3/water Fe_3O_4/water	Numerical investigation of the suspension of **0.01%** volume fraction of nanoparticles in a geothermal heat exchanger. (Fig. 12)	Nanoparticles tend to precipitate in a static position; however, with an increase in nanoparticle diameter, the rate of sedimentation also increases. The rate of sedimentation of nanoparticles could be eliminated by increasing the velocity.
Ratlamwala et al. (2019)	Al_2O_3/water Fe_2O_3/water	Comparative analysis of nanofluids utilization in integrated geothermal and solar energy generation to meet the needs of an inhabited district.	A water nanofluid with Al_2O_3 was more effective than one with Fe_2O_3. Al_2O_3-based nanofluid has about **0.9%** better performance results than Fe_2O_3 nanofluid. With the reduction in nanoparticle concentration, hydrogen generation and power generation increased. It was also noted that all parameters tend to increase with the increase of the surrounding temperature from **273 to 325 K.**

(*continued on next page*)

Table A1 (*continued*)

Refs	Nanofluid	Purpose of the study conducted	Results obtained from the analysis
Boyaghchi et al. (2015)	CuO/water	Numerical assessment of solar and geothermal energy-fed combined cooling, heating, and power heat exchanger utilizing nanofluid.	The daily thermal efficiency increased when utilizing CuO/water nanofluid instead of pure water. The decrease in product cost is also observed. The best selected fluid has a thermal efficiency of **52.058%**
Mokhtari Moghari et al. (2015)	Al_2O_3/water	Numerical investigation of pressure drops and thermal parameters utilizing nanofluid in the horizontal annuli of a heat exchanger.	The increase of nanoparticle concentration leads to an increased pressure drop, shear rate, and pumping power. The investigation revealed that with **1%** of nanoparticle concentration, the pressure drop was **22%,** while with **5%** concentration, the pressure drop increased significantly to **195%**
Maïga et al. (2005)	γAl_2O_3/water γAl_2O_3/EG	Utilization of nanofluids in heat transfer enhancement.	γAl_2O_3/water with a **7.5%** volume fraction of nanoparticles, the wall heat transfer coefficient increases by **45%** at the same Reynolds number. In contrast, when using γAl_2O_3/EG with the same volume fraction, the average wall heat transfer coefficient increases by **70%.**
Narei et al. (2016b)	Al_2O_3/water	Evaluating the potential of nanofluids to reduce the length of the ground heat exchanger.	It was concluded that nanofluid can reduce the length of the borehole by **1.3%.** Such low performance is grounded in the film thermal resistance between the fluid and the tube.
Bobbo et al. (2016)	Al_2O_3/water	Evaluation of nanofluid for application in shallow geothermal systems.	A 3wt% nano fluid could be applicable in temperatures beyond 40-50°C, possibly as a secondary medium to transfer heat carried by the condenser to fan coils or radiators. Additional viscosity and heat transfer coefficient measurements should, however, be conducted to determine its suitability in the intended heat pump system fully.
Khairul et al. (2013)	CuO/water ZnO/water Al_2O_3/water	Analysis of thermodynamic properties of nanofluids in helically coiled heat exchangers.	The heat transfer of CuO/water nanofluid performed the best among the others, at **7.14%.** The entropy generation rate was **6.14%.** Moreover, with the increased concentration and flow rate, heat transfer increased while the entropy generation rate decreased.
Ahmed et al. (2011)	Cu/water	Numerical study of heat transfer properties and pressure losses of nanoparticles in a corrugated channel.	It was concluded that heat transfer enhancement increases with Reynolds numbers of 100–1000 and concentrations of 0 to **0.05,** while there is a slight increase in pressure drop.
Lotfi et al. (2012)	MWNT/water	Experimental investigation of heat transfer enhancement of nanofluid in a horizontal shell and tube heat exchanger.	The study indicates that incorporating **0.015%** concentration enhances heat transfer, and quantitatively reports overall heat-transfer coefficient data versus nanofluid flow rate at two heating powers (280 and 630 W) in a horizontal shell-and-tube exchanger (14 tubes, 7-mm ID, 580-mm length), though no explicit % improvement is stated
Ghanbarpour et al. (2014)	Al_2O_3/water	Experimental study of thermal conductivity and viscosity of nanofluid.	Thermal conductivity and viscosity of nanofluids with increasing temperature and concentration from 293 to 323 K and concentration from **3% to 50%.** The enhancement in thermal conductivity ranged from **1.1 to 87%,** and viscosity increased from **18.1 to 300%.** The best ground for comparison of efficiency is equal pumping power in all cases.
Kapıcıoğlu and Esen (2020)	Al_2O_3/EG-water	Experimental study of a U-type and spiral ground heat exchanger under 2.5 m depth with a total length of 73.95 m.	A **19%** increase in output temperature was recorded in U-type and **22%** in spiral-type ground heat exchangers with a nanofluid concentration of **0.1%** compared to utilizing only EG-water. The performance coefficient increased to **2.5%** in the U-type heat exchanger, while in the case of the spiral-type, the increase was **3%.** However, a **0.2%** concentration did not achieve any significant improvement.
Kabeel et al. (2013)	Al_2O_3/water	Experimental investigation of a corrugated plate heat exchanger performance utilizing nanofluids.	A **13%** increase in the heat transfer coefficient was observed with a laminar flow of **4%** concentration nanofluid. The pressure drop was closely linked to concentration; a **45%** pressure drop was observed at a **4%** concentration, accompanied by a **95%** increase in power consumption. The optimal range was obtained with a **2%** concentration of pumping power, corresponding to **34%.**
Kwon et al. (2011)	ZnO/water Al_2O_3/water	Experimental study of thermal performance of nanofluid in a plate heat exchanger and pressure drop due to the use of nanofluids.	A **6**vol% Al_2O_3 nanofluid increased the overall heat transfer coefficient by **30%,** but the pressure drop increased by **40%** compared to water. Nevertheless, there was a minor improvement with lower concentrations of the volume, and the structural nature of the heat exchanger restricted the overall performance of the nanofluid.
Maré et al. (2011)	Carbon nanotube (CNTs)/water γAl_2O_3/water	Comparative study of two nanofluids' thermal performance application in a plate heat exchanger.	A **42%** and **50%** enhancement in heat transfer was observed in the laminar flow mode. The results indicate that Al_2O_3 nanofluid performs better in terms of pressure loss and thermal performance.
Koshta et al. (2020)	TiO_2/rGO	Study of the thermal performance of nanocomposite-based nanofluid in helical coiled heat exchanger.	Thermal conductivity and the heat transfer coefficient increase with higher concentrations of nanoparticles and Reynolds numbers. At **0.25vol%** and Re = 2170, the maximum heat transfer achieved was 493 $W/m^{2\circ}C$, indicating the advantage of the nanofluid of this type.
Tiwari et al. (2013)	CeO_2/water	Experimental study of heat transfer and pressure drop across a heat exchanger plate employing nanofluids.	It was concluded that the maximum heat transfer coefficient is **39%** higher than that of water at an optimum concentration of **0.75 vol%**. The increase in pressure drop at optimal concentration was negligible.

(*continued on next page*)

Table A1 (*continued*)

Refs	Nanofluid	Purpose of the study conducted	Results obtained from the analysis
Fotukian and Nasr Esfahany (2010)	CuO/water	Experimental research on heat transfer and pressure drop inside a circular tube.	**0.24vol%** of CuO/water nanofluid resulted in a **25%** increase in heat transfer, followed by a **20%** rise in pressure drop. Even with low concentrations of nanoparticles, a significant increase in flow resistance was observed.
Mansoury et al. (2020)	Al_2O_3/water	Experimental study of heat transfer enhancement and pressure drop in various heat exchangers utilizing nanofluid.	The double pipe heat exchanger exhibited the best heat transfer coefficient at **0.2, 0.5**, and **1vol%** concentration, with increases of **33%, 18%,** and **46%**, respectively. At the same time, the pressure drop rose from **8%** to **33%**, from **18%** to **72%**, and from **27%** to **83%**, respectively.
Duangthongsuk and Wongwises (2009)	TiO_2/water	Experimental investigation of the effect of nanofluid on pressure drop and heat transfer on a double-tube heat exchanger.	**0.2vol%** of nanoparticles agreed perfectly with the pressure drop caused by water, due to the small amount of nanoparticles, and no additional pumping power was required. At the same time, heat transfer increases by **6%–11%,** depending on the correlation used.
Calviño et al. (2024)	ZrO_2/PG*: water 10:90 *Propylene Glycol	Investigation of heat transfer performance of nanofluid in double pipe heat exchanger and plate heat exchanger.	**0.25wt%** of nanoparticle in PG: W 10:90 increased heat transfer by **8.3%** in turbulent flow conditions for a double pipe heat exchanger. In the case of the plate heat exchanger, a **0.75wt%** increase in heat transfer resulted in a **123%** increase in laminar flow, with moderate pressure drops showing promising results for ground heat exchangers.

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