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Nanotechnology applications in geothermal energy systems: Advances, challenges and opportunities

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Abstract:
Geothermal energy offers a sustainable solution to meet growing energy needs while mitigating environmental concerns associated with conventional fossil fuel sources. Meanwhile, nanotechnology presents innovative solutions to enhance the performance of renewable energy systems. However, its specific applications in geothermal energy are a dynamic field and have not been systematically reviewed. This paper presents an overview of the latest advancements in utilizing nanotechnology to enhance geothermal energy systems. The essential role of nanotechnology is examined across the entire life-cycle of geothermal development and utilization, encompassing various aspects including geothermal well construction, geothermal reservoir characterization, scaling and corrosion prevention, and resource recovery. The results suggest that nanotechnology holds significant promise for improving the efficiency, longevity, and profitability of geothermal energy systems. Furthermore, this paper outlines the potential challenges associated with nanotechnology adoption in technical, environmental, and economic terms, and offers strategies for mitigating them. Finally, the paper discusses some future perspectives on how nanotechnology can further advance geothermal energy, contributing to the global transition to a clean and renewable energy future.

1. Introduction

In the face of growing energy demands and environmental concerns tied to fossil fuels, the shift to cleaner, sustainable energy is crucial. Geothermal energy, derived from the Earth's interior, has gained prominence as a renewable resource It is usually harnessed by circulating heat carrier fluids in underground reservoirs or heat exchangers (Khodayar and Björnsson, 2024) for electricity generation and direct heating. Unlike wind and solar, geothermal energy offers consistent base-load capacity and features lower CO_2 emissions, reduced footprint, and lower operating costs (Soltani et al., 2019).

Meanwhile, a rapidly emerging scientific field known as nanotechnology has received significant attention in recent years. This applied science involves manipulating matter at the nanoscale (1-100 nm) to exploit unique material properties (Hussein, 2015), thus allowing for innovations in medicine, electronics, and various other industries. In particular, nanotechnology plays a significant role in renewable energy technologies, offering novel solutions to enhance energy efficiency, storage, and utilization. Comprehensive reviews on nanotechnology applications in renewable energy are provided by Hussein (2015) and Behera et al. (2025).

Despite the fact that nanotechnology has been widely ap-

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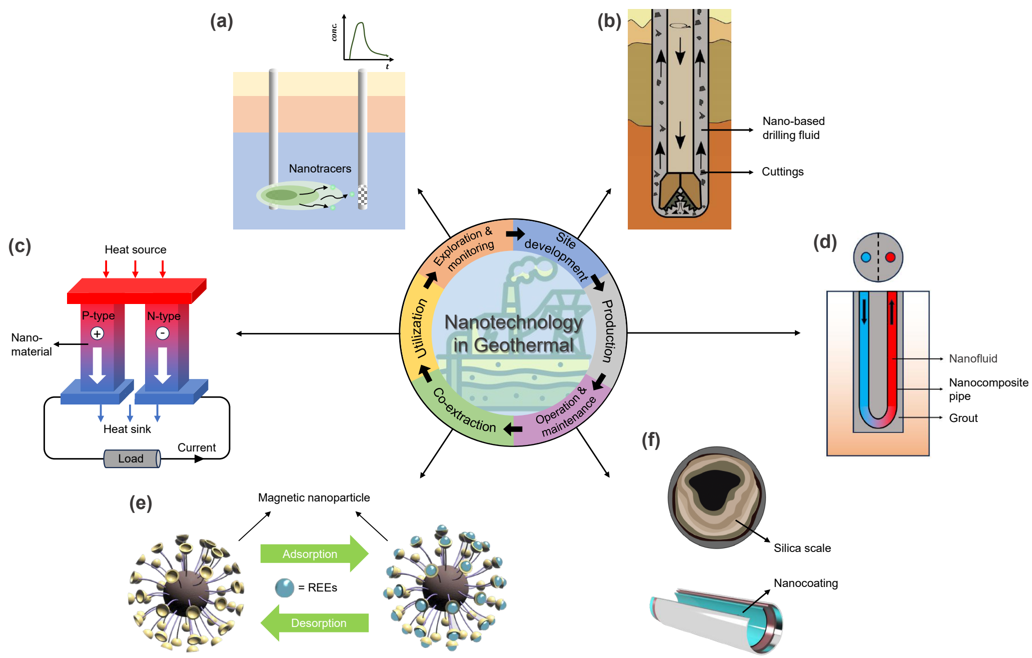

Fig. 1. Schematic diagram showing the various applications of nanotechnology in geothermal energy systems: (a) Exploration and monitoring of geothermal reservoirs, (b) enhancement of geothermal well drilling (reproduced from Canstrat Inc. (2024)), (c) thermoelectric power generation from geothermal waste heat, (d) improvement of GHE efficiency, (e) co-extraction of valuable resources from geothermal brine, and (f) prevention of corrosion and scaling in equipment and pipes (reproduced from Kurita Europe (2024)).

plied in renewable energy sectors, its specific implementations in geothermal energy remains an emerging area of research. Current efforts mainly focus on enhancing heat transfer in closed-loop geothermal heat exchangers. Studies have demonstrated the significant role of nanofluids in improving the performance of both shallow ground heat exchangers (GHEs) (Daneshipour and Rafee, 2017; Kapıcıoğlu and Esen, 2020) and deep abandoned oil and gas wells (Sui et al., 2017; Alqaed et al., 2024). Similarly, nanocomposite materials, with nanoparticles reinforcing a polymer matrix, can improve GHE tube thermal conductivity (Raymond et al., 2015; Narei et al., 2020). These advancements are expected to increase heat extraction efficiency and reduce the size of geothermal heat exchangers. Beyond heat transfer improvements, nanotechnology also shows potential in optimizing fluid extraction and distribution in geothermal reservoirs. However, these important advancements have not been systematically summarized and outlined.

The objective of this paper is to provide a brief overview of recent advances and future challenges in applying nanotechnology to geothermal energy systems. Unlike existing reviews predominantly focused on heat transfer improvements by nanomaterials and nanofluids (Rivas-Cruz et al., 2022; Soltani et al., 2022; Cui et al., 2024), it adopts a broader perspective, highlighting key approaches and specific applications where nanotechnology could enhance the entire life-cycle of geothermal energy development. These stages include exploration, production, operation, utilization, and management of geothermal resources. This paper also examines challenges in integrating nanotechnology into the geothermal industry and proposes strategies to address them. Additionally, the future development directions are outlined, providing a vision for a sustainable geothermal future powered by nanotechnology.

2. Current advances

As depicted in Fig. 1, recent explorations on nanotechnology applications in geothermal energy systems consist primarily of six key directions across different stages of geothermal project development:

1) Heat transfer enhancements of GHEs;
2) geothermal well construction;
3) sensoring and monitoring of geothermal reservoirs;
4) scale and corrosion prevention in geothermal equipments;
5) resource extraction from geothermal fluids;
6) thermoelectric power generation.

A summary of their field applications is presented in Table 1. Since Application 1) has already been reviewed extensively, this paper will mainly focus on Applications 2) through 5), while Application 6) will be highlighted in the discussion on future trends.

2.1 Geothermal well drilling

Drilling plays a crucial role in the exploration and extraction of geothermal resources, as it allows direct access to geothermal reservoirs, typically located several hundred to several kilometers below the Earth's surface. While geothermal wells are drilled similarly as oil and gas wells, they face harsher conditions, with formation temperatures of 150-300 °C and high salt content, particularly calcium ions (Aboulrous et

Table 1. Summary of field studies on the use of nanotechnology to enhance geothermal energy development.

Reference	Nanomaterial	Field condition	Application type	Advantages	Limitations
Kapıcıoğlu and Esen (2020)	Al_2O_3/ethylene glycol-water nanofluid	Test room with a floor area of 21 m^2	Heat transfer enhancements of geothermal heat exchangers	Improved thermal conductivity and reduced GHE length	Increased pressure drop
Hawkins et al. (2017)	Carbon nanoparticles (C-dots)	Mesoscale field site (∼14 m)	Sensoring and monitoring of geothermal reservoirs	Low toxicity, low diffusivity, and high detectability	Unstable at temperatures > 200 °C
Kong et al. (2018)	DNA-labeled silica nanoparticles	Unconsolidated aquifer with sandy gravels (∼ 3 m)	Sensoring and monitoring of geothermal reservoirs	Stability, versatility, and high detectability	Not neutrally buoyant, needs better robustness at high temperatures
Kittilä et al. (2019)	DNA-labeled silica nanoparticles	Fractured crystalline rock (∼10 m)	Sensoring and monitoring of geothermal reservoirs	High detectability and no susceptibility to background noise	Potential settling at low flow velocities, challenges in data interpretation
Borrmann and John-ston (2019)	Nano-structured calcium silicate hydrate	Pilot scale test rig in an operational geothermal field	Scale and corrosion prevention in geothermal equipments	Efficient transformation and easy separation	Tendency to agglomerate if reinjected with cooled brine

al., 2023). These challenges demand stringent safety and reliability in well design and construction, creating opportunities for nanomaterials with superior physical properties to enhance performance and durability.

An important application in geothermal well drilling involves integrating specially designed nanoparticles into drilling fluid formulations (Vryzas and Kelessidis, 2017; Cheraghian, 2021). Bentonite water-based muds (WBMs) are commonly used in complex formations, but their performance degrades under high-temperature and high-pressure conditions (Agwu et al., 2021), requiring further modification. Nanoparticles have been used to improve mud properties (Edalatfar et al., 2021), but they can negatively affect the filtration properties and cutting carrying abilities of WBMs (Ghasemi et al., 2018). To overcome the this limitation, a recent study investigated mud formulations with modified silica nanoparticles (nanosilica) and cetyltrimethylammonium bromide (CTAB) as cationic surfactant (Martin et al., 2023). The results showed a 29.5% reduction in filtration loss and a 28.7% decrease in mud cake thickness compared to mud with unmodified silica, especially at high temperatures. Optimal CTAB concentrations (1.0-2.0 wt.%) reduced agglomeration and enhanced thermal stability, decreasing the risk of mud degradation and potentially reducing costs. In addition to improving WBMs, nanoparticles have also been used to stabilize foam drilling fluids for geothermal wells. A foaming nanosystem composed of pectin, ferric vanadate oxide nanoparticles, and CTAB was developed (Aboulrous et al., 2023). This nanocomposite showed improved foam stability and could withstand high temperatures (up to 300 °C) and salt content (5 wt.% $CaCl_2$), while reducing cytotoxicity compared to pure CTAB.

Furthermore, research has explored the use of nanomaterials as modifiers to enhance well cementing materials (Makwana et al., 2021). Recently, a new nano SiO_2-basalt fiber composite cement was developed for geothermal reservoir applications (Wang et al., 2020). Experiments showed improved cement properties, including a 14% increase in compressive strength (from 35.8 to 40.9 MPa) and reduced crack formation. Additionally, Additionally, recent studies have examined nanosilica to enhance the sulfate resistance of cement used in geothermal wells (Luswata et al., 2023).

2.2 Geothermal reservoir characterization

Nanotechnology holds great potential for advancing geothermal energy development through improved sensing and characterization of reservoir conditions. The inaccessibility of geological reservoirs poses challenges for determining reservoir properties, which is crucial for the successful deployment and operation of geothermal power plants. Conventional solute tracers are commonly used to detect flow paths (Zhang et al., 2021), monitor reinjection effects (Aydin et al., 2018), and estimate mean reservoir temperatures (Ames et al., 2015). However, these tracers suffer from signal interference and provide limited spatial data on reservoir properties (Kong et al., 2018). In contrast, nanoparticle-based tracers (nanotracers) have been developed to overcome these issues (Alaskar et al., 2011; Suzuki et al., 2018; Ren et al., 2023). Thanks to their tunable properties and modular structure (Spitzmüller et al., 2023a), nanotracers offer extensive functionality in both hydraulic and thermal reservoir assessments, helping to optimize reservoir management and energy extraction.

A pioneering example of nanotechnology in geothermal reservoir characterization involves the use of carbon nanoparticles (C-dots) as inert tracers to study the hydrothermal behavior of geothermal fields (Hawkins et al., 2017). These C-dot nanotracers consist of a carbon core decorated with a highly fluorescent polymer and were used alongside thermally degrading tracers to examine heat exchange in fracture-dominated reservoirs. In a series of related studies, field tracer experiments were conducted in Switzerland to validate

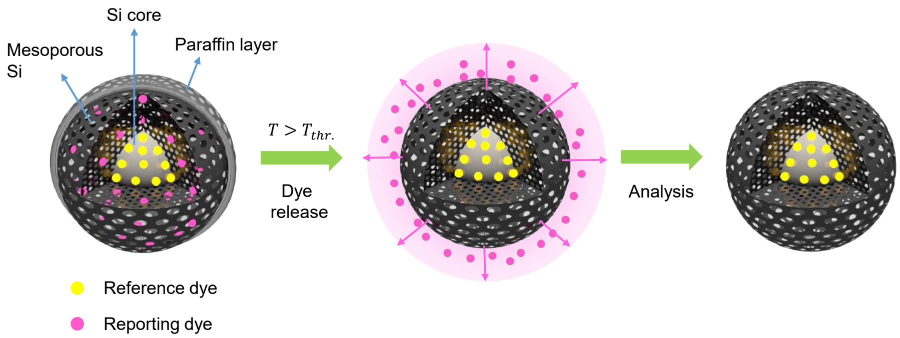

Fig. 2. Synthesis and sensing mechanism of the three-layer nanoparticle tracer for geothermal reservoir temperature sensing (reproduced from Rudolph et al. (2020)).

the performance of DNA-labeled nanotracers for determining hydrogeological parameters (Kong et al., 2018; Kittilä et al., 2019). The DNA nanotracers were synthesized by attaching negatively charged, double-stranded DNA molecules to positively charged silica particles, which were then encapsulated with silica layers to protect the DNA. The breakthrough curves (BTCs) from these nanotracers enabled the derivation of hydraulic conductivity profiles of the aquifer using tomography (Kong et al., 2018), which contributes to understanding hydraulic connectivity and preferential flow paths in geothermal reservoirs.

In the field of reservoir temperature detection, Rudolph et al. (2020) and Spitzmüller et al. (2023a) presented a novel approach using silica nanoparticles with a dual emission system for accurate temperature sensing. The nanoparticle tracers feature a three-layer structure (see Fig. 2). The core layer, approximately 50 nm in size, is fluorescent and remains stable under geothermal conditions. A mesoporous shell is then grown on the core using CTAB micelles as a template, increasing the tracer size to about 70 nm (Spitzmüller et al., 2023a). The pores of this shell are filled with a second fluorophore (Safranin O), and a temperature-sensitive pore blocker (paraffin) seals the pores. When the temperature exceeds the threshold of the paraffin coating, it melts, releasing Safranin O from the mesoporous shell. This release results in an increased fluorescence ratio between Safranin O and the reference dye, $Ru(bpy)_3^{2+}$. By measuring this fluorescence ratio, the temperature can be detected and quantified. Compared to previous temperature-reporting nanoparticles, these newly developed silica nanoparticles provide a robust core that encapsulates and protects the reference function, making them ideal for consistent temperature evaluation and monitoring in geothermal reservoirs.

As previously discussed, the synthesis procedure of nanotracers can be flexibly adjusted to modify their reporting functions. In follow-up work, Yan et al. (2024) numerically evaluated the potential of injecting multiple temperature-reporting tracers for the characterization of an enhanced geothermal system (EGS). The findings suggest that nanotracers with different temperature thresholds can provide valuable information on temperature ranges and distributions in geothermal reservoirs, with BTCs indicating the upper and lower temperature limits as well as the impact of reservoir heterogeneities.

2.3 Scaling and corrosion prevention

Geothermal fluids exhibit inherent complexity in their chemical composition due to fluid-rock interactions (Smith et al., 2017). Depending on the location and depth of geothermal wells, a wide range of chemical species can be present, including toxic elements like arsenic or selenium, valuable elements such as lithium or cesium, and environmentally benign yet problematic species such as dissolved silica and calcium carbonate. Thus, proper management of geothermal fluids is necessary to mitigate environmental risks, enhance resource recovery, and ensure the long-term efficiency of geothermal energy production.

Materials for geothermal pipelines and heat exchangers may negatively interact with the transported fluid, resulting in corrosion and scaling (Song et al., 2018). These material degradation phenomena present crucial challenges for global geothermal utilization, resulting in diminished operational efficiency and substantial economic losses (Schmitt et al., 2009). To address these challenges, protective measures such as coatings (Bhuvanendran et al., 2023; Fanicchia and Karlsdottir, 2023) and inhibitors (Haklıdır and Balaban, 2019; Shi et al., 2022) have been employed on geothermal fluid-wetted equipment. Recently, there has been growing interest in nanomodified surfaces for preventing corrosion and scaling, as these approaches are highly effective and economically viable. The performance of anti-corrosive SiO_2 nanocoatings has been investigated in both simulated and real geothermal environments , demonstrating good stability and improved corrosion resistance compared to untreated or polished substrates (Ning et al., 2012). Additionally, recent studies have focused on developing nanocoatings that mitigate both corrosion and scaling (Cai et al., 2016; Song et al., 2018). Regarding chemical inhibitors, a research team from New Zealand has developed a proprietary technology to prevent silica scaling in geothermal brine (Borrmann et al., 2009; Borrmann and Johnston, 2019). This method involves the rapid precipitation of supersaturated dissolved silica species as nanostructured calcium silicate hydrate (NCaSil) material by adding Ca^{2+} ions under specific alkaline conditions. Due to electrostatic repulsion, the formed NCaSil particles remain in suspension and do not form intractable sinter deposits. This method has been successfully demonstrated at a pilot plant, showing high silica removal efficiencies of 95% to 99%.

2.4 Resource recovery

Geothermal fluids are significant sources of valuable raw materials. Over the past decade, the integration of geothermal energy production with the co-recovery of marketable byproducts has emerged as an attractive strategy (Soltani et al., 2022). Rare earth elements and rare alkali metals are key components with widespread applications across industries. However, the low concentration of these elements in geothermal brines presents substantial challenges for their efficient recovery (Spitzmüller et al., 2021). To address this issue, recent research has explored the use of nanofluid-based methods for extracting these elements from natural brine resources, including geothermal water (Smith et al., 2017; Chen et al., 2022; Jiang et al., 2022). Functionalized magnetic nanoparticles, featuring a magnetic core and sorbent shell, have shown promising results in the selective absorption of rare earth elements, enabling simple separation through the application of an external magnetic field (McGrail, 2016; Ashour et al., 2017; Ye et al., 2023). Additionally, a recent study introduced a novel approach for synthesizing nanostructured mesoporous Prussian blue analogs via an ionic liquid-assisted co-precipitation method, which demonstrated improved cesium adsorption performance (Chen et al., 2022).

Beyond mineral extraction, geothermal solid waste (GSW), a byproduct of controlled silica precipitation in geothermal power plants, has shown great potential as a valuable source of silica-based nanocomposites due to its high silica content and large availability (Gomez-Zamorano et al., 2016). GSW has been studied as a secondary material for producing rubber, pastes, mortars, and concrete (Iñiguez-Sánchez et al., 2012). In particular, recent research has explored an environmentally friendly method for synthesizing silica-based fluorescent nanoparticles (FSNP), with potential applications in forensics. Jenie et al. (2020) utilized GSW from a power plant in Indonesia to synthesize silica nanoparticles, which were then modified with a fluorescent dye to form FSNP. These FSNP were optimized for use as fluorescent fingerprint powder to develop latent fingerprints on dry surfaces.

3. Challenges and perspectives

Although scientific research and engineering practices in applying nanotechnology to the geothermal industry have made significant progress, the efficient and sustainable development of such applications still faces several challenges, namely technical, environmental and economic. An overview of these challenges and potential strategies to address them is presented in Fig. 3.

3.1 Stability of nanoparticles

The stability of nanoparticles is crucial for their applications in harsh geothermal environments , where high temperatures and salinity can cause mass loss and limit their use. There are primarily three stability challenges for nanoparticles:

1) At low flow rates and high concentrations, nanoparticle aggregation may occur due to their high surface activity (Ouikhalfan et al., 2020). This agglomeration leads to particle settling and deposition driven by density effects, potentially leading to diminished thermal performance of nanofluids (Liang et al., 2022) and lower mass recovery of nanotracers (Zhang et al., 2022).
2) In high temperatures > 100 °C, the increased degradation and dissolution of nanoparticles can impair their integrity and functionalities like embedded dyes or DNA. Engineered silica nanoparticles face particular challenges, as their silica-based core and shell make them prone to dissolution in aqueous environments.
3) In high salinity conditions, the presence of cationic ions such as sodium, can alter the electrostatic interaction between nanoparticles and soil matrix. This alteration promotes the sorption and retention of nanotracers, resulting in tracer mass losses and inaccuracies in tracer analysis.

To address these challenges, researches have explored a variety of stabilization methods, including the addition of surfactants (Ouikhalfan et al., 2020) and chemical surface modifications (Jin et al., 2021). Surfactants, particularly anionic and cationic types, can modify the surface charge of nanoparticles to reduce aggregation and adsorption (Rudyak et al., 2021). However, they may also increase nanofluid viscosity, leading to higher pumping power demands in cementing or heat exchanger applications. Surface modification is an alternative method to improve nanoparticle stability. Spitzmüller et al. (2023b) evaluated various surface modification strategies aimed at preventing the dissolution and degradation of silica nanoparticles. Their findings revealed that the most effective stabilization method was calcination, which strengthened the silica network and made it more resistant to nucleophilic water attacks. Nevertheless, it was also noted that calcinating may not be suitable for subsurface tracing applications, as the organic dye molecules could not withstand the elevated temperatures (500-700 °C) required during the synthesis process. Given the above limitations, there is a clear need for further research to better understand the fundamental interactions occurring at particle-fluid and particle-rock interfaces.

3.2 Integrity and functionality of nanocoatings

As highlighted in Section 2.3, innovative nanocoatings offer a cost-effective solution to corrosion and scaling in geothermal facilities. Despite their advantages, nanocoatings encounter several challenges related to extreme environments, surface peeling (delamination) (Ning et al., 2012), and compromised heat transfer (Cheng et al., 2011).

To address these challenges, innovative nanocoating design, material selection, and application techniques are needed to ensure reliable protection for equipment exposed to geothermal fluid. For instance, a study on protecting carbon steel wellhead components used a polyphenylenesulfide nanocoating with montmorillonite (MMT) clay fillers, which increased the melting point by approximately 40 °C and effectively mitigated corrosion during 20 days of exposure to 300 °C brine (Sugama, 2006). Additionally, surface preparation and

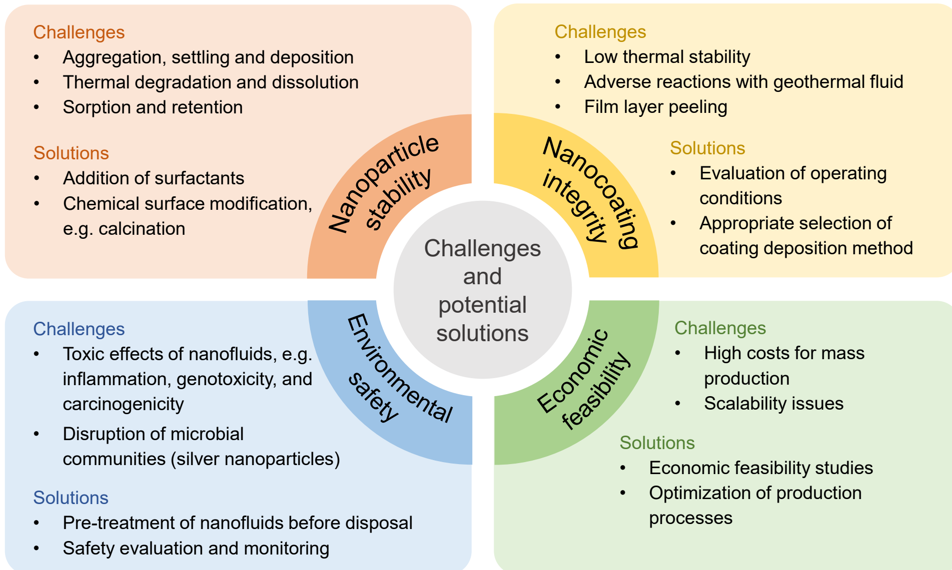

Fig. 3. Challenges associated with nanotechnology applications in geothermal energy and potential solutions to overcome them.

application techniques such as coating deposition are crucial for ensuring adhesion and avoiding detachment (Ning et al., 2012). By selecting the appropriate coating materials and methods, geothermal power plant operators can enhance the performance and durability of their equipment while minimizing maintenance costs.

3.3 Environmental and economic feasibility

Nanotechnology in geothermal energy systems has both environmental benefits and potential risks. It can help reduce the environmental footprint by improving resource efficiency and decreasing maintenance needs. However, nanofluids and nanoparticles can have different toxicity levels based on their composition and preparation methods (Elsaid et al., 2021). For example, ZnO and TiO_2 nanoparticles can generate reactive oxygen species, that may damage cellular components, potentially causing DNA mutations and cancer (Pordanjani et al., 2021). Additionally, high concentrations of nanoparticles, such as silver, can disrupt microbial communities and contribute to antimicrobial resistance, adversely affecting ecosystem health (Yonathan et al., 2022). To mitigate these risks, further research is needed to assess environmental impacts, implement safety measures, and optimize nanoparticle dosage. From an economic perspective, a thorough feasibility analysis is essential to determine if the benefits of nanotechnology justify the additional costs. Addressing mass production challenges and optimizing production processes can help reduce manufacturing costs and improve scalability in the geothermal industry.

4. Conclusions and outlook

This paper reviews recent advancements in applying nanotechnology to enhance geothermal energy systems. Nanotechnology has significant potential to improve the efficiency, longevity, and economic viability across various stages of geothermal development and utilization, including heat transfer, well construction, reservoir monitoring, equipment protection, and resource extraction. The paper also discusses challenges associated with nanotechnology adoption and suggests mitigation strategies to effectively address them.

Looking ahead, several key directions for future development are outlined below:

Next-gen nanotracers: Further studies should explore the tunable properties of nanoparticles for more effective geothermal reservoir characterization. While nanoparticles have shown promise in laboratory and conventional geothermal systems, their use in EGS and supercritical geothermal systems remains limited. Additional strategies are required to modify the structuring process of nanotracers, expanding their applicability to more challenging and complex reservoir conditions. Moreover, the diverse synthetic routes for nanoparticles provide opportunities for tailoring nanotracers to optimize their transport and reaction properties (Rudolph et al., 2020). By selecting suitable combinations of fluorescent dyes or other reporting functions, nanotracers can be designed to exhibit distinct emission spectra or intensity changes, enabling multiplexed sensing applications.

GHPs and hybrid systems: GHPs offer an energy-efficient and environmentally friendly solution for building heating and cooling. By optimizing the heat transfer properties of GHP components, nanomaterials and nanofluids can enhance their thermal efficiency and reduce the size of GHEs, thus contributing to overall system improvement. Additionally, the application of nanofluids in hybrid systems, which integrates GHPs with other renewable energy sources like biomass and solar, can significantly boost system efficiency while reducing both capital and operating costs (Tafavogh and Zahedi, 2021; Liu et al., 2023).

Low temperature power generation: Research into utilizing low-enthalpy geothermal resources for power production can benefit greatly from nanotechnologies. Currently, there is an increased interest in employing thermoelectric technology to improve the conversion efficiency of geothermal power plants (Chen et al., 2017). This is because mechanical processes like steam and binary cycles are not able to generate electrical power efficiently in low temperature ranges. Notably, nanoscale thermoelectric materials emerge as a viable option for high efficiency thermoelectric generation (Korkmaz and Kariper, 2021; Wei et al., 2022). The utilization of advanced thermoelectric materials can efficiently capture geothermal waste heat and directly convert it into electricity, thereby enhancing overall plant efficiency.

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Conflict of interest

The authors declare no competing interest.

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