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REVIEW PAPER

Nanomaterial-Induced Surface and Interfacial Phenomena in Underground Energy Storage

Hardawan Mohammed Hasan [a]; Abbas Khaksar Manshad [b, *]; Ali Esfandyari Bayat [a]

[a] *Department of Petroleum Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran.*
[b] *Department of Petroleum Engineering, Abadan Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Abadan, Iran.*

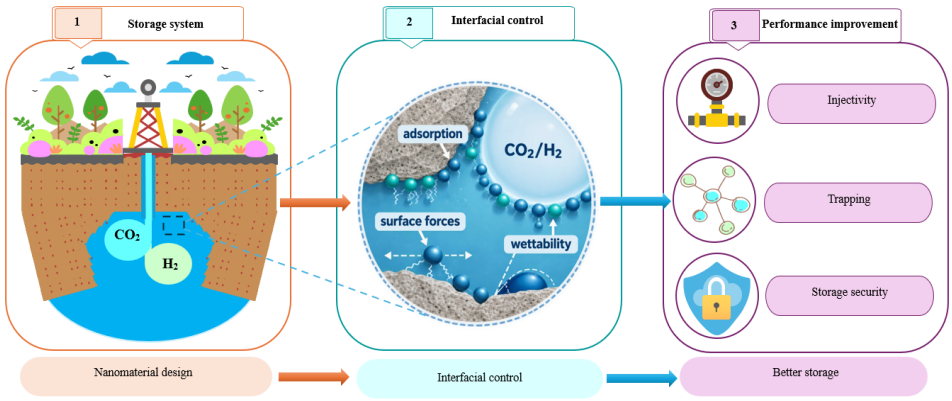
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A B S T R A C T

Underground storage of CO_2 and hydrogen is important for low-carbon energy systems, but its performance is strongly influenced by rock–fluid and fluid–fluid interfacial phenomena. This review synthesizes evidence on how nanomaterial characteristics, including composition, surface charge, size, and functionalization, affect wettability, interfacial tension (IFT), adsorption, disjoining interactions, and nanofluid stability under reservoir-relevant conditions. The evidence is explicitly separated into three levels: directly measured properties (e.g., contact angle, IFT, nanofluid stability, and selected core-flood or mobility responses), mechanistically inferred consequences (e.g., changes in capillary pressure and trapping behavior), and reservoir-scale outcomes. Available laboratory studies demonstrate that nanomaterials can modify wettability and interfacial behavior, particularly in CO_2-related systems; however, whether these changes translate into improved reservoir-scale trapping, storage efficiency, long-term containment, or safety remains insufficiently demonstrated. Direct nano-assisted UHS evidence is especially limited, and EOR-derived studies are therefore treated only as mechanistic analogues rather than proof of hydrogen-storage performance. The review identifies salinity-induced aggregation, nanoparticle retention, mechanistic ambiguity, scale-up uncertainty, and limited long-term data as major constraints, and highlights the need for reservoir-specific formulations, HPHT testing, pore-scale characterization, transport measurements, and multiscale modeling.



1. Introduction

The global transition toward low-carbon energy systems and the increasing share of renewable sources have significantly heightened the need for technologies capable of storing energy and strategic gases on a large scale and for extended periods. In this context, geological CO_2 storage, underground hydrogen storage (UHS), and natural gas storage have emerged as three key pathways for reducing greenhouse gas emissions, balancing energy supply and demand, and enhancing energy security. However, the safe and efficient operation of these systems depends not merely on the volumetric capacity of the reservoir but is largely governed by surface and interfacial phenomena within rock–brine–gas systems. In this context, rock wettability, interfacial tension, contact angle, capillary pressure, and fluid-rock interfacial interactions are among the most critical parameters determining injection mechanisms, phase distribution, gas migration, capillary and residual trapping, storage capacity, and ultimately, long-term reservoir safety. Fundamental studies on CO_2–brine–rock systems have demonstrated that variations in pressure, temperature, salinity, mineral type, surface roughness, and organic compounds can significantly alter wettability behavior, a factor that directly influences capillary pressure and CO_2 storage

* Corresponding Author: Abbas Khaksar Manshad
E-mail address: khaksar@put.ac.ir
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capacity [1–4]. More recent studies have also shown that these same concepts are fundamental to underground hydrogen storage, and that H_2–brine–rock behavior can determine injectivity, gas recovery, and caprock integrity [5–6]. In recent years, surface engineering using nanomaterials and nanofluids has emerged as a novel approach for controlling these interfacial phenomena. Nanoparticles can alter rock wettability and interfacial tension through mechanisms such as adsorption, modification of surface charge, formation of nanoscale layers, alteration of disjoining forces, and restructuring of the water layer adjacent to the mineral surface. For instance, the use of SiO_2 nanoparticles under reservoir conditions has been investigated to modify the wettability of calcite and sandstone and to alter the interfacial behavior of the CO_2–brine system [7–9]. Recent studies have also focused on the use of carbon nanodots, Al_2O_3, TiO_2, and nanoparticle-assisted foam systems to improve interfacial behavior and modify CO_2-storage-relevant interfacial behavior.

Publication activity in nanomaterial-assisted subsurface energy research has increased markedly during the last decade, with growing attention to CO2 storage, underground hydrogen storage, and nanomaterial-mediated control of wettability and interfacial behavior. However, the record-level dataset required to reproduce the previously reported 210% UHS growth rate, regional shares, and percentage distribution of nanomaterial classes was not preserved with sufficient detail. Those numerical claims have therefore been removed. Figure 2 is now presented only as a qualitative classification of the principal nanomaterial families represented in the reviewed literature.

Across the reviewed literature, CO2-related wettability and interfacial studies are more numerous than direct nano-assisted UHS studies. UHS publications in the included evidence base mainly address baseline H2-brine-rock wettability, interfacial properties, microbial interactions, and reservoir-condition effects. These baseline UHS studies are distinguished from direct nanomaterial studies throughout the revised manuscript.

No regional publication percentages or nanomaterial percentage shares are used as quantitative evidence in the revised manuscript because the original record-level classification dataset is not independently reconstructable. The manuscript therefore reports only reproducible qualitative trends and study-level experimental evidence.

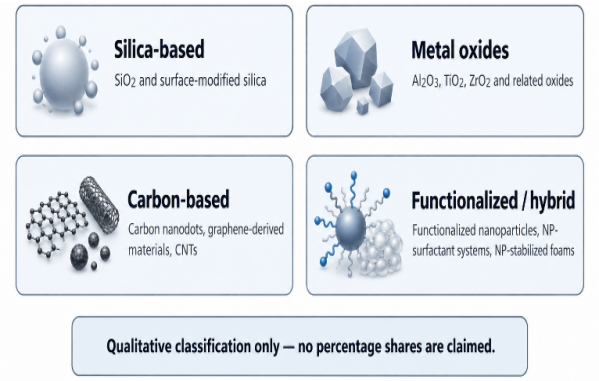


Figure 1. Qualitative classification of the principal nanomaterial families represented in the reviewed literature.

Source: Research Findings

Despite significant research progress, a comprehensive understanding of how nanomaterials behave under actual reservoir conditions remains lacking. Most existing studies have examined only one or a few variables such as nanoparticle type, concentration, pressure, temperature, or salinity in isolation; however, actual reservoir behavior emerges from the simultaneous interaction of brine composition, mineralogy, surface heterogeneity, pressure, temperature, gas type, nanoparticle characteristics, and interfacial forces. Furthermore, a substantial portion of current knowledge has been transferred from the field of enhanced oil recovery to storage studies, and the direct applicability of many of these mechanisms to CO_2 and especially H_2 systems still requires more rigorous evaluation.

Accordingly, this article aims to provide a unified perspective on the impact of nanomaterials on surface and interfacial phenomena in underground energy storage. The primary focus is on the relationships between nanomaterial properties, wettability alteration, interfacial tension, surface forces, and trapping mechanisms within CO_2, H_2, and natural gas systems. In addition to reviewing experimental results, molecular and multiscale studies are examined to elucidate the gaps between behaviors observed at the molecular, mineral-surface, pore, and reservoir scales. Finally, existing knowledge gaps and research priorities essential for transitioning nanomaterial technology from laboratory studies to real-world underground storage applications are identified.

1.1. Review Methodology and Literature Screening

The literature review was structured to distinguish the review methodology from the scientific discussion of experimental techniques. Scopus and Web of Science were used as the principal bibliographic databases, and ScienceDirect was used as a supplementary source for full-text retrieval and citation checking. The primary publication window was 2010-2025; seminal pre-2010 studies and relevant 2026 papers identified through backward and forward citation tracking were retained when they provided essential mechanistic or methodological context. The final search update was performed on 26 September 2026. The core Boolean search string was: (nanoparticle OR nanomaterial OR nanofluid) AND ("CO2 storage" OR "carbon storage" OR "hydrogen storage" OR UHS OR "geological storage") AND (wettability OR "contact angle" OR "interfacial tension" OR "surface energy"). Only English-language, peer-reviewed journal articles relevant to geological gas storage, rock-fluid/fluid-fluid interfacial behavior, or clearly transferable pore-scale mechanisms were considered.

Duplicate records were removed before title-and-abstract screening, followed by full-text eligibility assessment. Studies were excluded when they were outside the subsurface-storage/interfacial scope, were not peer reviewed, lacked sufficient methodological relevance, or did not provide interpretable experimental or mechanistic evidence. For evidence synthesis, eligible studies were classified into three groups: (i) direct nano-assisted CO2-storage evidence; (ii) baseline UHS evidence describing H2-brine-rock behavior without direct nanoparticle intervention; and (iii) EOR-derived mechanistic analogues used only to interpret adsorption, disjoining pressure, surface-charge modification, transport, and related pore-scale processes.

Study reliability was assessed qualitatively rather than by a numerical score. Greater weight was assigned to studies that clearly reported rock/mineral type, fluid composition, nanoparticle formulation, pressure and temperature, salinity, measurement method, replicate or uncertainty information where available, and complementary surface/electrokinetic characterization when mechanistic claims were made. Contact-angle or IFT measurements alone were treated as evidence of an interfacial response, not as proof of a specific mechanism or reservoir-scale benefit. A PRISMA-style record log was not preserved during the original search; therefore, exact numbers of records identified, screened, excluded, and included cannot be reconstructed retrospectively without introducing unsupported counts. This limitation is stated explicitly, and unsupported bibliometric percentages and growth-rate claims were removed rather than retained without an auditable dataset.

1.2. Fundamentals of Wettability and Surface Energy

Wettability is one of the fundamental properties of rock-fluid systems; it describes the relative tendency of a solid surface to preferentially contact one fluid phase in the presence of another and plays a direct role in capillary pressure, phase distribution, relative permeability, fluid displacement, and trapping mechanisms within porous media. In underground CO_2 and H_2 storage systems, wettability is typically characterized by the contact angle (θ) at the rock-brine-gas interface. From a thermodynamic perspective, the equilibrium among solid-gas, solid-liquid, and liquid-gas interfacial energies is described by Young's equation. Therefore, altering any of these interfacial energies can change the contact angle and, consequently, the rock's wettability state. Fundamental studies have demonstrated that wettability behavior under geological storage conditions is a function of mineral type and chemistry, pressure and temperature, brine salinity and composition, surface roughness, and the presence of organic compounds; thus, it cannot be regarded as a fixed property independent of reservoir conditions [1–4, 10–11]. For this reason, a shift from strongly water-wet conditions to intermediate-wet or gas-wet states can significantly influence capillary entry pressure, gas storage capacity, and caprock integrity. Surface energy and interfacial tension (IFT) are also inextricably linked to wettability, as they determine the magnitude of capillary forces and the stability of the contact between gas, brine, and mineral surface phases. Laboratory studies have shown that the IFT of CO_2–brine systems is sensitive to pressure, temperature, salinity, and the type of dissolved ions; these variations, alongside changes in contact angle, can govern gas migration and trapping behavior within porous media [12–16]. In recent years, surface engineering using nanomaterials has emerged as an effective method for controlling these interactions; mechanisms such as nanoparticle adsorption onto mineral surfaces, alteration of surface charge, modification of surface forces, and changes to the water film structure can alter effective surface energy, IFT, and contact angle. For instance, SiO_2 nanoparticles have been shown to modify the wettability of calcite and sandstone, as well as CO_2–brine interfacial tension under reservoir pressure and temperature conditions, while more recent studies have also demonstrated the role of carbon nanodots, Al_2O_3, TiO_2, and engineered nanofluids in controlling interfacial properties [7-9, 17-27].

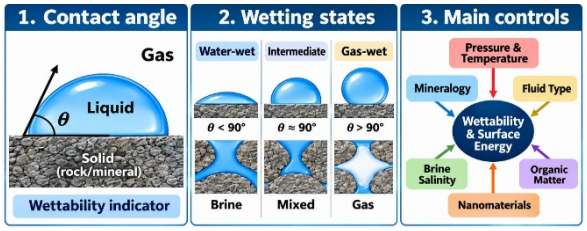


Figure 2. Schematic illustration of the fundamental concepts governing wettability and surface energy in underground gas storage systems, including Young's equilibrium, contact-angle-based wettability states, and the principal mineralogical, physicochemical, and nanomaterial-related factors controlling rock–brine–gas interfacial behavior.

Source: Research Findings

Therefore, a simultaneous understanding of surface energy, IFT, and contact angle provides an essential basis for predicting wetting behavior and designing suitable nanomaterials for the safe and efficient storage of CO_2, H_2, and other energy-related gases in geological formations. The studies summarized in Table 1 show that nanomaterials can modify measured rock–brine–gas interfacial properties, most commonly wettability and IFT. Within the literature included in this review, SiO_2 is the most frequently investigated nanomaterial, particularly in CO_2-related wettability and interfacial studies. Reported contact-angle or IFT changes are treated as measured responses; adsorption, surface-energy modification, disjoining pressure, and related physicochemical pathways are described as proposed or inferred mechanisms unless independently supported by surface, electrokinetic, adsorption, or thin-film characterization. Direct evidence is substantially stronger for CO_2-related systems than for nano-assisted UHS [28-34].

Table 1. Representative experimental studies on nanomaterial effects relevant to geological storage

Nano-material	Rock/System	Application	Main Finding / Proposed or Inferred Mechanism	Reference
SiO_2 nanoparticles	CO_2–brine system	CO_2 storage	Measured IFT modification; interfacial adsorption proposed/inferred	Al-Anssari et al. [9]
SiO_2 nanofluid	Sandstone	CO_2 storage	Measured shift toward more water-wet conditions; surface adsorption proposed/inferred	Ali et al. [7]
SiO_2 nanoparticles	Carbonate	CO_2 storage	Measured wettability/interfacial response; mechanism requires independent confirmation	Tan et al. [35], Energy & Fuels
Carbon nanodots	Carbonate	CO_2 storage	Measured wettability alteration with limited IFT change; mechanism not assigned from contact angle alone	Sakthivel et al. [36], Fuel
Al_2O_3 / TiO_2	Sandstone	CO_2 storage	Different measured responses: Al_2O_3 mainly affected wettability; TiO_2 mainly reduced IFT	Lee & Lee [25]
Nanoparticle-stabilized foam	Saline aquifer	CO_2 storage	Measured foam-stability/mobility response; reservoir-scale storage benefit not directly established	Li et al. [26]

Source: Research Findings

1.3. Nano-Chemical Materials for Wettability Alteration

Due to their small size, high specific surface area, tunable surface chemistry, and adsorption capability at the rock-fluid interface, chemical nanomaterials have been investigated as potential tools for wettability engineering in geological storage systems. Existing studies categorize these materials into several main groups, including silica-based nanoparticles, metal-oxide nanoparticles, carbon-based nanomaterials, functionalized nanoparticles, and nanoparticle-assisted formulations. Among them, SiO_2 possesses the most extensive experimental backing; studies involving calcite, sandstone, and CO_2–brine systems have demonstrated that SiO_2 adsorption onto mineral surfaces can alter surface energy and contact angles, shifting undesirable CO_2-wet or oil-wet surfaces toward water-wet conditions. Nanoparticle size, concentration, temperature, salinity, and surface chemistry play a fundamental role in the magnitude of this change [7-9].

These results are also consistent with more fundamental nano-EOR studies that have reported the roles of adsorption, surface charge alteration, the formation of nanometric layers on minerals, and structural disjoining pressure in wettability alteration [21-23]. A new generation of nanochemical materials has expanded the scope of these mechanisms. Al_2O_3 and TiO_2 can influence capillary behavior by altering surface charge and energy as well as modifying interfacial tension, whereas carbon nanodots primarily induce wettability reversal in the carbonate–CO_2–brine system through adsorption and the modification of surface free energy. Furthermore, functionalizing nanoparticles or combining them with surfactants can enhance colloidal stability in saline brines and prevent particle aggregation and sedimentation factors essential for nanoparticle transport within porous media. In more advanced systems, nanoparticle-stabilized foams control CO_2 mobility in addition to altering interfacial properties.

Consequently, the performance of nanomaterials in wettability alteration is not the result of a single mechanism but rather stems from the interplay of surface adsorption, surface-charge modification, interfacial-tension modification, structural disjoining pressure, and the stabilization of thin aqueous films; the relative importance of each mechanism depends on the nanoparticle type, rock mineralogy, and conditions of pressure, temperature, and salinity [25, 26].

Table 2. Major classes of nanochemical materials and their dominant wettability-alteration mechanisms

Nanomaterial class	Representative materials	Proposed / inferred mechanism	Main wettability effect
Silica-based	SiO_2	Surface adsorption, disjoining pressure	Shift toward water-wet
Metal oxides	Al_2O_3, TiO_2, ZrO_2	Surface-charge and IFT modification	Wettability/IFT control
Carbon-based	Carbon nanodots	Surface-energy modification, adsorption	Wettability reversal
Functionalized NPs	Surface-modified SiO_2	Electrostatic/steric stabilization	Stable surface modification
Nano-hybrid systems	NP–surfactant / NP-foam	Interfacial adsorption, film stabilization	Wettability and mobility control

Source: Refs [7-9], [21, 22, 25, 26]

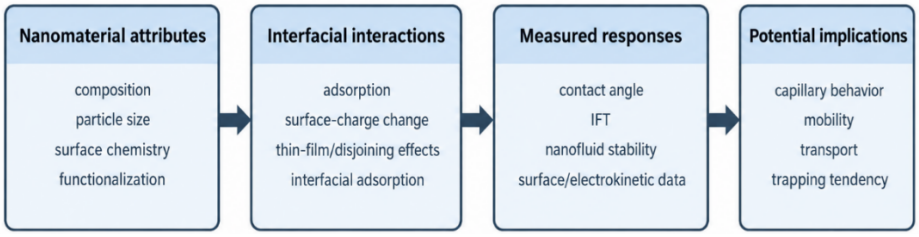


Figure 3. Dominant mechanisms of nano-induced wettability alteration in geological storage systems, including surface adsorption, surface-charge modification, structural disjoining pressure, nano-texture formation, interfacial adsorption/IFT modification, and aqueous-film stabilization.

Source: Refs [7-9, 25-26]

2. Method

2.1. Methodology

This section summarizes experimental methods reported in the reviewed literature and organizes them into a recommended evaluation framework; it does not describe experiments performed by the authors of this review. Across the literature, nanofluid stability under reservoir-relevant salinity is commonly assessed first because aggregation and deposition can restrict nanoparticle transport. Wettability alteration is then evaluated through contact-angle measurements under controlled pressure and temperature, while IFT measurements are performed independently to separate gas–brine interfacial effects from rock-surface effects. Surface and electrokinetic characterization (e.g., SEM/EDS, AFM, XPS, zeta potential, or adsorption measurements, where available) is required before attributing a measured contact-angle change to adsorption, surface-charge modification, nano-layer formation, or disjoining pressure. Core-flooding and transport experiments provide a further level of evidence by examining dynamic mobility, retention, pressure-drop evolution, and displacement behavior. Accordingly, the strongest mechanistic interpretation arises from combining stability, contact angle, IFT, surface characterization, and dynamic transport measurements rather than from contact-angle data alone. Figure 4 integrates the principal methods reported in the literature into a staged evaluation sequence. The workflow is intended as a literature-derived framework for comparing nano-assisted storage studies, beginning with nanomaterial/nanofluid characterization, followed by reservoir-condition stability tests, rock preparation, contact-angle and IFT measurements, and where feasible dynamic core-flooding and transport assessment. Measured responses should be distinguished from inferred

mechanisms, and reservoir-scale storage implications should not be claimed unless supported by dynamic or scale-relevant evidence.

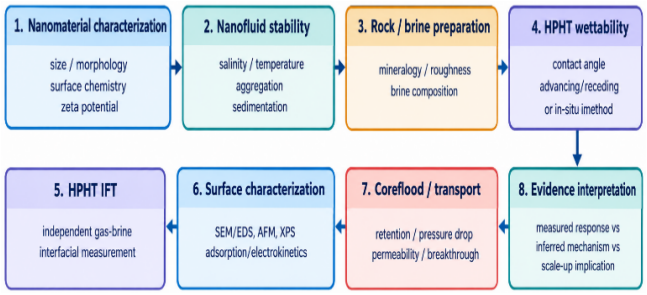


Figure 4. Integrated workflow for nanomaterial preparation, wettability/IFT evaluation, and coreflooding studies in geological storage systems.

Source: Refs [4,7,17,24]

3. Results and Discussion

The experimental evidence is synthesized by rock type, fluid system, application, and evidence class because wettability and interfacial responses depend strongly on both material formulation and test conditions. Cross-study comparison therefore considers nanoparticle size and concentration, pressure and temperature, salinity and ionic composition, mineralogy and surface condition, contact-angle measurement configuration, IFT measurement method, and nanofluid stability whenever these variables are reported. In sandstone and siliceous systems, direct CO2-storage studies commonly report shifts toward more water-wet conditions and changes in CO2-brine interfacial behavior, but the magnitude of the response cannot be compared meaningfully without accounting for these experimental differences. In carbonate systems, sizeable wettability responses have also been reported; however, proposed mechanisms such as adsorption or surface-energy modification require independent characterization where contact-angle data are the primary measurement. EOR-derived studies are retained only as mechanistic analogues and are not interpreted as direct evidence of geological gas-storage performance. A critical comparison also shows that apparently conflicting results can arise from differences in measurement protocols. Contact angles obtained by sessile-drop, captive-bubble, advancing/receding, or in-situ HPHT methods are not directly interchangeable, and IFT values depend on pressure, temperature, brine chemistry, equilibration time, and the selected tensiometric method. Likewise, a formulation that is effective at low salinity may aggregate or sediment at reservoir salinity. For this reason, Table 3 records the key quantitative fields available in the present manuscript and marks unavailable parameters as NR rather than estimating them. In saline aquifers, nanoparticle-assisted foam may reduce CO2 mobility, whereas for UHS the literature remains dominated by baseline H2-brine-rock studies; extrapolation from CO2 or EOR contexts is therefore treated cautiously.

In saline aquifers, the use of nanoparticle-assisted foam has also been proposed as a strategy to reduce CO_2 mobility and improve containment [26]. In contrast, regarding UHS, the available literature primarily covers fundamental studies on H_2–brine–rock wettability, and there is currently insufficient direct evidence concerning nano-assisted hydrogen storage; consequently, extrapolating results from CO_2 or EOR contexts to H_2 applications requires caution.

Table 3. Summary of experimental findings by rock type and application

Rock / System	Application / Evidence class	Representative Nano-System	Main Experimental Finding	Representative References
Sandstone	Direct nano-assisted CO_2-storage evidence	Nanofluid / SiO_2-based systems	Shift toward more water-wet conditions; modification of CO_2–brine interfacial behavior	Ali et al. [7]; Zheng et al. [24]
Calcite / Carbonate	Direct nano-assisted CO_2-storage evidence	SiO_2 nanofluids	Strong wettability alteration through surface adsorption and surface-energy modification	Al-Anssari et al. [8, 9]
Carbonate	Direct nano-assisted CO_2-storage evidence	Carbon nanodots	Wettability reversal with comparatively limited IFT change	Al-Yaseri [30]
Carbonate	EOR-derived mechanistic analogue	ZrO_2 and other metal oxides	Significant shift toward water-wet conditions; nano-texture and adsorption effects	Karimi et al. [22]; Nazari Moghaddam et al. [21]
Sandstone / porous media	EOR-derived mechanistic analogue	Hydrophilic nanoparticles	Improved displacement and coreflood response; mobility and fluid–rock interaction control	Hendraningrat et al. [17, 18]
Saline aquifer	Direct nano-assisted CO_2-storage evidence	Nanoparticle-stabilized foam	Reduced CO_2 mobility / improved foam response; reservoir-scale containment benefit remains to be demonstrated	Li et al. [26]
Sandstone / carbonate / shale	Baseline UHS evidence (no direct nano intervention)	— No direct nano evidence in supplied set	Baseline H_2 wettability strongly depends on mineralogy and reservoir conditions	Hashemi et al. [27]; Higgs et al. [28]; Yekeen et al. [37]

Source: Research Findings

Table 4. Quantitative evidence matrix for representative studies (NR = not reported in the present manuscript)

Study	Extracted quantitative fields and interpretation
Al-Anssari et al. [9]	SiO_2; CO_2–brine. Particle size NR; concentration NR; salinity NR; pressure/temperature: HPHT reported; initial/final contact angle and Δθ NR; initial/final IFT and ΔIFT NR. Wettability/IFT measurements provide direct interfacial evidence; mechanism requires independent surface/electrokinetic support.
Ali et al. [7]	SiO_2 nanofluid; sandstone. Particle size NR; concentration NR; salinity NR; pressure/temperature: reservoir conditions; contact-angle and IFT numerical values NR in the present manuscript. Direct measured wettability response.
Lee & Lee [25]	Al_2O_3/TiO_2; sandstone. Particle size, concentration, salinity, pressure, temperature, θ and IFT numerical values NR in the present manuscript. Contact angle and IFT indicate that different oxides affect different measured properties.
Li et al. [26]	Nanoparticle-stabilized foam; saline aquifer. Particle size/concentration NR; saline brine; pressure/temperature NR; θ and IFT NR. Foam-stability/mobility response is direct dynamic evidence; reservoir-scale containment benefit remains unproven.
Sakthivel et al. [36]	Carbon nanodots; carbonate. Particle size, concentration, salinity, pressure, temperature and numerical θ/IFT values NR in the present manuscript. Contact angle and IFT show wettability alteration with comparatively limited IFT change.

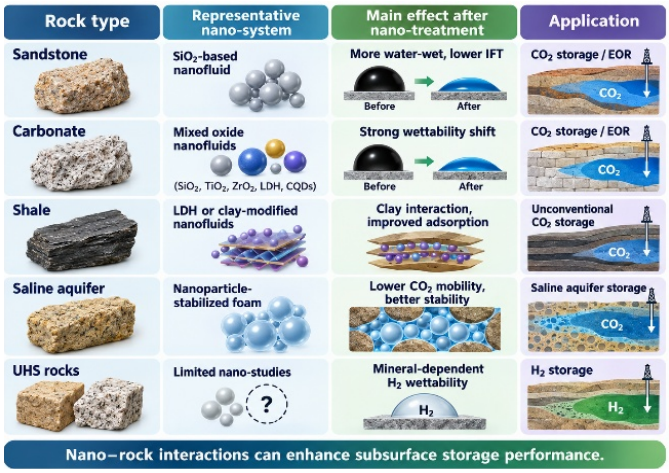


Figure 5. Rock-type-dependent evidence relevant to nanomaterial-assisted geological storage. CO_2 panels summarize direct nano-assisted evidence or mechanistic analogues as indicated in the text; the H_2 panel represents baseline UHS rock–brine–H_2 evidence and should not be interpreted as direct nano-assisted UHS evidence.

Source: Refs [7-9, 17, 26- 28]

3.1. Contradictory, Weak, and Condition-Dependent *Evidence*

The reviewed evidence is not uniformly favorable. In several studies, substantial contact-angle changes occur with comparatively small IFT changes, showing that improvements in one interfacial metric cannot be assumed to imply improvements in another. Different metal oxides may preferentially influence wettability or IFT, while high ionic strength can destabilize nanofluids through aggregation and sedimentation. The magnitude and even the direction of the response can vary with mineralogy, surface roughness, organic contamination, nanoparticle concentration, brine composition, pressure, and temperature. Consequently, wettability alteration is not treated here as universally beneficial; each reported response must be interpreted within the specific rock–fluid–nanoparticle system and experimental conditions. A further source of inconsistency is the evidence used to assign mechanisms. Contact-angle measurements demonstrate a wettability response but do not, by themselves, prove adsorption, surface-charge alteration, nano-layer formation, or structural disjoining pressure. Such mechanistic claims are considered stronger only when supported by complementary measurements such as zeta potential, adsorption data, SEM/EDS, AFM, XPS, or direct thin-film/disjoining-pressure characterization. This distinction is reflected in the revised tables through the use of "proposed/inferred mechanism" where independent mechanistic evidence is unavailable.

Despite promising laboratory results, the transition of nanomaterial-assisted interfacial modification to actual geological storage sites faces substantial limitations. First, nanofluid stability in high-salinity brines is a fundamental challenge because increased ionic strength can promote aggregation and sedimentation, thereby reducing nanoparticle mobility and effectiveness. Second, wettability response depends strongly on mineralogy, pressure, temperature, salinity, surface roughness, and organic matter;

therefore, results obtained on a single quartz or calcite surface cannot necessarily be generalized to a heterogeneous reservoir [1, 4, 29]. Nanoparticle transport and retention within porous media, together with adsorption, concentration loss, and possible pore restriction along the flow path, can also cause dynamic behavior to differ substantially from static contact-angle and IFT measurements [19, 20]. Another limitation is the difficulty of separating simultaneous effects of adsorption, surface-charge modification, IFT change, and wettability alteration. A reduction in contact angle, for example, does not necessarily imply a comparable decrease in IFT [7, 30]. Finally, most nano-related evidence concerns CO2 storage or mechanistic EOR studies, whereas direct nano-assisted UHS studies remain scarce; extrapolation to H2 storage should therefore be made with caution [5, 6, 31, 32]. fundamental challenge, as increased ionic strength can lead to aggregation and sedimentation thereby reducing nanoparticle mobility and efficiency an issue directly investigated in the study by Al-Anssari et al. Second, the wettability response is strongly dependent on mineralogy, pressure, temperature, salinity, surface roughness, and organic matter; Therefore, results obtained from a quartz or calcite sample cannot necessarily be generalized to a heterogeneous reservoir [1, 4, 29]. Furthermore, nanoparticle transport and retention within the porous medium along with the potential for adsorption/retention and property changes along the flow path can cause their actual performance to differ from the results of static contact angle and IFT tests [19, 20]. Another significant limitation is distinguishing the relative contributions of simultaneous mechanisms such as surface adsorption, surface-charge modification, IFT alteration, and wettability reversal; this is because a reduction in contact angle does not necessarily imply a significant decrease in IFT, and the effect of each nanomaterial can vary [7, 30]. Ultimately, the majority of existing nano-related evidence pertains to CO_2 storage or mechanistic EOR studies, whereas direct nano-assisted studies for underground hydrogen storage remain very limited, with current literature focusing primarily on H_2–brine–rock wettability and fundamental hydrogen storage challenges; therefore, the direct extrapolation of CO_2/EOR results to H_2 applications should be approached with caution [5, 6, 31, 32].

4. Conclusions

Transport and field feasibility require particular caution. Where reported, breakthrough/retention, concentration loss, permeability change, pressure-drop evolution, and pore restriction should be used to assess whether nanoparticles can reach target zones without unacceptable plugging. Much of the available transport evidence originates from nano-EOR rather than geological gas-storage experiments, so these observations are treated as mechanistic analogues rather than direct proof of storage-scale injectivity. Likewise, the present literature does not support a robust quantitative conclusion on lifecycle impact, nanoparticle recovery or disposal, toxicity, material cost, treatment volume, or field-scale economics. These factors remain unresolved requirements, and the field feasibility of nano-assisted storage should therefore be regarded as unproven.

4.1. Future Research Directions

Future research in nano-assisted geological storage will likely shift toward the design of smart, sustainable, and reservoir-specific nanomaterials; rather than relying on a generic nanoparticle, parameters such as surface chemistry, size, coating, and concentration would be optimized based on the specific mineralogy, salinity, pressure, and temperature of each reservoir [33, 34].

Table 5. Key challenges and limitations of nanomaterial-assisted wettability and interfacial modification for geological storage.

Challenge / Limitation	Main Concern	Implication for Geo-Storage	Representative References
Nanofluid stability	Aggregation and precipitation at high salinity	Reduced nanoparticle mobility and effectiveness	Al-Anssari et al. [38]
Reservoir-condition sensitivity	Strong effects of P, T, salinity and mineralogy	Laboratory results may not transfer directly to other reservoirs	Iglauer et al. [1]; Al-Yaseri et al. [4]
Rock heterogeneity	Variable mineralogy, roughness and surface chemistry	Spatially variable wettability response	Arif et al. [29]; Garing & Benson [39]
Nanoparticle transport/retention	Adsorption, trapping and possible pore restriction	Loss of active nanoparticles during transport	Ju & Fan [19]; Agi et al. [20]
Mechanistic ambiguity	Wettability, IFT and surface-charge effects occur simultaneously	Difficult identification of the dominant mechanism	Al-Anssari et al. [9]; Ali et al. [7]
Scale-up limitation	Static/contact-angle tests differ from core- and reservoir-scale flow	Uncertainty in field-scale performance	Hendraningrat et al. [17]; Krevor et al. [40]
Long-term behavior	Persistence and reversibility of surface modification are uncertain	Uncertain long-term storage security	Ali et al. [41]; Yekeen et al. [42]
Limited nano-UHS evidence	Few direct nanoparticle studies for H_2 storage	CO_2/EOR mechanisms cannot be assumed valid for H_2	Pan et al. [5]; Heinemann et al. [31]; Gbadamosi et al. [6]

Source: Research Findings

This approach will prioritize functionalized nanoparticles, hybrid nanocomposites, nanoparticle-stabilized foams, and reservoir-responsive materials to effectively control wettability and IFT while enhancing nanoparticle stability and transport in high-salinity brines [43, 44]. Furthermore, research methodologies must evolve from static contact angle and IFT tests to include HPHT core-flooding, pore-scale imaging, multiscale studies, and molecular-to-reservoir scale simulations, thereby clarifying the relationship between surface mechanisms and actual reservoir performance. Another significant gap lies in the direct development of this technology for underground hydrogen storage; this is because, compared to CO_2, empirical data regarding the impact of nanomaterials on H_2–brine–rock interactions remain limited. Ultimately, the assessment of long-term stability, wettability alteration reversibility, nanoparticle retention and transport, environmental impacts, and the feasibility of economic scale-up will determine which nano-systems are capable of transitioning from the laboratory to actual underground storage projects. The studies reviewed here show that nanomaterials can measurably modify selected rock-fluid and fluid-fluid interfacial properties under laboratory conditions. The strength of evidence varies substantially with nanoparticle formulation, experimental protocol, rock mineralogy, brine chemistry, pressure, and temperature. Reservoir-scale implications are therefore separated explicitly from directly measured laboratory responses [45, 46, 47, 48].

The studies reviewed here show that nanomaterials can measurably modify selected rock–fluid and fluid–fluid interfacial properties under laboratory conditions. The implications for reservoir-scale storage performance are more uncertain and are therefore separated from directly measured evidence. The key findings are summarized as follows:

1. Wettability and IFT are two key parameters in geological storage. Changes in contact angle, surface energy, and IFT directly influence capillary pressure, phase distribution, injectivity, gas migration, and residual and structural trapping mechanisms.

2. Nanomaterials are capable of engineering rock surface wettability. The most significant mechanisms include nanoparticle adsorption onto mineral surfaces, alterations in surface charge and energy, structural disjoining pressure, modification of the water film structure, and in certain systems changes in IFT.

3. Within the literature included in this review, SiO_2 is the most frequently investigated nanomaterial, particularly in CO_2-related sandstone, carbonate, and CO_2–brine wettability/interfacial studies. This frequency of investigation does not demonstrate superior effect size or reproducibility; the measured response remains dependent on particle formulation, concentration, salinity, temperature, pressure, and rock-surface condition.

4. Carbon nanodots, Al_2O_3, TiO_2, functionalized nanoparticles, and nanoparticle-stabilized foams broaden the range of measured interfacial responses. However, changes in contact angle, IFT, or mobility should not be interpreted automatically as improved storage capacity, long-term containment, or safety without scale-relevant evidence.

5. The effect of nanoparticles is highly rock-specific. The responses of sandstone, quartz, calcite, carbonate, and shale differ; factors such as mineralogy, surface roughness, organic matter, pressure, temperature, and brine composition can dictate the direction and magnitude of wettability alteration. Consequently, a single formulation cannot be considered optimal for all reservoirs.

6. Nanofluid stability and transport represent significant hurdles for reservoir applications. High salinity can induce aggregation and sedimentation, while nanoparticle adsorption or retention within the porous medium may limit access to target zones; therefore, contact-angle and IFT measurements alone are insufficient to predict performance at the reservoir scale.

7. Reliable mechanistic assessment requires a multi-scale, multi-test approach. Contact-angle measurements demonstrate wettability alteration, whereas adsorption, surface-charge modification, nano-layer formation, or disjoining pressure require complementary surface/electrokinetic characterization. Integrating nanofluid stability, contact angle, HPHT-IFT, surface characterization, transport measurements, and core-flooding reduces over-interpretation of static tests.

8. Direct nano-assisted evidence is concentrated in CO_2-related systems. For UHS, the included studies primarily establish baseline H_2–brine–rock wettability, interfacial behavior, microbial effects, and reservoir-condition sensitivity. EOR-derived studies are used only as mechanistic analogues, and their results should not be presented as evidence of improved UHS performance.

9. A substantial gap remains between laboratory-scale interfacial responses and field deployment. Nanoparticle transport and retention, concentration loss, permeability change, pore plugging, long-term reversibility, formation-water compatibility, environmental impact,

treatment volume, material cost, and field-scale economics remain insufficiently quantified. Field feasibility is therefore not yet demonstrated.

Overall, the evidence supports nanomaterials as promising tools for targeted modification of wettability and interfacial phenomena, particularly in CO_2-related laboratory studies. Their reservoir-scale value will depend on reproducible transport, long-term stability, reservoir-specific formulation, and direct demonstration of storage-relevant outcomes rather than on interfacial measurements alone.

Author Contributions

All authors contributed equally to the conception, preparation, and writing of this manuscript.

Conflict of Interest

A. Khaksar Manshad, in the capacity of Editorial Board, had no involvement in the selection of reviewers or the management of the peer-review process, and the other authors, while observing publication ethics in referencing, declare the absence of any conflict of interest.

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