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A Review of Factors Affecting the Mechanical Behavior of Rock in Geothermal Reservoirs, with Special Attention to the Type of Working fluid

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Abstract

This research investigates the factors influencing the mechanical behavior of rock in geothermal reservoirs, also examining the role of working fluid in extracting heat from geothermal systems. Geothermal reservoirs involve several processes: thermal, hydraulic, mechanical and chemical. Thermal, hydraulic, and mechanical processes can lead to the generation of stresses and related changes in the structural properties of the rock, which will impact the heat extraction performance and the overall stability of the geothermal reservoir. Choice of working fluid, such as water or carbon dioxide, would affect the performance of heat extraction - but, more importantly, alter the mechanical and structural behavior of the rock. Some studies have shown that supercritical carbon dioxide can enhance heat extraction efficiency due to its combination of thermal and chemical properties, thereby minimizing environmental impacts. This working fluid alters rock mechanical properties through chemical reactions, including dissolution and precipitation, which can also impact rock integrity and permeability. Through examinations of laboratory data and existing models from previous studies, this research will conclude the central importance of managing the factors that affect the mechanical and structural behavior of the rock and ensuring optimal operational conditions for the sustainable performance of geothermal systems. This research demonstrated that effectively managing factors affecting rock properties and changes in their condition can optimize stability in geothermal reservoirs and improve energy output. Finally, this study provides suggestions for improving the performance of geothermal systems under different operating conditions.

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1. Introduction

Geothermal technology involves extracting heat from within the Earth's crust. Geothermal energy extraction mainly occurs from reservoirs less than 5 km deep that have temperatures between 100 and 400 °C [1, 2]. Although geothermal energy may ultimately be extracted from reservoirs at extreme depths, the realization of geothermal energy must be defined through technical studies that consider all economic factors, costs, and technical capabilities. The first step in preparing and constructing an energy system based on deep geothermal energy is to identify an adequate reservoir, where the rock temperature is as high as possible, at a depth of 4 to 5 km. Under normal ground conditions, the average thermal gradient is 25 to 30 degrees Celsius per km. However, the temperature of the ground is observed to reach 5 km, where it is as hot as 250 °C, in certain locations, specifically the western United States, which corresponds to a gradient of 50 °C per depth [3]. The second step involves drilling wells into hot rocks to inject and extract the hot fluid. Once the system has been created, the working fluid is injected via the injection wells, flowing through existing rock pathways, absorbing heat, and increasing temperature. During the third step, heated fluid flows through the production well to the site for electrical production. The energy production system is a closed loop, so after leaving the generation site, the fluid is returned to the thermal cycle and re-injected into the well in the HTHP/Hot-Dry-Rock systems. The collected thermal energy can be converted directly to electricity in a district heating network [4]. Over the past 20 years, research on geothermal energy has experienced significant growth. Energy extraction from geothermal reservoirs involves intersecting processes co-occurring within the reservoir. These processes include hydraulic (fluid movement), thermal (heat transfer from the rock to fluid), and mechanical (reservoir deformation and fracturing). In addition to these processes, chemical processes related to mineral precipitation, mineral dissolution, and changes to rock properties due to reactions with the fluid can also be included [5].

Geothermal reservoirs, like any subsurface structures, are also subjected to in-situ stresses. The vertical stress is associated with the weight of rock and fluid from the reservoir to the surface, whereas the horizontal stress is associated with vertical stress and tectonic processes. The principal stresses (vertical and horizontal) act on three mutually perpendicular planes. Geological history, driven by long-term tectonic processes, may lead to maximum in-situ stress due to its non-vertical orientation and changing direction. In some instances, the in-situ stresses are tensile rather than compressive stresses, typically due to tectonic activity within the rock mass [6, 7]. Technical, economic, and geological challenges are among the primary barriers to developing a successful geothermal system. The mechanical behavior of rock during geothermal energy extraction is affected by several variables. For example, the mechanical behavior of rock is influenced by the mechanical properties of the rock as well as the quantity, type, and direction of the stresses experienced. In most cases, shear and tensile failure mechanisms coincide because of the complicated combination of geological factors. In addition, under variable stress conditions, pore pressure and temperature variations can affect the rock's nonlinear and non-uniform thermal and mechanical properties, consequently complicating the examination of rock behavior discovered during geothermal energy extraction. Researchers have studied the mechanical behavior of rock in geothermal reservoirs from numerous perspectives. Kao et al. (2016) analyzed the stresses evolving in the rock matrix using a thermo-plastic model, which captured the porosity and permeability changes over time. The researchers also developed a thermo-hydro-mechanical model to investigate the mechanical behavior of rock, enabling them to assess the convective heat transfer process between the rock matrix and the fluid in the reservoir. Their work determined that energy extraction efficiency depends on many factors, including the size of the stimulated hydraulic zone, the rate of fault-exited fluid injection, and the thermal conductivity. When cold high-pressure fluid is injected, the viscosity of the fluid rises. This process generates a significant negative effective stress that increases rock permeability, resulting in increased fluid flow velocity and a higher heat extraction rate from the reservoir [8]. Yang et al. (2017) carried out uniaxial compression tests in their study to investigate the impacts of high-temperature thermal treatment (200, 300, 400, 500, 600, 700, and 800 degrees Celsius) of granite on fracturing, strength and deformation, and their observations showed that in all cases the fracture threshold, strength, and static elastic modulus of granite increased at 300 degrees Celsius; after which they decreased gradually to the maximum temperature of 800 degrees Celsius. For the dynamic Poisson's ratio, granite first decreased rapidly at 600 degrees Celsius, then increased rapidly with further increase in temperature. They explained these observations in terms of thermal expansion of rock grains, that is, at low temperatures, they improved the structure of rock, and the stiffness of the rock would be greater; for high temperatures, this thermal expansion creates internal cracks and fractures in rocks that decrease both strength and stiffness [9]. To simulate the thermal cycling effects, Rong et al. (2018) heated rock specimens to 600 degrees Celsius, simulating the conditions of geothermal reservoirs for four hours, at which point the specimens were allowed to cool naturally to room temperature. Experimental observations revealed a substantial reduction in mechanical properties, including Young's modulus, wave velocity, and uniaxial compressive strength, with increasing thermal cycles. The decrease in mechanical performance is suspected to be due to multiple thermal cycling creating micro-fractures in the rock matrix, which eventually coalesce to form macroscale fractures [10]. Shu et al. (2020) studied fractured granites. They found that, at high and constant confining pressure, permeability decreased as temperature rose, due to fracture closure. At low confining pressure, heating improved hydraulic properties and increased permeability. These results underscore the importance of considering confining pressure in research and engineering applications that involve the hydraulic properties of fractured granites [11].

The mechanical response of geothermal reservoirs is primarily affected by several key controls: the in-situ stress regime of the rock, the rock's mechanical properties, permeability, the number and properties of natural pre-existing fractures, and the number and properties of natural pre-existing fractures. This is particularly important in deep geothermal reservoirs, where the rocks typically have low permeability, as compounded by compaction and compression, and any natural movement of fluid is insufficient for adequate heat transfer. Therefore, weakening the rock for proper geothermal production could involve artificially fracturing the rock by injecting fluid, and the induced fractures will control the permeability, allowing the fluid to move, thereby allowing heat to be transferred via the fluid, i.e., heat energy to be extracted from the geothermal reservoir [12-16]. Since rock fracturing depends on the rock's mechanical properties and the applied stress, it is essential to understand the rock's behavior.

The type of working fluid used in geothermal energy extraction is one of the most important elements influencing the mechanical behavior of geothermal reservoirs, even compared to what has already been discussed. Fluid interactions with temperature, pressure, and rock lead to changes in Young's modulus, uniaxial compressive strength, and rock permeability, and subsequently modify the mechanical behavior of the rock. Furthermore, most rocks' natural heterogeneity and anisotropy make the prediction of rock mechanical behavior more complex. This study aims to review relevant research on the effect of working fluid type on the mechanical behavior of rock in geothermal reservoirs.

2. Theoretical Part Theory and Basic Concepts

Geothermal reservoirs exhibit a range of physical, mechanical, and geological properties. Geothermal reservoirs can occur in different types of rock and geological structures. Table 1 lists some major geothermal reservoirs and their dominant rock types, as identified [1]. On initiation, a geothermal reservoir typically has one injection well and one production well. If the project is viable, then additional production wells will be drilled. Based on the reservoir's depth, geothermal energy can be extracted from three different reservoirs, as seen in Figure 1. The first case is for geothermal energy extraction from shallow reservoirs. At shallow depths, the soil temperature is warmer during cold seasons than the ambient air temperature, and during hot seasons, it is cooler than the atmospheric temperature. Therefore, these reservoirs can increase or decrease temperatures in interior building spaces.

The second case is for geothermal energy extraction from medium-depth reservoirs. It is normal for energy to be used directly from these reservoirs; the difference is that hot water is extracted and used due to the larger total depth, compared to shallow geothermal reservoirs. The temperature of these reservoirs is not hot enough to be useful for electricity generation. In the third case, geothermal energy can also be extracted from deep reservoirs situated at depths greater than four kilometers and can possibly be used for electricity generation based on elevated ground temperatures [17–20].

Table 1: A list of several known geothermal reservoirs, with prominent rock types.

Location	Dominant Rock Type
Zubair Subzone, Iraq	claystones (specifically the Barremian Zubair and Aptian-Albian Nahr Umr formations)
Kurdistan region , Foothills Zone, Iraq	low-heat-conductive carbonate beds (calystones)
Mahallat Region, Sanandaj-Sirjan Zone, Iran	Coal-rich caprock, a diverse set of sedimentary rocks, and plutonic masses of granite
Area between Muscat and the Batinah coast, Oman	Carbonates, shale, fine-grained limestone
Kaifeng area, China	Sandstone
Southern Tuscany, Italy	Carbonate rocks (limestones and dolomites)
Clear Lake volcanic field, United States	Low-permeability Franciscan sediments with granite at deeper levels
Kilauea Volcano, Hawaii, United States	Basalt

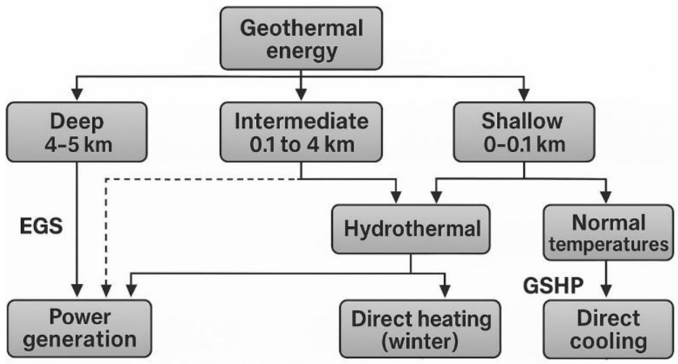


Figure 1: Different methods of geothermal energy extraction based on reservoir depth [20].

3. Rock Properties and Geothermal Characteristics in the Middle East

The regional geological context plays a fundamental role in the mechanical behavior of rocks in geothermal reservoirs. Throughout the Middle East, sedimentary basins predominantly control the geothermal environment, with carbonate formations being the most common type in places like Iraq, Oman, and Iran. In Iraq, the preferred rock formations are claystones found in the Zubair Subzone (Barremian Zubair and Aptian-Albian Nahr Umr formations) and low-heat conductive carbonate beds (calystones) found within the Foothills Region of the Kurdistan area [21]. The thermal conductivity of these formations varies significantly, where calystones have a lower thermal conductivity value, contributing to a higher geothermal gradient in the northern part of Iraq. The carbonate formations commonly found in Iraq, such as the Asmari Formation, have different mechanical properties than other rock types, which therefore affect their response to fluid injection [22]. Carbonates have an increased likelihood of reacting to CO_2 injection through the dissolution of rock minerals compared to volcanic rocks; this has a beneficial effect on permeability but negatively impacts the mechanical stability of the rock structure [23].

The sedimentary basin in northern Oman along the Muscat Batinah coast primarily consists of carbonates, shales and fine-grained limestones. Thermal conductivity values from this area range between 1.8 to 3.2 W/mK, with the lowest values coming from the shale-rich sections of the sedimentary basin. This variability in thermal conductivity plays an important role in managing variations in heat transfer in geothermal systems. This sedimentary sequence in Oman has undergone several tectonic events which have formed complex structure that influences fluid flow pathways [24]. While faults and fractures in these sedimentary structures may create preferred pathways for geothermal fluids, these same features may impact the integrity of the reservoir while injecting working fluid. Table 2 summarizes the thermal conductivity values of various rock types across Middle Eastern sedimentary basins.

Table 2: Thermal Conductivity of Rock Types in Middle Eastern Sedimentary Basins

Rock Type	Location	Thermal Conductivity (W/mK)	Ref
Fossiliferous limestone	Northern Oman (Barzaman Fm.)	2.36-2.49	[24]
Conglomerate, Diagenetic alteration	Northern Oman (Barzaman Fm.)	1.79-2.38	[24]
Basalt	Northern Harrat Rahat, Saudi Arabia	1.43-1.97	[25]
Metasedimentary (basement)	Northern Harrat Rahat, Saudi Arabia	2.62-3.46	[25]
Claystones	Southern Iraq (Zubair Subzone)	Low thermal conductivity	[26]

The Mahallat geothermal region of Iran, situated on the Sanandaj-Sirjan Zone is an area of geological complexity with coal-rich caprock, varied sedimentary rocks, and plutonic masses of granite. The area contains several warm springs with temperatures from 34.8°C to 49°C and are therefore promising locations for shallow geothermal structures. The travertine deposits attest to ongoing geothermal activity, and the faulting systems in the region provide pathways for hydrothermal fluid circulation [27]. The mechanical properties in these rocks are

substantially different than volcanic rocks, with sedimentary rocks being more susceptible to dissolution under CO_2 -charged water, especially in parts that are carbonate-rich.
Overall, the geothermal characteristics found within the Middle East represent sedimentary basin conditions, rather than high-temperature volcanic systems. According to Amoatey et al. (2022), the majority of countries in the Middle East possess low-to-medium enthalpy (<150°C) resources; therefore, the style of engineering considered will differ significantly when comparing to high-temperature systems [28]. The thermal conductivity of sedimentary rocks in the Middle East is noted to vary by a range of 1.5 to 3.5 W/mK, where carbonate formations exhibit a higher value range than shale-dominated formations [24]. The variation in thermal properties will have a significant effect on the efficiency of heat extraction, and it must be considered when designing geothermal systems. With regards to Iraq, the mechanical behaviour of carbonate-dominated formations subjected to different working fluids, would be anticipated to be a deviation from the volcanic rock studies largely referenced in literature. The solubility of carbonates in CO_2 -charged water is high [23] and indicates that CO_2 -based systems should create a greater degree of permeability enhancement, but at a risk to wellbore stability, when compared to water-based systems. This specificity by region reiterates the importance of understanding the mechanical behaviour of rock formations within the Middle East when selecting an appropriate working fluid for geothermal applications.

Recent research in Saudi Arabia has yielded important information on both volcanic and sedimentary geothermal systems. In the Harrat Rahat volcanic field in northern Saudi Arabia, drilling information indicated a geothermal gradient of approximately 60°C/km up to 500m, with 80°C reached at a depth of 500m [25]. The volcanic rocks from this area (basaltic and trachytic) exhibited different alteration and fracturing characteristics that influenced the measurement of permeability and thermal properties. Thermal conductivity of the 29 samples measured ranged from 1.43 to 3.46 W/Km, where volcanic rock thermal conductivity was measured to be the lowest (average thermal conductivity of 1.73 W/Km) [25]. Conversely, the sedimentary basin systems in Saudi Arabia, such as the Al-Wajh Formation in the Yanbu Basin, show different properties. The Al-Wajh Formation was shown to have sufficient permeability (20-200mD) and porosity (11-20%), so hydraulic fracturing was not needed to produce from these systems. The target temperature for production intervals ranged from 112°C to 128°C [29]. Reservoir modelling with multiple-point statistics has been used to capture complex heterogeneities in these sedimentary formations, resulting in detailed geomodels that incorporated lithology, porosity, permeability, and thermal properties [30].

These regional characteristics underscore the necessity of knowing the specific geothermal properties and rock behavior of Middle Eastern formations, especially since sedimentary basins are predominant and not volcanic systems referenced in geothermal studies and literature and typically with the exception of one geothermal livro. The mechanical behavior associated with carbonate formations found in Iraq, Oman, and Iran is very distinct from volcanic rock formation, highlighting the need for region-specific investigation for purposes of developing geothermal resources.

4. Cost-Benefit Analysis of Geothermal Reservoirs in the Middle East

The economic potential of geothermal reservoirs in the Middle East is mainly contingent on geological properties, which influence high capital expenditures (40%–60% exploratory/drilling; $5M–$20M per well) and low operational expenditures [28, 31]. In Saudi Arabia’s Yanbu Basin (Al-Wajh Formation, 112–128 °C), either binary cycle plants are preferred with a levelized cost of electricity (LCOE) of $0.05/kWh to $0.10/kWh, which is competitive with wind but higher than solar due to drilling expenditures, with fuel costs remaining affordable once the plant was established [29, 32, 33]. In Iraq (gradients of 14.9 °C/km to 29.7 °C/km), reusing oil wells for low temperature applications may offer short-term feasibility while decreasing capital expenditures (CapEx); enhanced geothermal systems using organic Rankine cycle (ORC) from abandoned wells may provide approximately 2500 MWh electricity at ~ $3.6/kWh [33, 34]. Oman and Qatar may have similar opportunities, using exhausted reservoirs for the production of electricity, cooling, and agricultural purposes [35, 36]. The financial feasibility of geothermal systems in the Middle East shows major variation depending on the region. For example in Iraq's sedimentary basins, there are moderate gradients (21-26°C/km) that support low temperature applications at competitive LCOE of $0.05-$0.10/kWh (Table 3 and 4). The costs of the geothermal systems in Iraq reflect the constraints of the geology and possibilities to take advantage of existing infrastructure, especially in terms of repurposing existing oil wells (Table 4).

Table 3: Levelized Cost of Electricity (LCOE) for Different Geothermal Systems

System Type	Location	LCOE ($/kWh)	Reference
Hydrothermal systems	Global average	2.9 €-ct/kWh	[31]
Enhanced Geothermal Systems (EGS)	Global average	16.9 €-ct/kWh	[31]
Binary-cycle power plants	Saudi Arabia (Yanbu Basin)	$0.05-$0.10	[29]
EGS using ORC from abandoned wells	Global	$3.6/kWh	[34]
Ground source heat pumps	Jordan	Not specified	[37]

Table 4: Economic Benefits of Geothermal Development in the Middle East

Country	Potential Application	Estimated Benefit	Ref
Iraq	Low-temperature applications using existing oil wells	Reduced initial capital costs	[33]
Saudi Arabia	Sedimentary basin systems (Yanbu Basin)	No hydraulic fracturing required	[29, 30]
Iran	Mahallat region with fault systems	Enhanced permeability through existing fractures	[27]
Jordan	Hybrid solar-geothermal systems	Energy savings and reduced CO_2 emissions	[37, 38]

5. Geothermal systems

Geothermal systems consist of various types, each with its characteristics and applications. Advanced Geothermal Systems (AGS) (Figure 2) can use closed loops, so they do not need to interact with an underground water source; instead, they use carbon dioxide (CO_2) as the working fluid. AGS is a more efficient system given the self-pressurizing thermal properties of CO_2 and is also the only means of addressing the groundwater contamination and induced seismicity caused by artificial stimulation by closed loops; nonetheless, drilling costs can be high [39].

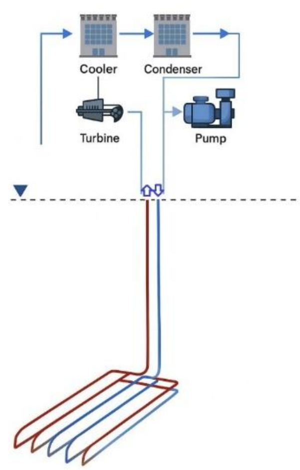


Figure 2: Advanced Geothermal System (AGS) [39].

Enhanced Geothermal Systems (EGS) utilize carbon dioxide (CO_2), rather than water, to extract heat from hot, low-permeability rock formations by using artificial fractures, which improves thermal efficiency and potentially serves as a means of carbon storage. In Enhanced Geothermal Systems, underground hot rocks are used to generate energy, even in cases where these rocks are not highly porous. EGS has two main designs (Figure 3): the dual-well (two wells, one for injection and one for heat extraction) and a triple-well (three wells to increase contact with hot rock). A recent study by Hu et al. (2025) identified that the dual-well system outperformed the three-well system because the dual-well system allowed for better fluid flow distribution throughout the reservoir without establishing a preferential flow pathway [40].

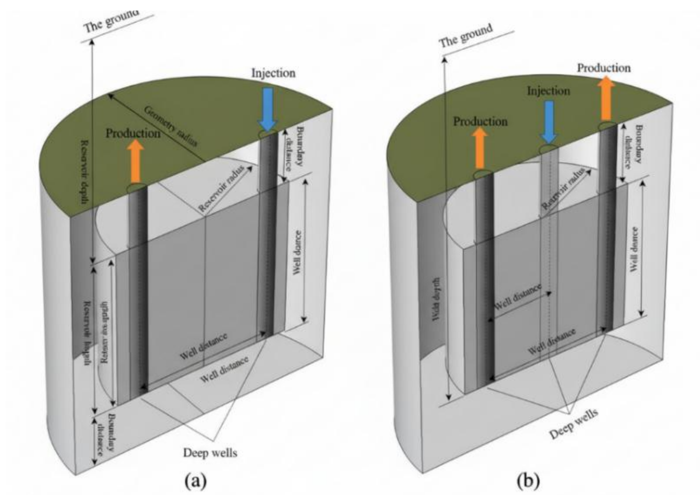


Figure 3: Common configurations of Enhanced Geothermal Systems: (a) Triple-well configuration and (b) Dual-well configuration [40].

In contrast, hydrothermal systems utilize a combination of underground water and CO_2 cycles at the surface, exploiting the one-of-a-kind thermodynamic attributes of CO_2 for power generation. Finally, Co2-Plume Geothermal (CPG) uses high-pressure CO_2 as the primary working fluid and produces energy while storing the CO_2 underground. As a result, rather than using underground water resources, mainly in arid regions, the system does not use water [39].

Besides reservoir rock type and depth, the working fluid used in geothermal energy extraction also affects the mechanical performance of rock and the formation of artificial fracture networks in deep reservoirs. Typically, fluids used in practical geothermal reservoir operations include water, brine, CO_2, air, and nitrogen. Water and CO_2 have been researched and more widely implemented into geothermal extraction than air and nitrogen. The principal difference between water and brine is the fluid type and related physical properties. CO_2 differs from water and brine. After all, it has certain unique thermal, physical, and chemical properties because it is a gas. Figure 4 depicts a conceptual schematic of geothermal energy extraction using CO_2 as the working fluid [41, 42].

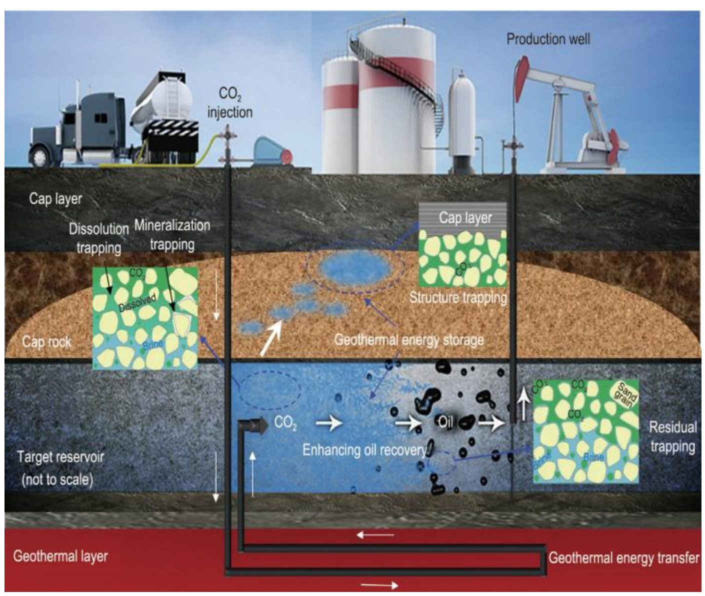


Figure 4: Conceptual schematic of an advanced geothermal system using carbon dioxide as the working fluid [42].

Geothermal systems differ in cost, efficiency, and environmental impact. Advanced Geothermal Systems (AGS) employ a much less cost-competitive economic approach due to their high drilling costs and lower efficiency of electricity generation. The environmental safety of AGS systems is due to the geological conditions limiting contact with underground water sources. At the same time, the lack of water means AGS systems are not cost-effective, leading to further sustainability concerns. Enhanced Geothermal Systems (EGS) and CO_2 -Plume Geothermal (CPG) systems exhibit enhanced efficiency due to the artificial fractures, allowing the CO_2 to flow slightly better than a "normal" water-based system. Hydrothermal systems based on purchasing/renting secondary CO_2 lose efficiency with an expected lifetime due to having water under high-flow conditions, with the added concern of having secondary CO_2 needing auxiliary pumping to be effective.

From an environmental perspective, Enhanced and Plasma Geothermal Systems bolster their value proposition as dual-purpose systems for energy production as well as for CO_2 storage. Advanced Geothermal Systems have a lesser environmental risk due to less subsurface interaction. Ultimately, the choice of systems will depend upon geological conditions, resource availability, and carbon reduction pathways since every system has its own positives and negatives [39-41]. Finally, Table 5 compares the various parameters of geothermal systems.

Table 5: Comparison of different types of geothermal systems.

Parameter	Hydrothermal	CPG	EGS	AGS
Working Fluid	Water + CO_2	Dense CO_2	CO_2	CO_2
Reservoir Type	Natural	Natural	No reliance on natural permeability	No reliance on natural permeability
Advantages	Simpler infrastructure	Reduced pumping needs	High thermal efficiency	No groundwater contamination
Limitations	Dependence on water resources	Monitoring and corrosion-resistant material costs	Engineering complexity	High drilling costs

In deep geothermal systems with water as a working fluid, loss of water through leakage is a major adverse effect. Removing CO_2 from the atmosphere and injecting it into the wells (instead of water) in a deep geothermal system would prevent water loss and CO_2 from entering the atmosphere, thus reducing greenhouse gas emissions. Moreover, it has been shown that CO_2 can enhance heat transfer in the geothermal system up to five times that of water or brine [43, 44]. Conversely, it should be recognized that water is a polar liquid; it has a propensity to dissolve salts (found in rocks) that create unwanted flow channels in the reservoir, which can short-circuit the flow path and decrease the energy efficiency of the geothermal system. Moreover, this rock dissolution and subsequent formation of new voids is more likely to alter the mechanical characteristics of the rock. The precipitation of dissolved salts in flow paths and pore spaces of the rock can cause blockage and/or deviation of flow, this does not occur when CO_2 is injected into the subsurface [45]. The differences between water and CO_2 injection into geothermal systems are summarized in Table 6 [46].

Table 6: Comparison between water injection and carbon dioxide injection in geothermal systems [46].

Comparison Index	Water Injection	Carbon Dioxide Injection
Chemical Behavior	Produces ionic dissolution products, serious dissolution or precipitation issues	No ionic dissolution products, no serious dissolution or precipitation issues
Fluid Circulation in Wells	Low compressibility, moderate expansion	High compressibility and expansion
Ease of Flow in Geothermal Reservoir	High density and viscosity	Low density and viscosity
Heat Transfer	High specific heat capacity	Low specific heat capacity
Fluid Loss	Barrier to reservoir development, high cost	Can lead to carbon dioxide storage

6. Mechanical Behavior of Rock in Geothermal Reservoirs

Geothermal reservoirs and other subsurface formations reflect heterogeneity in their complex geological and structural nature. This heterogeneity makes understanding the mechanical behavior of rocks difficult because studying these effects at the laboratory scale is impossible. These effects can include variations in rock matrix composition, texture, layer orientation and dip, degree of crystallization and gusto sorting, particle size distribution, vein mineralogy, the influence of fault or faults, and intensity of fractures, along with changes to primary and secondary porosity [47]. Rock mechanics testing on a homogeneous rock typically exhibits predictable behavior, which can be described with elastic or elasto-plastic mathematical stress-strain models [48].

Heterogeneous rocks exhibit intricate structures of weak and strong components resulting in unexpected failure and mechanical behavior which makes predicting their response difficult. These types of rock demonstrate unexpected strength as they continue to strain due to the complexity associated with multiple components. In order to examine rock behavior under strain, a triaxial test must be performed with cycles of loading, unloading, and reloading. Hysteresis loops will be observed in the stress-strain diagrams within each cycle, which represent the cycles of loading-unloading and the formation of micro-fractures [49].

The in-situ stress field is important for the mechanical behavior of geothermal reservoirs. The amount and orientation of the stress field create the failure pattern. Therefore, the type of failure pattern can be studied to help characterize the in-situ stress field [50]. The principal stresses are rotated in situ during drilling and hydraulic fracturing, particularly at geothermal reservoirs that have known faults or have experienced previous fracturing impacts.

Discontinuities and fractures in the reservoir rock also have an important effect on rock mechanical behavior, fluid flow, and ultimately the performance of a geothermal system in producing energy. With injection or production, pore pressure in the reservoir changes, which results in a change in effective stresses acting on the reservoir. The pressure changes cause deformations in the fracture and the rock matrix [51]. The extent of a pressure drop in geothermal wellbores is influenced by several parameters, such as the inclination angle of the wellbore, its depth and diameter, the roughness of the borehole and pipe walls, the contraction and expansion of the wellbore path, any rotational and axial movements, the velocity of working fluid, and the flow regime in the circulation system, all of which may significantly affect heat-extraction effectiveness. Since the fracture network is more ductile as compared to the rock matrix, the fracture system is more susceptible to changes in pressure, temperature, and stress. Ultimately, the fractures govern the fluid flow regime in the reservoir through their permeability.

It is essential to acknowledge that the permeability of the fracture network is influenced by the geothermal reservoir's chemical, thermal, hydraulic, and mechanical properties. These processes interact with the rock and fluid and will definitely influence the closure of the fractures and their deformation [45, 53].

7. Effect of Fluid Type on Petrophysical Properties of Rock

The type of fluid used in geothermal systems can significantly affect the petrophysical properties of rock, such as permeability and wettability. Most studies regarding the effect of fluid type have been done in regard to enhanced oil recovery (EOR), but their findings can also be relevant to geothermal systems. Kashkooli et al. (2022) [54] investigated gas trapping and relative permeability curves under continuous injection of carbon dioxide (CO_2) during an EOR method. They demonstrated that residual gas saturation increased as gas transitioned from a dissolved phase to a trapped gas phase under continuous CO_2 flooding. Oil swelling and lower interfacial tension also affect the manner under which the relative permeability curves are shaped, allowing additional gas trapping space within the throat sections of pore space. Trapping CO_2 in porous media enhances both the capacity and security of storage.

Gandomkar et al. (2020) [55] studied controlled mobility of CO_2 using a CO_2 -tooling molecular thixotropical during oil recovery. They utilized polydimethylsiloxane (PDMS) as a CO_2 -philic thickening agent in various molecular weight categories. Their results demonstrated that PDMS affected relative viscosity and allowed for a thickening of the CO_2 stream. They noted that injection of CO_2 thickened with PDMS, if injected parallel, could delay breakthrough time, the time gas enters the production well, significantly. Gandomkar et al. (2022) [56] studied the impact of a predesigned and systematic comprehensive study of alternating CO_2 and low-salinity water injection in carbonate reservoirs characterized by a similar oil-wet character have been published. They found that monovalent ions, including sodium chloride or potassium chloride, allowed brine to desalinate more significantly than the divalent salt solutions, including calcium chloride or magnesium chloride. Their study found that low-salinity alternating CO_2 would replace the late breakthrough issue in conventional water-gas injection methods. Nevertheless, these fluids (water and CO_2) will chemically and mechanically interact with the reservoir rock and, as a result, change its porosity and permeability. Understanding these effects is important for the efficient operation of heat extraction in geothermal operations. Generally, porosity and permeability are two important properties for determining the productivity of geothermal reservoirs.

Zhang et al. (2020) [57] studied the effect of the size of the particles on the permeability by separating the particles into fine and coarse particles. The results showed that the reservoir permeability increases as the fine particles migrate, but decreases as coarse particles (the coarse particles are more likely to block or occlude the pores). Once the particles have migrated, the process of pore compaction and further migration can be facilitated by the influence of the stress field, thereby further reducing pore space connectivity and flow [58].

To conclude, the injection of water and carbon dioxide into geothermal reservoirs has excellent effects on porosity and permeability, depending on how many different capacities change. For example, dissolution can improve fluid flow, while precipitation and clay reactions would clog it. Nevertheless, long-term management of geothermal reservoirs requires careful monitoring of fluid chemistry, continual chemical management, and planned or responsive injection into the reservoir to maintain productivity.

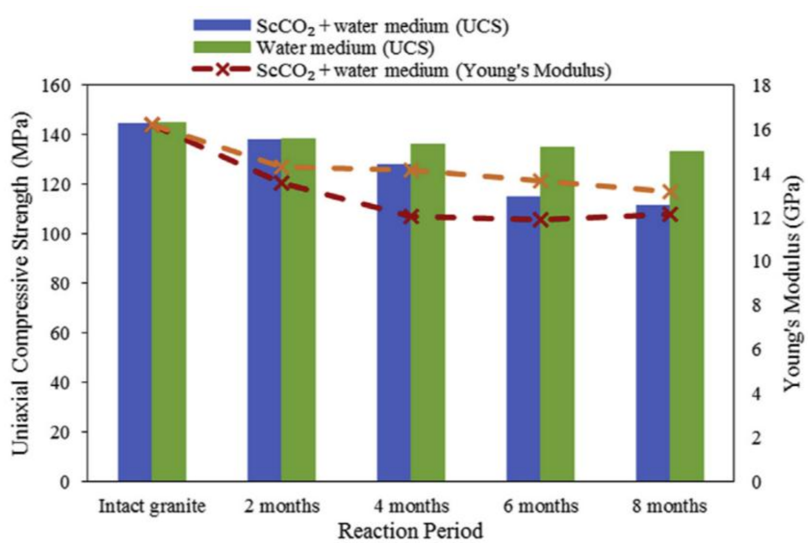


Figure 5: Changes in uniaxial compressive strength and elastic modulus of samples after fluid saturation [59].

Rock sample fluid saturation illustrated a declining uniaxial compressive strength and elastic modulus, as shown in the figure. The previous section referred to this mechanical weakening as the consequence of changes at both a microscopic and mineralogical level, arising from dissolution of the rock minerals responsible for decoupling particles from the rock framework. In Figure 6, CT scan images are included of core samples with and without fluid illustrating visually, the dissolution of particles and weakening of the rock framework. Shen et al. (2020) conducted a closely related study to evaluate water and supercritical carbon dioxide injection on the mechanical properties of granite for geothermal resource applications. In their assessment, they conducted triaxial testing on granite samples varying confining pressures (2 to 20 MPa), pore fluids (− using the terms in their study, water or CO_2 was included at 10 MPa), and temperature (setting 25 to 150 °C). Figure 7, taken from the triaxial testing on granite samples, under CO_2 and water injection, engages the reader with sample results under different temperature settings [60].

σ_1 is the maximum principal stress, σ_3 is the minimum principal stress, ε is the axial strain (positive values) and radial strain (negative values). As you can see from the graphs, under a CO_2 environment, the compressive strength of granite will increase as the temperature is raised to 90 °C; at the point where the granite was raised to 150 °C, the strength decreased, and the axial strain at peak stress was also reduced. However, this is in direct contrast to the water-saturated environment, whose peak stress recorded decreased as temperature increased. The lowest strength was at 150 °C under CO_2 , considering it was not previously shown in this section [60].

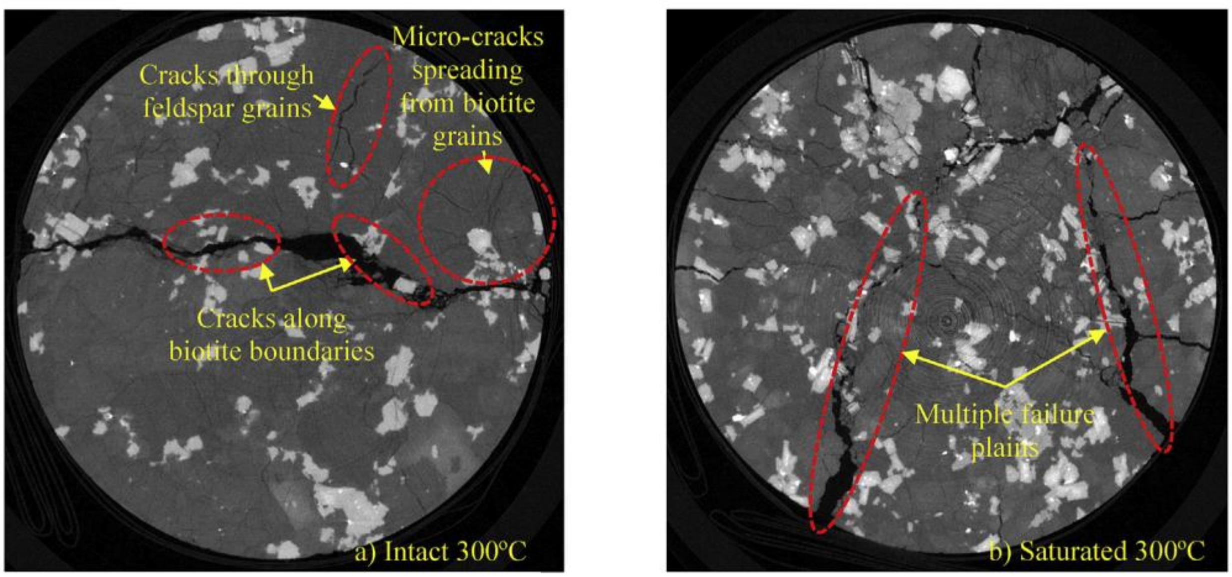
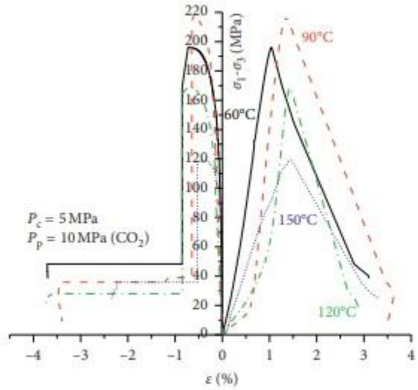
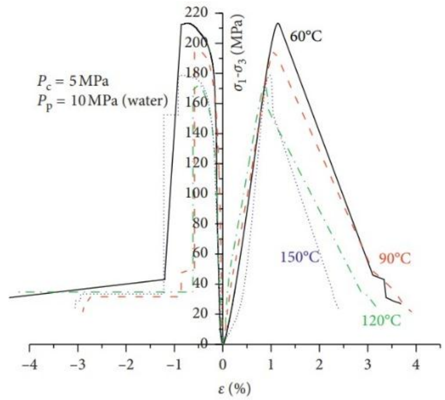


Figure 6: CT scan images of granite samples: (a) Untouched rock (b) Rock after reaction with fluid [59].

As demonstrated in the preceding findings, The researchers reiterated that water is much more viscous than CO2, hence, it is more difficult for the water to enter the fractures immediately after formation. This may explain the overall higher strength found for all granite samples at 60 °C and 150 °C during the water injection condition versus CO2 injection condition. Overall, this study confirmed that fluid (water or CO2) injection weakens elastic modulus and rock strength, and CO2 has a more significantly larger weakening effect on rock strength. Furthermore, it was determined that changing the type of fluid to inject did not significantly affect granite strength under a constant confining pressure [60].



(a)



(b)

Figure 7: Results of triaxial testing on granite rock samples: (a) Under carbon dioxide (CO_2) injection (b) Under water injection [60].

In a review paper from a geochemical perspective, Zhou et al. (2024) elaborated on the reaction mechanism of water/CO_2 and rock in advanced geothermal systems and the effect of that reaction on the mechanical properties of the reservoir rock. Reviewing numerous studies, the authors concluded that mineral dissolution and precipitation reactions (for example, salts) are the dominant geochemical processes involved in geothermal energy extraction with either water or carbon dioxide (CO_2). The degree of your reactions is variable and influenced by various factors, including temperature, pressure, total injection rate, salinity, pH, and microbial activity [23]. Dissolution and precipitation processes cause mechanical property changes in rock in geothermal reservoirs. Zhou et al. summarized the findings from laboratory studies. They reported that the uniaxial compressive strength and elastic modulus of rocks decreased after contact with both water and CO_2, and the strength reduction from CO_2 was greater (Figure 8).

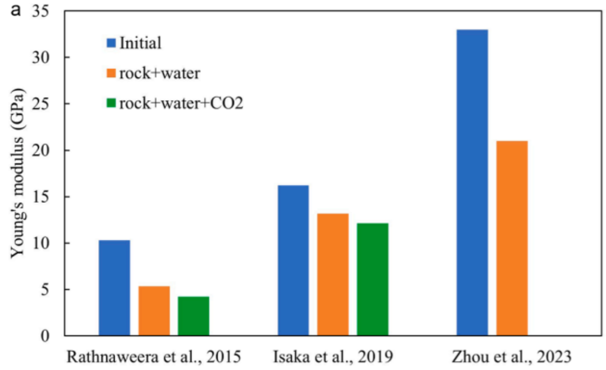


Figure 8: Changes in elastic modulus and uniaxial compressive strength of rock after fluid reaction (compiled by Zhou et al.) [23].

The effects of carbon dioxide (CO_2) on rock mechanical properties are highly dependent on the reservoir's original (initial) water saturation. When water saturation is high, water and CO_2 reactions partially dissolve rock particles and the binding material around them, thus reducing the rock strength. Therefore, the effects of CO_2 on rock strength will be less significant in rocks with original (initial) water saturation lower than 75% [61, 62]. The mineralogical composition of the geothermal reservoir rock is another relevant aspect in evaluating the potential impacts of CO_2 injection on mechanical properties. Akono et al. (2019) already reported that the effects of CO_2 on mechanical properties are not distinguishable until a long time has passed if quartz is the main mineral and carbonate minerals are present in minor amounts [63]. The primary concern regarding safe CO_2 injection activities is whether wellbores remain mechanically and chemically sound, emphasizing the importance of learning and preventing degradation mechanisms at the rock scale to ensure long-term containment and operational safety [64].

Table 7: comparison of CO_2 vs. water injection experiments.

Study (Year)	Rock Type	Fluid(s) Tested	Experimental Setup	Temperature Range (°C)	Pressure Conditions	Duration	Analytical Techniques Used
Marbler et al. (2012)	Sandstone	$scCO_2$ + brine	Autoclave + triaxial cell	In situ (~80–150°C)	Confining & pore pressure varied	2–4 weeks	SEM, XRD, polarized microscopy, ICP-MS/OES, ion chromatography, triaxial strength testing
Zhang et al. (2020)	Sand-packed tube	Water	Core flooding with sand/mud mixtures	20–90°C	Confining pressure controlled	Variable	Turbidity monitoring, particle counting, CMG STARS kinetic modeling
Isaka et al. (2019)	Granite	$scCO_2$, H_2O	Triaxial + uniaxial tests + AE + CT scanner	25–200°C	Confining pressure up to 30 MPa	Weeks–months	SEM, CT, AE monitoring, UCS, Young's modulus, crack threshold analysis
Shen et al. (2020)	Granite	Water, $scCO_2$	Modified triaxial shear-flow apparatus	25–150°C	Pore fluid = 10 MPa; confining 2–20 MPa	Hours–days	SEM (failure surfaces), geochemical modeling, UCS, elastic modulus

Geothermal systems, especially Enhanced Geothermal Systems (EGS), involve complex thermal, hydraulic, mechanical, and chemical interactions. These systems use geothermal reservoirs to produce sustainable energy. Geochemical impacts and reactive flow are key because they influence key reservoir properties such as permeability, porosity, and temperature distribution [65-67]. In geochemistry, several numerical methods and models have been developed to study these complex interactions. These tools help better characterize changes in permeability, porosity, and temperature, which are critical for typical EGS systems. Table 8 summarizes these tools.

Table 8: Comparison of numerical methods for modeling coupled processes.

Numerical Method	Coupling Type	Advantage	Limitation	Ref
Fully Coupled	Full coupling	High accuracy in complex interactions	High computational cost	[67]
Sequential Non-Iterative	Sequential decoupling	Simplicity and reduced computation time	Numerical oscillations under dynamic conditions	[68]
Finite Difference Method (FDM)	Flow/heat transfer	Geometry simplification	Low accuracy in complex geometries	[69]
Finite Element Method (FEM)	Multiphase/reactive flow	Flexibility in fracture modeling	Requires complex meshing	[70]

8. Comparison of Various Challenges Based on Lithology in Geothermal Systems

Challenges from different rock types impact geothermal energy system development. Table 9 summarizes these challenges.

Table 9: Comparison of various parameters based on lithology in geothermal systems.

Parameter	Granite	Carbonate	Sandstone
Natural Permeability	Very low	High (dependent on fractures)	Moderate (dependent on porosity)
Chemical Challenges	Silicate mineral alteration	Carbonate precipitation and dissolution	Ion exchange and scale formation
Induced Seismicity	High (due to hydraulic fracturing)	Moderate (due to CO_2 leakage)	Low (due to stress conditions)
Thermal Management Challenges	Thermal stress from cold fluid injection	Fracture stability at high temperatures	Textural changes due to thermal stress
Gas Storage Capacity	Moderate (reaction with silicates)	High (carbonate formation)	Low (unstable scale formation)

Granitic structures have low natural permeability, so hydraulic fracturing is needed to create artificial fractures. However, hydraulic fracturing can cause induced seismicity [23] and is costly. These factors may also cause thermal and chemical instability in the reservoir. Introducing a cold fluid such as water or CO2 will generate thermal stress and fluid will react with the silicate minerals in granite altering the minerals and pore structure [71]. Compared to other geological formations, carbonate formations have greater inherent permeability due to more extensive fracture and fault networks. Greater permeability leads to more complex fluid flow and higher potential for mineral scaling in pipelines [72]. Additionally, the interaction of carbonates with carbon dioxide or water has the potential to compromise reservoir integrity by creating pathways for carbon dioxide to escape and also increasing ecological risks [73].

Sandstone formations face permeability changes and future scale formation because their clay minerals and high chemical reactivity reduce fluid flow [71]. Since sandstone formations are typically shallow, they have lower temperatures than deeper geologic formations, which limits energy production [73]. While sandstone usually has greater mechanical stability than granite, the porosity of rocks increases upon fluid injection, leading to increased stresses downstream and eventual surface subsidence [23]. Potential reservoir formations should be selected on an optimal balance of thermal conductivity and CO_2 storage capacity and with techno-economic and environmental risk considerations to limit impact on human health and the environment. Each lithological unit requires engineering solutions that consider their specific petrophysical and geomechanical properties.

9. suggestions for future research

As suggestions for future research, we recommend the following concrete recommendations.

- Standardized Testing Protocols: Establish international standards for geothermal rock-fluid interaction trials, with representative conditions having temperature (25-300˚C), pressure (10-30 MPa), and fluid chemistry conditions related to some lithology (granite, carbonate, sandstone).
- Long-Term Monitoring Frameworks: Create at least 10-year building monitoring programs to monitor key parameters for pilot CO_2 -EGS work, including integrity of the reservoir (tolerance of <0.5% change in overall permeability per year), induced seismicity (magnitude <2.5), and chemical evolution (monthly fluid sampling).
- Regional-Specific Optimization: Important observations should be made at a regional-specific basis for sedimentary basins in the Middle East, having thermal conductivity of 1.43-3.46 W/mK and geothermal gradient of 14.9-29.7˚C/km. These observations would measure the optimum CO_2 injection rate (average rate of 0.5–2.0 kg/s per well), maximizing the extraction of heat while maintaining reservoir stability.
- Hybrid Fluid Systems: Investigate the technical and economic feasibility of hybrid water/CO_2 injection systems especially for carbonate reservoirs where water-saturated zones may limit CO_2 dissolved while giving 30–40% higher heat extraction rates than pure water systems.

10. Conclusion

This study accurately examines the processes producing rock mechanics in geothermal reservoirs, particularly how various working fluids induce change. Our results indicate that injected fluids alter fundamental mechanical properties with reservoir rocks thereby creating barriers to further advancements. Critical results include quantitative measures demonstrating that CO_2 revolution systems provide five times heat transfer performance of water-based systems and therefore provide an opportunity to reduce carbon storage to 0.5-1.2 kg CO_2 /MWh of energy produced. These performance changes, due to the working fluids injected into the rock formation also need to be understood in terms of potential mechanical degradation; studies suggest that uniaxial compressive strength may loose 15-30% or elastic modulus potentially loosing 10-25% of stiffness in carbonate-rich formations at water saturations of above 75%. The economical implications of these technologies become considerably larger as demonstrated by levelized costs of electricity production reaching $0.05-$0.10/kWh for binary-cycle plants in the Yanbu Basin of Saudi Arabia, or $3.6/kWh for EGS systems that utilize organic Rankine cycle or reclaimed abandoned wells.
As geothermal energy attracts attention in the race to cut emissions, significant technical and geological obstacles remain. The key summary conclusions below spotlight the defining factors and consequences uncovered by this review:

- Because of its unique physical and chemical characteristics, carbon dioxide (CO_2) has the capability to substantially improve heat extraction by reducing fluid viscosity and increasing heat transfer, which improves the performance of geothermal systems. CO_2 also has favorable thermodynamic characteristics for heat transfer and pumping cost efficiency. CO_2 can also absorb carbon, which enhances the efforts to decrease greenhouse gas emissions. However, one must also think of possible physical and chemical changes to reservoir rock properties before implementing CO_2 injection on any significant scale.

- Selecting water or carbon dioxide as the working fluid in advanced geothermal systems creates different effects on rock mechanical properties. Chemical interactions between fluid and reservoir rock shape reservoir characteristics. Mineral dissolution and precipitation alter rock structure and directly affect permeability and mechanical strength. For example, reactions involving water or carbon dioxide can induce fracture formation or expansion. This may enhance or compromise reservoir stability.

- Chemical interactions between CO_2 and reservoir rock can lead to changes in mineralogy and material microstructure, which may increase the permeability of reservoir rock, but can also decrease or lessen the mechanical strength of the rock. Under a high-pressure and high-temperature gaseous environment, CO_2

injection changes Young's modulus, axial compressive strength, and all other mechanical material properties. The induced changes depend on many factors, including the mineralogical composition, initial water saturation, and the rate at which a fluid is injected.

Assessing the literature shows that temperature, rock type, and fluid composition have differing effects on results. Often, these differences come from the method of sample collection, whether surface or subsurface, and testing conditions. To minimize the impact of these variations, experiments should be well-controlled to simulate true geological environments before drawing conclusions about the behavior of the rock. For this reason, future studies need to evaluate the use of both CO_2 and water at the same time in order to assess the geothermal energy recovery. This methodology could result in geothermal systems that are more efficient and sustainable.

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