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Investigating the Effects of CO_2 Gas in the Development of Reinjection Strategies in Geothermal Fields with Case Studies

Tuğbanur Özen Balaban[1], Füsun Servin Tut Haklıdır[2]*
[1]İzmir Katip Çelebi University, Department of Project General Coordination, İzmir, Türkiye
[2]İstanbul Bilgi University, Department of Energy Systems Engineering, Eyüp, İstanbul, Türkiye
*fusun.tut@bilgi.edu.tr

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ABSTRACT

Reinjection action plans and techniques are vital for sustainable production in geothermal fields. New reinjection strategies are being developed to prevent rapid pressure drop during energy production in geothermal fields and to minimize environmental concerns, especially in liquid-dominated systems. Especially within the scope of global CO_2 emission reduction targets, European Commission supported projects are being tested in geothermal fields in countries such as Iceland and Türkiye, where significant progress has been made in the results for the disposal of CO_2 gas from geothermal power plants. In these tests, where fluid chemistry and reservoir rocks are important in geothermal systems, direct underground injection of gas is not possible due to pump technical specifications and high energy requirements in some fields. Sometimes, this gas is mixed with injection water, and it is generally considered risky by the investor because it is not possible to monitor the chemical behavior of this gas in the subsurface and quickly understand its effect on reservoir conditions. Within the scope of this study, the PHREEQC program will be used to investigate the possible effects of gas addition in reinjection on underground geochemical conditions, considering fracture structures. A case study for a few geothermal fields in Türkiye has been presented.

1 INTRODUCTION

The reinjection of produced geothermal fluids is a fundamental component of sustainable geothermal reservoir management. In liquid-dominated geothermal systems, reinjection maintains reservoir pressure, compensates for mass extraction, and helps sustain long-term energy production (Axelsson, 2003). In addition to its hydraulic benefits, reinjection minimizes environmental discharge, reduces surface pollution, and improves operational compliance. Despite these advantages, reinjection can create various operational challenges that negatively impact injection capability and long-term reservoir performance, such as pressure decline, thermal fracture, scaling, and fracture blockage (WB, 2014). Scaling, particularly from carbonate and silica minerals, remains one of the most persistent problems affecting well conditions, reinjection lines, and reservoir flow paths.

High-temperature geothermal systems contain significant amounts of dissolved CO_2 along with geothermal fluids. Globally, geothermal power plants can emit between 5 and 900 g CO_2/kWh depending on reservoir conditions, and tectonically active volcanic regions generally have higher emissions (Fridriksson et.al 2017)). These CO_2 values, which are environmentally significant, especially in the early years of production, tend to decrease as the production period lengthens, causing reservoir pressures to drop as well. However, in the context of international climate agreements and national carbon emission reduction targets, reducing these emissions is becoming increasingly important. In summary, geothermal operators worldwide are exploring the reinjection of CO_2-rich fluids and in-situ mineralization as viable strategies to reduce geothermal CO_2 emissions. Dissolving CO_2 into reinjection water can reduce atmospheric discharge and simultaneously initiate mineral carbonation reactions that immobilize CO_2 underground. This approach is compatible with global carbon neutrality goals and may offer geothermal fields the opportunity to transform into systems that combine energy production and CO_2 capture.

Over the past decade, CO_2 reinjection and mineralization have been successfully tested in several geothermal fields worldwide. The CarbFix project in Iceland is the most prominent example, demonstrating rapid and permanent mineral trapping of injected CO_2 in basaltic formations. At the Hellisheiði Geothermal Power Plant, CO_2 dissolved in water has been injected at rates exceeding 10,000 tons per year, leading to carbonate mineral formation within less than two years (Matter et al., 2016; Snæbjörnsdóttir et al., 2020). These results have established in situ mineral carbonation as a scientifically validated and operationally feasible method for CO_2 disposal.

Several studies emphasize that CO_2-rich fluids significantly alter pH and mineral equilibria, affecting both dissolution and precipitation pathways.

In Türkiye, geothermal systems in the Büyük Menderes (BMG) and Gediz Grabens (GG) produce substantial quantities of CO_2 together with geothermal brines. In the Kızıldere (Denizli) geothermal field, fluids containing significant amounts of dissolved CO_2 are produced from carbonate reservoirs (over 3% by weight, depending on depth). Although this gas decreases over time, CO_2 gas at a certain concentration is still released into the atmosphere by the cooling towers. The Kızıldere geothermal field, in particular, is known for its naturally high CO_2 flux, and several hydrogeochemical studies have examined CO_2 behavior, calcite scaling, and reinjection performance (Mutlu & Güleç, 1998).

Especially in Kızıldere geothermal field, as part of the SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal Energy Deployment) project, a dynamic reservoir model of the Kızıldere geothermal field was developed by the researchers (Durucan et. al, 2025). In a separate study, two power plants in the field were examined with and without CO_2 reinjection as part of the same project. Without injection, life cycle CO_2 emissions were estimated at 140 kg CO_2/MWh for Kızıldere II and 444 kg CO_2/MWh for Kızıldere III. With CO_2 reinjection: It is estimated that CO_2 reinjection will reduce emissions for Kızıldere II to 110 kg CO_2/MWh. It is stated that emissions for Kızıldere III will be reduced to 186/185 kg CO_2/MWh (Nie et al., 2025). Before this study, assessment studies (Mainar-Toledo et al., 2023) were also conducted at Unit 1 of the Kızıldere-3 power plant to reduce CO_2 emissions by 10% as part of the GECO project (Geothermal Emission Gas Control). Beside the CO_2 reinjection, the feasibility of using Distributed Acoustic Sensing (DAS) cables in active seismic surveys for CO_2 monitoring at the Hellisheiði geothermal field in Iceland for the purpose of monitoring CO_2 reinjection is being investigated (Meneghini et al., 2024).

The recent research emphasizes complex geochemical reactions triggered by reinjection into fractured metamorphic and sedimentary lithologies, especially carbonate-rich units. The reinjection application and geothermal mineral scaling have a close relationship and have also been widely documented at different geothermal fields in Türkiye such as Germencik, Kızıldere, Alaşehir, Salavatlı, and Tuzla, highlighting the importance of understanding carbonate and silica equilibria under reservoir conditions (Tut Haklıdır and Özen Balaban, 2019, Tut Haklıdır et al., 2020; Filiz et al., 2015). Türkiye's geothermal sector has also been increasingly motivated to pursue CO_2 reinjection due to relatively high geothermal CO_2 emission intensities, which can exceed 500 g/kWh in certain fields . The current studies on global emission reduction primarily focus on mineral carbonation efficiency and long-term CO_2 storage safety, while research explicitly addressing the short-term hydrogeochemical effects of CO_2-enriched reinjection water on fractured geothermal reservoirs is less common. Some of these gaps include the extent to which dissolved CO_2 alters pH, carbonate equilibrium, and aqueous speciation at high temperatures and pressures; changes in mineral saturation indices (SI) for major phases such as calcite, aragonite, dolomite, quartz, amorphous silica, and feldspars; and the scaling trend of dissolution under varying CO_2 concentrations. These gaps require robust, site-specific geochemical modeling approaches capable of capturing the complex interactions between CO_2 dissolution, fluid-rock interactions, and mineral equilibria under reservoir conditions. Some of these gaps include the extent to which dissolved CO_2 alters pH, carbonate equilibria, and aqueous speciation at elevated temperature and pressure; the resulting changes in mineral saturation indices (SI) for major phases such as calcite, aragonite, dolomite, quartz, amorphous silica, and feldspars; and the tendency for dissolution to scale under changing CO_2 concentrations. These gaps necessitate robust, site-specific geochemical modeling approaches capable of capturing the complex interplay between CO_2 dissolution, fluid–rock interactions, and mineral equilibria under reservoir conditions.

The primary aim of this study is to evaluate the hydrogeochemical effects of adding CO_2 to reinjection water in fracture-dominated geothermal reservoirs, using PHREEQC simulations constrained by field data from selected geothermal sites in Türkiye. The study is designed to systematically quantify geochemical responses to CO_2 enrichment and assess their implications for reservoir sustainability and reinjection management.

2 MATERIAL AND METHODS

Table 1 contains the physical and chemical data of the wells in the study. The data in Table 1 was evaluated with PHREEQC version 3.8 (Parkhust and Appelo, 2013) was used with the llnl.dat thermodynamic database. Reservoir temperatures were applied to each solution, and CO_2 addition was modeled through REACTION blocks. EQUILIBRIUM_PHASES were used to determine calcite and quartz saturation states under in-situ conditions. CO_2(g) was incrementally dissolved to simulate a loading of 1 mol CO_2 per kg of geothermal water. The resulting pH, aqueous speciation, and calcite saturation indices (SI) were computed for each well. Mineral reaction molecules from PHREEQC outputs were converted to tons per year using brine flow rates.

Table 1. The hydrogeochemical analysis and measurements of the selected geothermal wells in the study area

Well ID	Region	BHT (°C)	Flowrate (tph)	pH (20-22 °C)	EC (µS/cm)	K^+	Na^+	Ca^{2+}	Mg^{2+}	Li^+	B	SiO_2	HCO_3^-	Cl⁻	$SO4^{2-}$	Reference
KD-13	Kızıldere	201	150	8,2	4640	188	1150	10,4	<1	3,2	16,7	428	1901	103	698	*Tut Haklıdır et al., 2021*
R-1	Kızıldere	242	200	8,1	5570	290	1380	1,48	<1	4,6	27,6	663	2667	128	721	*Tut Haklıdır et al., 2021*
OB14	Germencik	228	809	7,8	6660	149	1364	17,9	<1	7,8	55	409	1428	1700	26,6	*Karakuş and Şimşek, 2013*
OB17	Germencik	228	321	7,6	6661	174	1565	12,3	<1	10,6	59	535	1461	1565	20	*Karakuş and Şimşek, 2013*
Alkan-1	Alaşehir	190	250	7,1	1029	90	534	2,09	<1	6,3	83	366	1389	166	10,2	*Tut Haklıdır and Şengün, 2020*
Alkan-2	lAaşehir	200	285	7,1	993	79	560	2,27	<1	6,2	101	501	1443	182	14,6	*Tut Haklıdır and Şengün, 2020*

3 GEOLOGICAL SETTINGS

The Western Anatolia hosts some of the most productive high-enthalpy geothermal systems in Europe and the Eastern Mediterranean. The geothermal fields of Kızıldere, Germencik, and Alaşehir, which constitute the focus of this study, occur within the actively extending BMG and GG systems. These grabens represent major neotectonic structures formed under N–S directed crustal extension, driven by the rollback of the Hellenic slab and associated lithospheric thinning. High geothermal gradients (up to 140°C/km), active normal faulting, and deep magmatic–metamorphic CO_2 sources create favorable conditions for the development of high-enthalpy geothermal reservoirs.

Regionally, the geological framework is dominated by the Menderes Massif, a complex metamorphic basement composed of schist, gneiss, and marble (Bozkurt, 2001, Şimşek, 2003). These rocks form the primary geothermal reservoir units due to their extensive fault-controlled secondary permeability. The basement is unconformably overlain by Neogene sedimentary units, including lacustrine claystone, sandstone, limestone, and conglomerate, which act as caprock sequences across the grabens. Quaternary alluvium fills the present-day valley floors and plays a limited role in reservoir processes. The geothermal systems are structurally controlled by major E–W trending high-angle normal faults, which form the boundaries of both grabens. These faults serve as deep fluid conduits, enabling rapid ascent of high-temperature geothermal waters and CO_2-rich fluids from depth. Secondary faults trending NE–SW and NW–SE act as transfer zones, creating zones of enhanced fracture permeability where geothermal production wells are concentrated. The interplay between these structures governs fluid flow, reservoir compartmentalization, heat transport, and reinjection performance in all three geothermal areas.

The Kızıldere geothermal field, located in the western segment of the BMG, is one of Türkiye's oldest and most studied geothermal systems. The geothermal reservoir is hosted primarily within marble and fractured gneiss units of the Menderes Massif, offering high fracture permeability along deep-seated fault zones. The overlying Neogene sediments form an effective caprock that restricts vertical flow and maintains reservoir pressure. Structurally, Kızıldere lies along an E–W trending normal fault system with significant vertical displacement. Deep, CO_2-bearing fault zones intersect the metamorphic basement, allowing extensive degassing and creating the characteristically CO_2-rich fluids of the field. Reservoir temperatures range from 180 to 245°C, making Kızıldere one of the Türkiye's highest-enthalpy systems. The dominant hydrochemical type is Na–Cl–HCO_3, with high dissolved CO_2 contributing to strong carbonate equilibria and widespread calcite scaling (Tut Haklıdır and Özen Balaban, 2019). Reinjection wells commonly experience permeability reduction due to carbonate and silica precipitation, highlighting the importance of geochemical modeling.

The Germencik (Aydın) geothermal system is situated in the central BMG and is one of the hottest geothermal fields in Türkiye (Tut Haklıdır and Şengün, 2020). The reservoir is hosted in fractured schist, gneiss, and marble units, similar to Kızıldere, but with higher structural permeability along the Germencik Fault Zone, a major E–W trending normal fault system. The Neogene sediments that cover the metamorphic basement act as a thick caprock, enhancing reservoir confinement. The field is characterized by high subsurface temperatures of 180–250°C, intense natural fracturing, and strong convective fluid flow. CO_2 contents are slightly lower than in Kızıldere geothermal field and hydrochemically, the fluids are predominantly Na–Cl type. Germencik experiences substantial silica scaling, particularly in reinjection lines and at formation temperatures conducive to amorphous silica precipitation. Fault intersections and high extensional strain rates promote both production and reinjection efficiency, but also increase sensitivity to geochemical changes during CO_2-enriched reinjection.

The Alaşehir (Manisa) geothermal field is located within the GG, northeast of the BMG. Unlike Kızıldere and Germencik, which lie within a single graben system, Alaşehir sets in a distinct, but tectonically related extensional basin. The reservoir is hosted primarily in fractured marble and schist units of the Menderes Massif (Tut Haklıdır and Şengün, 2020). The caprock consists of Miocene–Pliocene sediments, including sandstone, claystone, and lacustrine deposits that efficiently seal the reservoir. The field is controlled by the Alaşehir Fault, one of the most active normal faults in the Western Anatolia. High-angle fault zones provide deep, permeable pathways that deliver around 160–215°C geothermal fluids to the near-surface environment. CO_2 contents range

from moderate to high, depending on structural connectivity to deeper metamorphic–magmatic sources. The field is particularly susceptible to carbonate scaling, owing to the strong interaction between CO_2-rich fluids and carbonate-bearing metamorphic rocks. Reinjection wells often encounter injectivity decline associated with calcite deposition and fracture clogging. The selected geothermal fields are high-temperature geothermal fields developed due to tectonism, especially in graben structures, and therefore require site-specific simulation to evaluate the geochemical effects on long-term reservoir sustainability.

3 RESULT AND DISCUSSION

The geochemical simulations conducted in this study provide an integrated assessment of how CO_2-enriched reinjection water interacts with fracture-dominated geothermal reservoirs in Western Anatolia. By combining reservoir-specific fluid compositions with PHREEQC-based reactive modeling, the results reveal systematic trends in pH evolution, mineral saturation states, and the potential for calcite scaling or mineral dissolution across the three major geothermal regions studied: Kızıldere, Germencik, and Alaşehir.

Overall, the introduction of CO_2 into reinjection water leads to a pronounced decrease in pH under reservoir temperature and pressure conditions. This acidification, in turn, exerts a strong control on the saturation indices (SI) of key mineral particularly calcite which governs the long-term injectivity and sustainability of reinjection operations. The degree of pH shift and the resulting mineral reactions vary significantly among wells, reflecting differences in reservoir lithology, fluid–rock interaction capacity, and baseline water chemistry.

High-enthalpy carbonate-dominated systems such as Kızıldere show the strongest response to CO_2 addition, with large pH reductions and near-complete suppression of calcite supersaturation, thereby minimizing scaling risk. In contrast, the siliceous–metamorphic reservoir systems of Alaşehir exhibit more moderate geochemical shifts but indicate potential for enhanced mineral dissolution under CO_2-rich conditions. Germencik wells display intermediate behavior but suggest that CO_2-driven saturation changes may help to control calcite scaling while promoting limited silica destabilization. The results obtained in the modeling were evaluated in Figure 1. Figure 1 presents a stacked column diagram that combines initial pH, final pH, initial calcite saturation index (SI), final SI and the calculated annual calcite scaling (ton/year) for all modeled wells in Kızıldere (R1, KD-13), Germencik (OB14, OB17) and Alaşehir (Alkan-1, Alkan-2). The height and internal partitioning of each column illustrate how CO_2 dissolution modifies both acidity and mineral saturation in a field-dependent manner.

R1_Kızıldere and KD-13_Kızıldere show the highest absolute pH values and the largest pH drop after CO_2 injection, reflecting their strong carbonate buffering and high dissolved CO_2 content. In R1 the stack also includes the largest positive contribution from annual calcite scaling (4.34 ton/year), consistent with its near-equilibrium final SI and the strong tendency for carbonate precipitation. KD-13, in contrast, shifts to slightly negative SI and therefore exhibits negligible net scaling.

In Germencik, OB14 and especially OB17 display intermediate behaviour. OB17 retains a clearly positive final SI and accumulates approximately 1.39 ton/year of calcite, indicating a moderate but operationally relevant scaling risk. OB14 shows much smaller scaling (0.136 ton/year), close to the transition between precipitation and dissolution regimes. The Alaşehir wells form a distinct group: both Alkan1 and Alkan2 exhibit negative initial and even more negative final SI values, with no calcite scaling term in the stacked columns. This confirms that Alaşehir behaves as a dissolution-dominated system under CO_2-enriched reinjection and represents the most favourable candidate for large-scale CO_2 storage and reinjection among the studied fields.

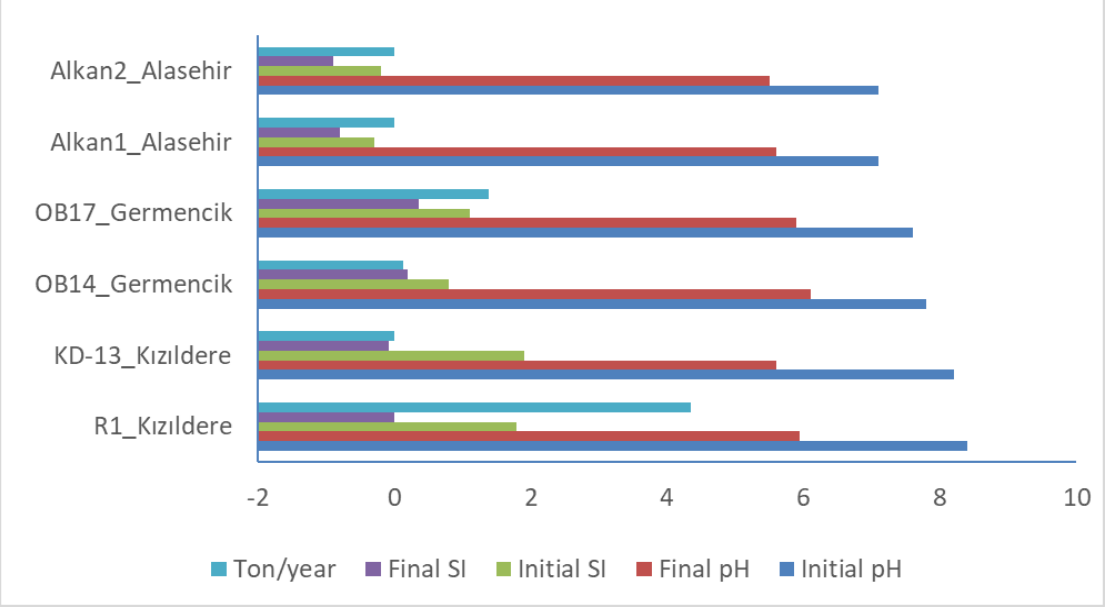


Figure 1. Stacked column diagram of wells.

In this study, the variation of the calcite saturation index (SI_calcite) with pH and CO_2 partial pressure was investigated in six thermal wells (KD-13, R-1, OB-14, OB-17, Alkan-1, and Alkan-2). First, an empirical calcite SI model function was calibrated for each well using chemical parameters derived from field analyses (Ca^{2+}, alkalinity, temperature, ionic strength, etc.). The model was run on a two-dimensional grid consisting of pH and log pCO_2, generating a 60x60 SI surface for each well. This resulted in three-dimensional CO_2–pH–SI surfaces and two-dimensional SI maps in the pH–log pCO_2 plane.

The 3D surfaces generated for wells R-1 and KD-13 demonstrate that the model accurately captures the expected geochemical trend: as pH increases (alkalinity remains constant), calcite SI generally increases, approaching saturation with respect to calcite. As CO_2 partial pressure increases (log pCO_2 increases), SI decreases, meaning the solution becomes more acidic and calcite is more prone to dissolution (Figure 2).

The SI surface is approximately linear in both wells, confirming that the regression model used is represented by predominantly first-order terms against pH and log pCO_2. The differences between the two wells arise from well-specific parameters such as Ca^{2+} concentration, alkalinity, and temperature. Because these parameters are higher in R-1 than in KD-13, SI values are generally less negative (closer to saturation) in R1 under the same pH and log pCO_2 conditions, while KD-13 exhibits more pronounced undersaturation. The SI contours along the pH axis exhibit approximately parallel slopes, indicating that increasing pH has a regular and significant increasing effect on SI. Along the log pCO_2 axis, the contours slope downward; as CO_2 pressure increases, SI decreases. The color distribution on the map is generally concentrated in the negative SI range, indicating that the KD-13 well has a high dissolution potential for calcite within the study range (Figure 2).

Belong to OB14 well of the Germencik geothermal field, high silica and high boron concentrations affect carbonate balances. Therefore, a broad positive SI region is observed in the medium-high pH range. Because OB17 contains slightly less calcium than OS14, the positive SI region remains within a narrower range. Increasing CO_2 also induces a significant dissolution tendency here (Figure 2).

Alkan-1 well within the Alaşehir geothermal field, the calcite SI value approaches the positive region as pH increases, while a systematic decrease in SI values occurs with increasing CO_2. Under high CO_2 conditions, dissolution tends to dominate, while high pH conditions increase the potential for precipitation. The Alkan-2 well exhibits a geochemical behavior similar to Alkan-1, with the SI approaching positive values as pH increases. Increasing CO_2 increases calcite solubility, pushing SI values toward the negative region (Figure 2). The above results are summarized in Table 2.

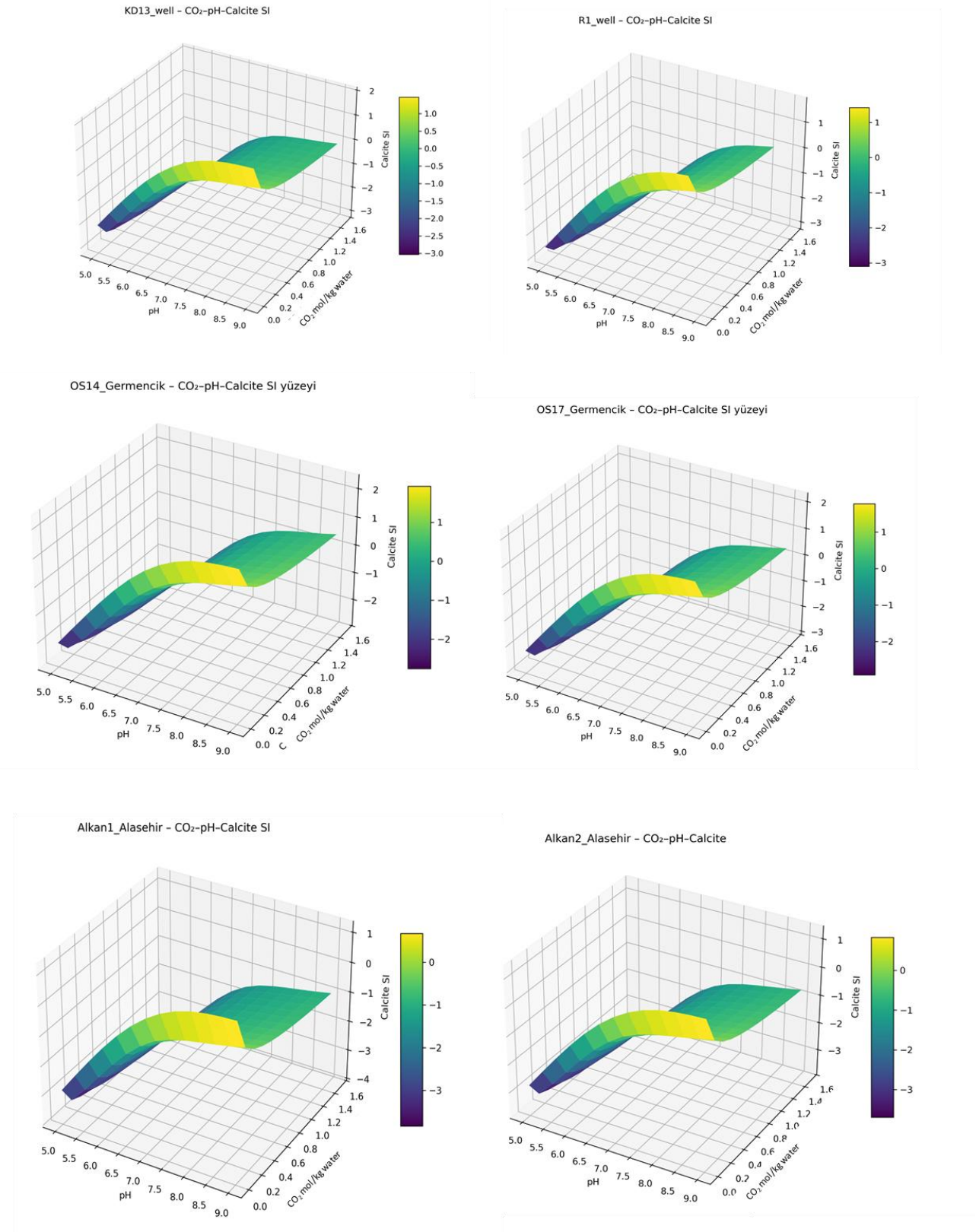


Figure 2. 3D surface graphics and pH–CO_2–SI relationship of the wells.

Table 2. Summarized CO_2 Storage of Geothermal Fields.

Field	Dominant Lithology	pH Response	Calcite SI Change	CO_2 Storage	Injectivity Impact
Kızıldere	Carbonate-rich	Strong decrease	SI → 0 / negative; KD-13 shows stronger undersaturation	High in R-1; limited in KD-13	Strong improvement, especially in R-1
Germencik	Mixed schist–gneiss–carbonate	Moderate decrease	OB14: broad positive SI; OB17: narrower positive SI	Moderate; silica–boron have buffering effect	Stable / slightly improved
Alaşehir	Silica-rich	Moderate decrease	Strongly negative SI under high CO2; positive tendency at high pH	None or very low	Improved; CO2 increases dissolution and enhances flow

CONCLUSION

The results highlight the dual role of CO_2 in geothermal reinjection: (1) reducing carbonate scaling through acidification, thereby protecting injectivity, and (2) potentially enhancing mineral dissolution, which may widen fracture apertures but also increases the mobility of certain elements.

When integrated with field-scale CO_2 emission rates, the modeling outputs demonstrate that CO_2-enriched reinjection can serve not only as a mitigation strategy for surface emissions but also as a subsurface operational tool for optimizing reservoir sustainability.

When the results are evaluated for the Kızıldere geothermal field, the Calcite SI value in well R1 decreases sharply from +1.79 to 0.00, indicating complete suppression of carbonate scaling. It was concluded that the calcite SI concentration in well R1 increased significantly as pH increased, while the SI decreased as CO2 loading increased. The transition band around SI≈0 in the central part of the surface represents the precipitation/dissolution equilibrium of calcite.

In well KD-13, the Calcite SI value decreases from +1.91 to -0.08, indicating mild dissolution potential. These changes indicate that CO_2-rich reinjection water can effectively maintain or restore injectivity in long-term operation by preventing calcite accumulation in fractures.

The Germencik, OB-14, and OB-17 wells exhibit moderate pH declines (ΔpH ≈ -1.7) associated with their mixed lithological composition of gneiss, schist, and localized carbonate lenses. Silica SI values remain near equilibrium throughout the process. This suggests a balanced geochemical behavior where CO_2 prevents calcite precipitation without causing excessive silicate dissolution. The dissolution process and fracture geometry are expected to have minimal impact on controlled CO_2 reinjection into the field.

The Alaşehir reservoir, located primarily in metamorphic schist and quartzite, responds differently to CO_2 addition compared to carbonate-rich systems. Both Alkan-1 and Alkan-2 wells show similar trends, with the pH decreasing from ~7.1 to ~5.5-5.6. The initial silica SI is slightly negative (-0.3 to -0.2) and becomes more negative (-0.8 to -0.9). Thus, Alasehir is the most dissolution-dominated system of the selected sites. CO_2-enriched reinjection may increase injectability but does not significantly contribute to long-term CO_2 storage.

In conclusion, R1 and KD-13 are wells with high $CaHCO_3$ contents and a strong carbonate buffer against CO_2. The SI is close to zero or positive over a wide pH range. The potential for calcite precipitation and associated mineral CO_2 sequestration with CO_2 injection is high. Similar to R1/KD-13, wells OB14 and OB17 (Germencik) are also saturated with calcite, and the SI > 0 area is particularly large in OB14. These wells can be evaluated for both existing carbonate mineralization and additional CO_2 injection.

In Alaşehir/Alkan1 and Alkan2 wells, the SI surfaces are generally more negative; calcite saturation conditions prevail over a wide pH/CO_2 range. Therefore, dissolution rather than precipitation is dominant, and the mineral-based CO_2 sequestration capacity is more limited compared to the Kızıldere and Germencik wells. In this regard, the Kızıldere/R1 and KD-13 wells and the Germencik/OB14 and OB17 wells are most suitable for CO_2 mineralization via calcite. The Alkan1 and Alkan2 wells in the Alaşehir field are more dissolution-controlled, with a narrow mineralization window. Therefore, structural hydrodynamic traps become more critical when designing CO_2 storage strategies in such fields.

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