ghg GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Assessing the potential for CO_2 storage in saline aquifers in Brazil: Challenges and Opportunities

Nathália Weber, Research Centre for Greenhouse Gas Innovation (RCGI), University of São Paulo, São Paulo, Brazil, Polytechnic School, University of São Paulo, São Paulo, Brazil, and CCS Brasil, São Paulo, Brazil
Saulo B. de Oliveira, Research Centre for Greenhouse Gas Innovation (RCGI), University of São Paulo, São Paulo, Brazil, Institute of Energy and Environment, University of São Paulo, São Paulo, Brazil, and Institute of Geosciences, University of São Paulo, São Paulo, Brazil
Allan Cavallari, Polytechnic School, University of São Paulo, São Paulo, Brazil
Isabela Morbach, CCS Brasil, São Paulo, Brazil
Colombo C. G. Tassinari, Research Centre for Greenhouse Gas Innovation (RCGI), University of São Paulo, São Paulo, Brazil and Institute of Energy and Environment, University of São Paulo, São Paulo, Brazil
Julio Meneghini, Research Centre for Greenhouse Gas Innovation (RCGI), University of São Paulo, São Paulo, Brazil and Polytechnic School, University of São Paulo, São Paulo, Brazil

Abstract: This study underscores the critical role of carbon capture and storage (CCS) in mitigating greenhouse gas emissions and addresses the potential for CCS projects in saline aquifers in Brazil, one of the world's largest carbon emitters. The country's ability to adopt CCS is significantly influenced by the availability of data related to regional CO_2 storage potential and identifying suitable geological framework for CO_2 injection. While oil and gas reservoirs have traditionally been prioritized, saline aquifers represent an underexplored and potentially higher capacity storage option. Despite Brazil's 31 sedimentary basins, the data quantity and availability for these contexts remain insufficient for advanced studies on the geological storage of CO_2 considering saline aquifers. An initial study was conducted indicating five potential targets in the Paraná and Potiguar Basins for geological storage in saline aquifers based on available public data, mainly drilling data. This review reveals substantial challenges related to the evaluation of Brazil's CO_2 storage capacity, such as the lack of modern seismic studies, the absence of a regulatory framework for CO_2 storage, and insufficient investment in new well exploration. These challenges necessitate multistakeholder collaboration, the development of a supportive regulatory environment, and investment in extensive site characterization campaigns.

Correspondence to: Nathália Weber, Research Centre for Greenhouse Gas Innovation (RCGI), Universidade de São Paulo, São Paulo, 05508-010, Brazil.
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Addressing these barriers is fundamental to realizing the country's CCS potential and contributing to global decarbonization efforts. © 2024 Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: CCS; saline aquifer; CO_2 geological storage; site screening

Introduction and context

Carbon capture and storage (CCS) projects play a pivotal role in reducing carbon emissions, with their feasibility strongly influenced by the maturity of institutional environments, comprised of legislation, public financing policies, and macroeconomic variables. The viability of CCS projects also relies on the understanding, by the agents within the organizational environment, of these technologies' potential applications and the necessary infrastructure for the rapid implementation of projects.

A key factor is the evaluation of regional CO_2 storage potential, crucial in understanding CCS's role in emissions reductions in specific regions and countries. As one of the major greenhouse gas contributors, Brazil emitted over 2.3 billion tonnes of CO_2 equivalent in 2022, with approximately 21% from the energy and industrial sectors, thus showing potential for implementing carbon capture processes.[1]

As CCS is a chain of technological processes, understanding its potential must cover how much CO_2 can be captured considering the main applications, as well as how much CO_2 can be injected for permanent storage. In addition, the distances between sources and sinks are important factors to be analyzed case by case to determine costs and geographical and legal challenges for transportation networks.

For current CO_2 emissions from operating stationary sources, industrial processes, bioenergy production, and power plants, CCS could be applied to reduce around 190 million tonnes of CO_2 per year.[2] Although this number may vary significantly according to technological assumptions and changes in production from the considered sectors and even the introduction of new technologies (such as blue hydrogen), it is relatively simple to identify the order of magnitude of the capture potential. However, the Brazilian storage potential estimates remain unclear, with only a few studies focused on specific areas[3–5] or reservoir type.[6]

Identifying suitable geological contexts for CO_2 storage necessitates a set of properties: sufficient depth, sealing integrity, adequate storage capacity, and effective petrophysical reservoir properties. This leads to simplified thresholds for assessment such as (i) sufficient depth to ensure the CO_2 supercritical phase; (ii) sealing integrity to contain the CO_2 within the safety limits, to avoid undesirable migrations; (iii) sufficient storage capacity; (iv) effective petrophysical reservoir properties to ensure that CO_2 injection can be economically feasible and that sufficient CO_2 can be retained.[7–10] In practical terms, these properties lead to the following simplified thresholds: (i) 800 m of depth; (ii) the presence of a layer with a low permeability above the reservoir; (iii and iv) adequate combination of porosity, permeability and thickness. However, evaluating CO_2 storage potential on a regional scale proves challenging, with a tendency towards focusing on depleted oil and gas reservoirs. Furthermore, saline aquifers, though presenting greater storage capacity, are often underestimated in these assessments.

This review provides an overview indicating the main sources of publicly available data in Brazil for CCS research, in order to encourage new projects in the country, and also discusses through an initial study in onshore basins the potential for geological storage of CO_2 in saline aquifers, indicating possible initial targets for exploration.

Institutional environment for CO_2 storage in Brazil

Brazil currently stands at an embryonic stage when it comes to a formalized regulatory framework for permanent geological storage of CO_2. As of now, there are no formal rules that regulate the injection of CO_2 for permanent storage purposes. The existing injection operations are framed within advanced oil recovery (EOR) processes, exemplified by a project led by Petrobras in the Santos Basin.[11] Despite this regulatory void, there are nascent endeavors within the Brazilian Congress aimed at establishing a legal framework for CCS. Specifically, bill 1.425/2022 is under consideration, which seeks to regulate CO_2 injection as an economic activity.[12] Additionally, bill 4.516/2023, known as the "Combustível do Futuro" bill, also addresses the carbon storage theme.[13]

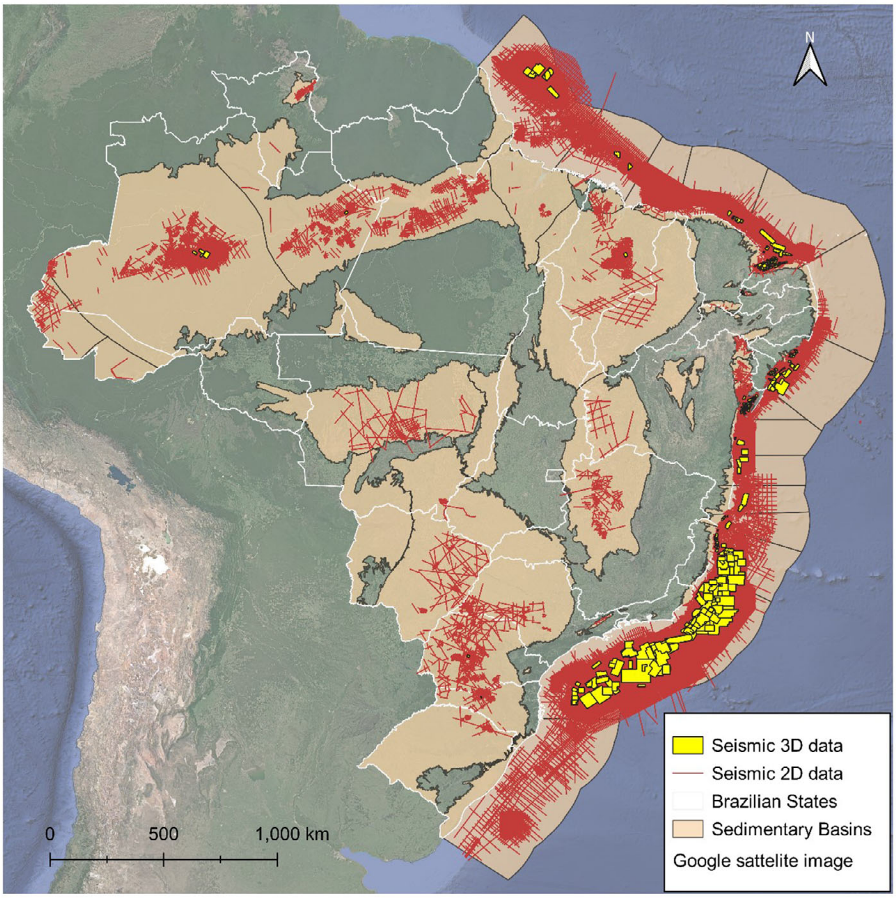

Figure 1. Seismic data publicly available in Brazil.[18]

On a more technical front, the Empresa de Pesquisa Energética (EPE) has unveiled a term of reference (TOR) that carries the potential to spearhead the identification of regional potentials for geological CO_2 storage.[14] This term is designed primarily to engage specialized technical consultancy in Underground Storage of Natural Gas (USNG), equipping EPE with a holistic view of the underground potential. While it majorly focuses on the USNG, it also tangentially touches upon CCS.

Nevertheless, it is crucial to highlight that, as of the current landscape, no explicit policy initiatives or efforts targeting fresh subsurface data surveys have been identified. Such data is vital for a broader estimate of the CO_2 storage capacity within the country.

Geological context and data availability

Brazil has 31 sedimentary basins, 13 onshore and 18 offshore,[15,16] which provide an important indication of significant potential for CO_2 storage capacity. However, most of the subsurface knowledge is linked to the exploration and production of hydrocarbons with 14 sedimentary basins currently producing oil and gas, reaching 3.021 Mbbl/day and 138 Mm^3/day in 2022, the 8th largest production in the world.[17] Expressive activity of the petroleum industry occurs mainly in two offshore basins: Santos and Campos, where the majority of geological and geophysical data essential for CCS research are concentrated.

In Brazil, assessing the CO_2 storage potential can be challenging due to the limited availability of some data. There is a significant difference in data between onshore and offshore basins, with a major concentration of information available for offshore basins (Figs. 1 and 2, Table 1) due historical development of Brazil's oil and gas market. Onshore fields were developed earlier in the 1980s/1990s, so data from that period had a different acquisition workflow, which did not include digital systems, in most cases,

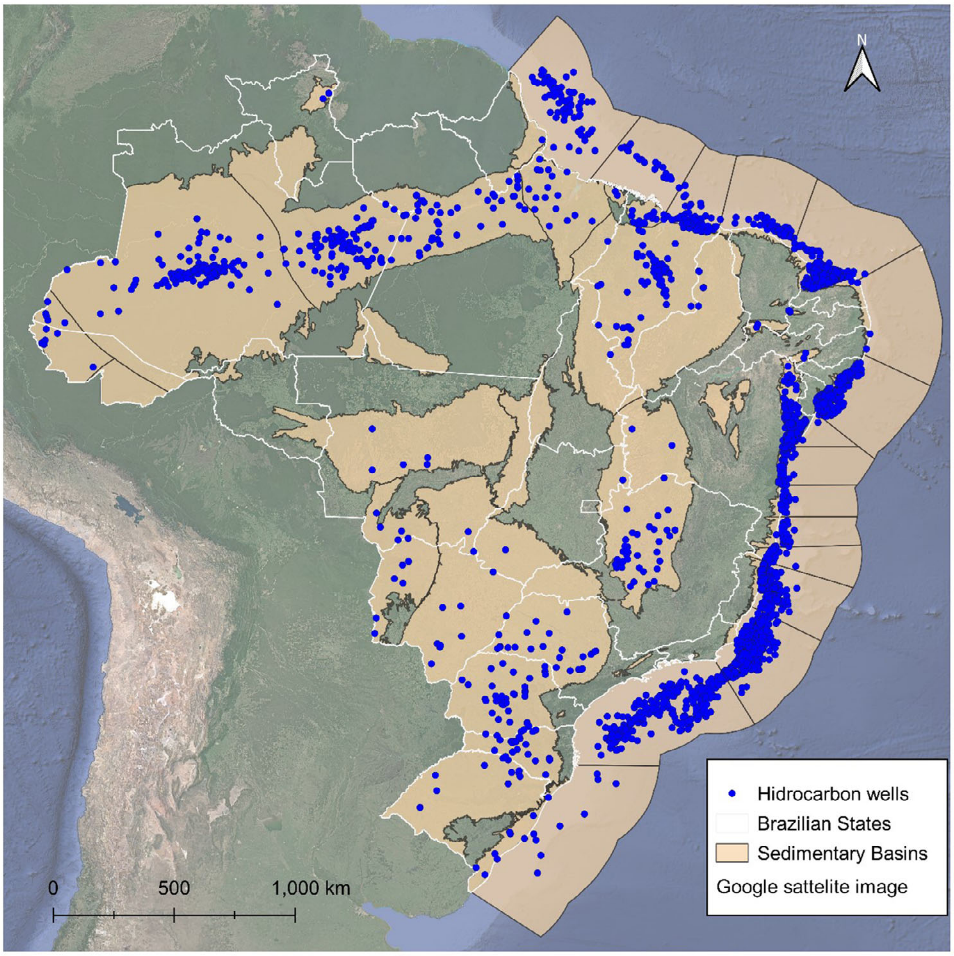

Figure 2. Hydrocarbon wells data publicly available in Brazil.[18]

Table 1. Number of hydrocarbon exploration wells and seismic data for selected basins.

Basin	Basin type	Area (km^2)	Seismic covered area (km^2)	Seismic covered area (%)	Wells	Wells per Km^2
Campos	Offshore	174,199	131,492	75%	3,557	0.02
Santos	Offshore	304,665	238,856	78%	873	0.01
Potiguar	Onshore	222,123	77,236	35%	9,441	0.04
Parecis	Onshore	352,077	141,408	40%	5	<0.01
Recôncavo	Onshore	9,089	6,707	74%	6,767	0.74
Paraná	Onshore	1,119,987	415,817	37%	124	<0.01

and all information was recorded handwritten or with the assistance of a typewriter, as shown in Fig. 3. For comparison purposes, data on hydrocarbon-producing offshore basins even allowed the assessment of CO_2 storage capacity in 84 Brazilian offshore oil and gas fields.[6] Table 1 presents information regarding the data availability for selected basins.

An important initiative of the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP) in partnership with the Brazilian Geological Department (SGB, former CPRM) made historical well data and geophysical and geochemical surveys of onshore basins publicly available through the REATE platform (https://reate.cprm.gov.br/anp/TERRESTRE).

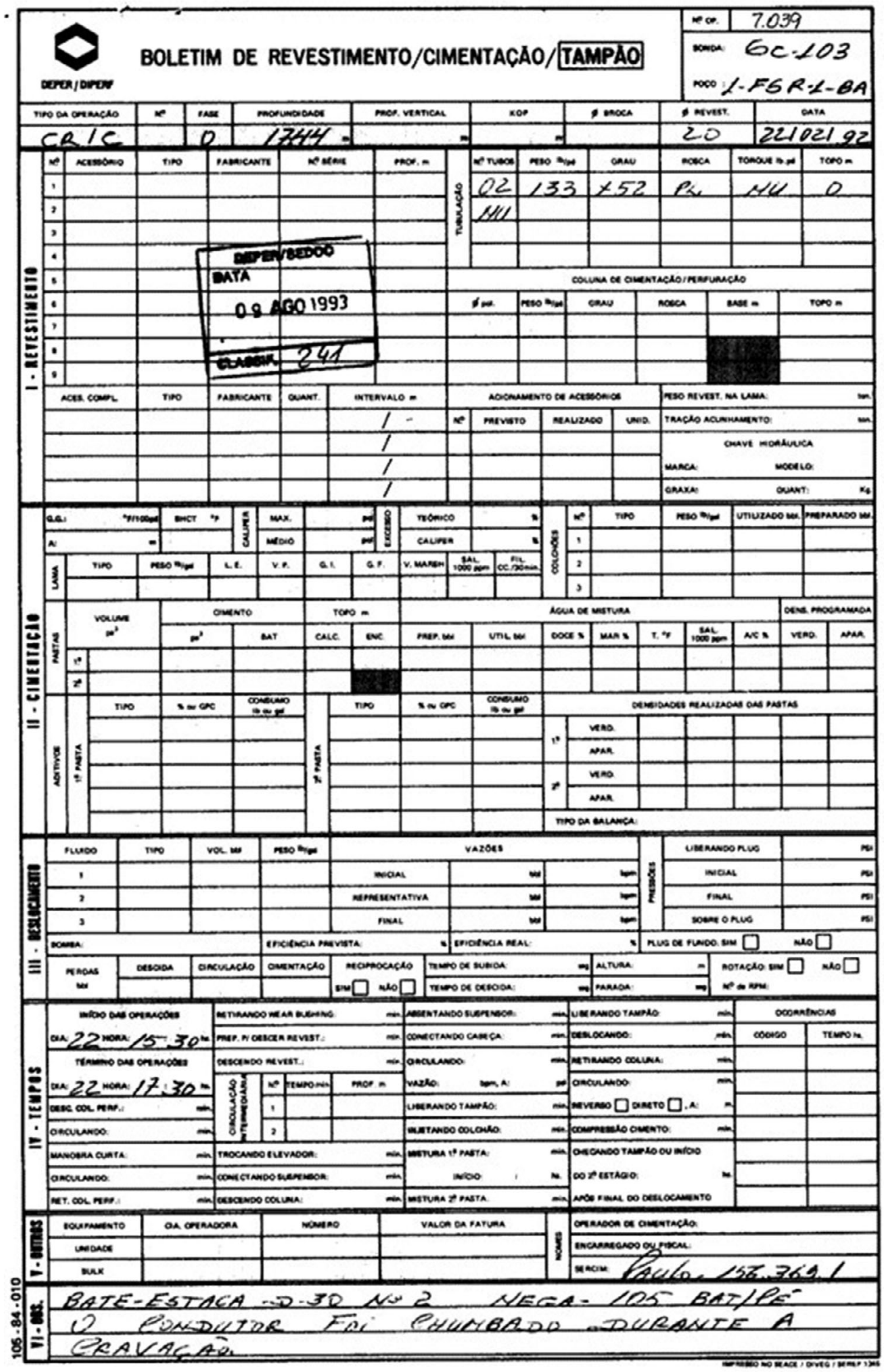
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Figure 3. Example of a well log document from 90's.

Publicly available data from wells and seismic studies presents reports dated from exploration campaigns, most of them from decades ago, developed with the technology available at that time. The information available relies on the objective of exploring the wells for hydrocarbon production, so the main characteristics acquired were for proving if a well zone was able to produce, petroleum, not if it's a saline

Figure 4. Groundwater wells data publicly available in Brazil,[19] with wells with total depth greater than 800 m highlighted.

aquifer. This is evident by none of the well documents providing information on any characteristics from water found, such as TDS (total dissolved solids), for example.

Another important Brazilian geological underground database is the SIAGAS system, an SGB (former CPRM) online platform,[19] which provides subsurface data from wells drilled for groundwater purposes, with a total of more than 367,000 wells (Fig. 4). However, the vast majority of these wells are shallow (Fig. 4).

Criteria for potential saline aquifers

Although the IEA-GHG[20] recommends the use of parameters such as TDS (total dissolved solids) and EC (electrical conductivity) to identify potential saline aquifers for CO_2 storage, they are not definitive regarding the cutoff as such values vary according to local regulations. For example, in the United States, the Environmental Protection Agency (EPA)[21] defines a saline aquifer as one with a conductivity greater than 3,000 microsiemens per centimeter (µS/cm) at 25°C. The Organization for Economic Co-operation and Development (OECD) defines a saline aquifer as one with a conductivity greater than 4,000 µS/cm at 25°C. In Europe, the directive on the geological storage of carbon dioxide defines a saline aquifer as one that contains more than 10,000 milligrams of chloride per liter (mg/L).[22] The US Department of Energy (DOE) considers an aquifer to be saline for CCS if it contains more than 10,000 mg/L of TDS following EPA regulations.[23] The International Energy Agency (IEA) recommends that aquifers intended for the geological storage of CO_2 should have a salinity high enough to prevent the dissolution of CO_2, that is, generally more than 20,000 mg/L of TDS. The Brazilian Conselho

Table 2. Groundwater wells with total depth greater than 800m and conductivity greater than or equal to 3,000 μS/cm.

ID Siagas	Latitude	Longitude	State	Sedimentary Basin	Total Depth (m)	Conductivity (μS/cm)
2600000439	-5.204444	-37.357500	Rio Grande do Norte	Potiguar Basin	1,020.00	3,000
2600023495	-4.860555	-37.351944	Rio Grande do Norte	Potiguar Basin	851.00	4,650
2600024384	-4.995555	-37.219722	Rio Grande do Norte	Potiguar Basin	960.00	12,680
2600030324	-5.022500	-37.019722	Rio Grande do Norte	Potiguar Basin	1,733.00	36,200
3500016902	-24.555032	-54.043931	Paraná	Paraná Basin	810.00	5,100
3500040967	-25.565249	-54.557532	Paraná	Paraná Basin	845.00	3,820
4300016899	-27.675833	-52.238611	Rio Grande do Sul	Paraná Basin	902.00	5,342
4300028457	-27.860833	-54.495833	Rio Grande do Sul	Paraná Basin	1,220.00	4,620

Nacional do Meio Ambiente (CONAMA) establishes in its Resolution No. 20/1986 as a water potability standard the limit of 5,000 mg/L of TDS.

In short, the minimum value to consider an aquifer as saline for CCS can vary according to the definition adopted by the competent authorities in each region or country. Frequently beneficial use options require TDS concentrations ranging anywhere from 175 mg/L (irrigation with no limitations) to as high as 13,000 mg/L (livestock drinking water). There are also water use options where higher salinity is not a primary concern or even an asset, including recovery of geothermal heat, salts, and/or minerals.[24] The main idea is that the water in the aquifer has no future use, and it is important to emphasize that the choice of the aquifer for CO_2 injection must be based on a careful assessment of its hydrogeological parameters, mainly onshore, in order to guarantee environmental safety and the effectiveness of the storage process.

In the present research, a cutoff of conductivity greater than 3,000 μS/cm at 25°C was applied for each groundwater well, after a data filter through wells that reached more than 800 m depth (Fig. 4). From the more than 367,000 wells from Siagas, 156 wells are more than 800 m in total depth. Among these, 114 wells have electric conductivity data. Finally, only eight wells have more than 3,000 μS/cm of conductivity indicating suitability as saline aquifers (Table 2).

The results indicate five macro prospective locations, with four inside the Paraná Basin and one in the Potiguar Basin. Although there are four wells in the Potiguar Basin, they are very close spatially, and for the purpose of this country-scale evaluation, they are considered as a single target.

Discussion

The Paraná Basin is one of the Brazilian onshore basins with the greatest potential for geological storage of CO_2 in saline aquifers due to its favourable geographical location,[25] with a well-developed transport network and infrastructure and one of the largest concentrations of stationary sources emitting CO_2.[26,27] Therefore, several CCS studies have already been developed in the Paraná Basin focusing on different types of geological reservoirs. Studies considering geological storage of CO_2 in the Paraná Basin focusing on the black shales of the Irati Formation were conducted by Weber,[28] Abraham-A and Tassinari,[29,30] de Oliveira et al.,[3,31] Rocha[32]. The Rio Bonito Formation composed of sandstones and shales[33] has most recently focused on CCS studies. Assessments in sandstone reservoirs,[26,34,35] and hydrocarbon reservoirs of the Rio Bonito Formation were developed.[35] The coal seams of the Rio Bonito Formation were also, specifically, the subject of studies for CO_2 storage.[4,5,36] Research on saline aquifers was only addressed in the works of Ketzer et al.,[37] and Lima et al.[38]

The four targets with potential for CO_2 storage in this initial study are distributed in the west of the Paraná State and in the north of the Rio Grande do Sul State (Fig. 4). These locations have not yet been studied for CCS and the available data do not allow the calculation of theoretical storage capacities. The stationary CO_2-emitting sources around the Paraná Basin are concentrated on the eastern border of the basin.[25–27]

The Potiguar Basin is located on the easternmost section of the Brazilian equatorial margin and extends from onshore to offshore.[39] Both the Potiguar Basin

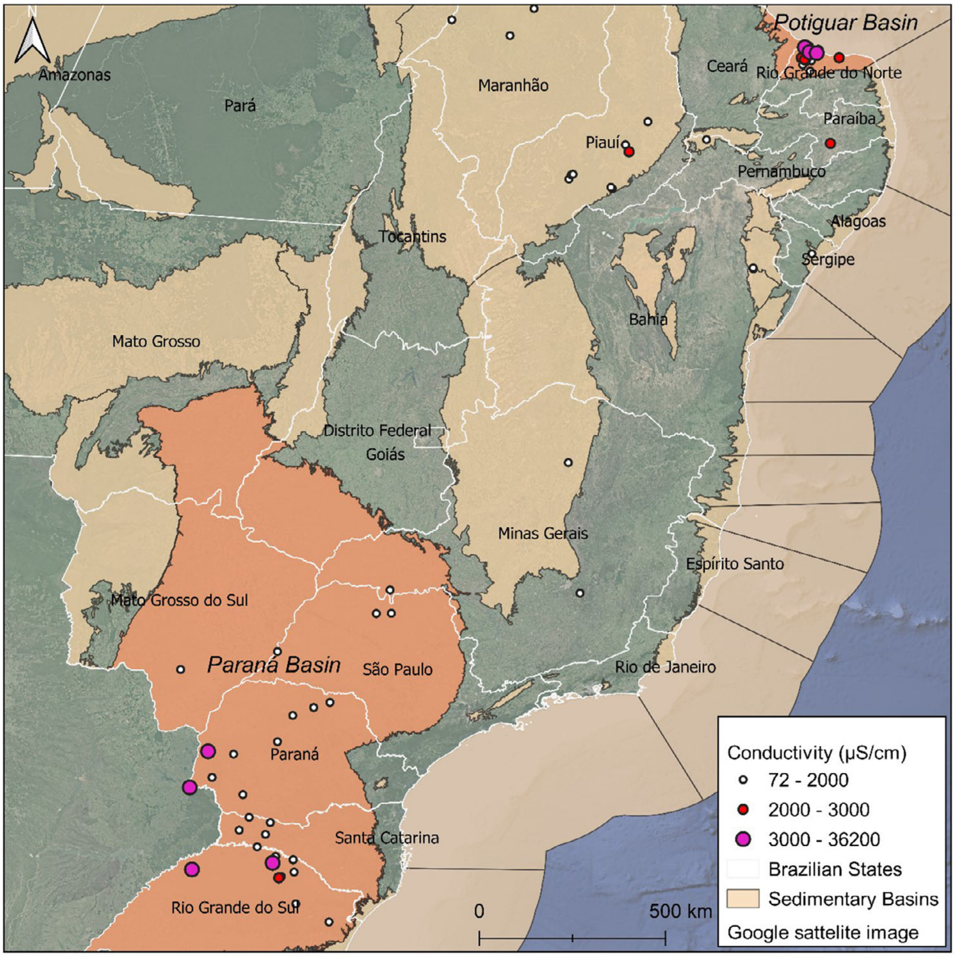

Figure 5. Filtered groundwater wells with depths greater than 800 m indicating potential for geological storage of CO_2 in saline aquifers in Paraná and Potiguar basins, Brazil.

and the Paraná Basin were classified as highly prospective for storage by Ketzer et al.,[25] in an assessment of all Brazilian sedimentary basins taking into account criteria such as emission sources, hydrocarbon production, occurrence of coal, saline formations, and infrastructure. Both basins' potential for CCS was also assessed through CO_2 capture from biomass sources with a focus on bioethanol production facilities.[40] The Potiguar Basin has fewer studies focused on CCS than the Paraná Basin. Ciotta et al.,[6] calculated its offshore storage capacity, considering current oil and gas reservoirs, and Wechi Benedet et al.,[41] presented a CCS study with a combined-cycle natural gas-fired thermopower plant considering the Potiguar Basin's potential for CO_2 storage.

The groundwater wells with an indication of saline aquifers in the Potiguar Basin are concentrated in the north of Rio Grande do Norte State, a region with a relatively low concentration of stationary sources of CO_2, as presented in Fig. 5.[25,27] Even if the targets indicated in this work do not coincide geographically with the emission sources, they are still interesting because in general, saline aquifers have large storage capacities and these locations should be targets for regional studies of transport modes for CCS.

Following the classification of phases of CO_2 storage projects proposed by Goodman et al.,[23] the evaluation presented here would correspond to the site screening phase, where selected areas are presented, based on regional and local geological data.

In general, at this stage, geological data are insufficient to allow a calculation of theoretical storage capacity, as is the case for the areas highlighted here. For example, to delimit a potential reservoir for CO_2, or more precisely the volume of one, information such as local faults and geological discontinuities, among others, is necessary, which is data that goes beyond the scope and scale of work of this research.

The next phase, called site selection,[23] would involve the more detailed analysis of the most promising selected areas, such as the ones presented here, to ensure that only those that meet critical technical and economic criteria advance to further evaluation. At the site selection phase, geological information such as effective thickness, porosity, permeability, stratigraphic or structural traps, and sealing conditions are obtained and allow an assessment by listing qualified sites and then presenting a calculation of theoretical storage capacity.

The data from the databases consulted in this work do not present these parameters or they are presented insufficiently, as the majority of them are wells drilled for groundwater purposes. Therefore, future geological studies are recommended in all the selected areas, both in the Potiguar Basin and in the Paraná Basin, with better detail of these targets, concerning sealing rock, porosity, permeability, and storage capacity.

It is important to note that this work does not end the search for potential saline aquifers in Brazil. It just started the studies, limited by the existing available data. Other basins and even other regions within the studied basins still have great potential to have reservoirs for storing CO_2 in saline aquifers.

Challenges and conclusion

This work aimed to identify possible sites for assessing CO_2 storage potential for saline aquifers in Brazil, conducting a survey to understand the availability and quality of the subsurface data, and the main gaps to be addressed.

It was found that, even with the low density of geological data available for a CO_2 geological storage study, it was possible to identify four locations (targets) with potential in the Paraná Basin and one location in the Potiguar Basin. Nevertheless, substantial investments are needed in basic geological research with the acquisition of new geophysical surveys and new exploration wells that allow progress in the studies of these CO_2 reservoir targets or the generation of new ones.

The assessment of Brazil's CO_2 storage capacity in saline aquifers faces a myriad of challenges, including high costs for seismic studies, a lack of formal policy on CO_2 emissions reduction, and an absence of a regulatory framework for CO_2 storage. Overcoming these hurdles requires collaboration and coordination among various stakeholders and the implementation of CO_2 storage regulations and pricing mechanisms. By tackling these issues, Brazil could play a crucial role in reducing its CO_2 emissions and contribute significantly to global decarbonization efforts.

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References

1. SEEG. Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa: Observatório do Clima [Greenhouse gas emissions and removals estimation system: climate observatory]. http://seeg.eco.br/. (2023).
2. CCS-Brasil. 1° Relatório Anual de CCS Brasil [1st CCS Brazil annual report]. São Paulo, Brazil: CCS Brasil; 2023.
3. de Oliveira SB, Tassinari CCG, Abraham-A RM, Torresi I. 3D implicit modeling applied to the evaluation of CO_2 geological storage in the shales of the Irati Formation, Paraná Basin, Southeastern Brazil. Greenhouse Gases: Sci Technol. 2021;11:1024–42.
4. Pelissari MR, Cañas SSM, Barbosa MO, Tassinari CCG. Decarbonizing coal-fired power plants: carbon capture and storage applied to a thermoelectric complex in Brazil. Results Eng. 2023;19:101249.
5. Kalkreuth W, Holz M, Levandowski J, Kern M, Casagrande J, Weniger P, et al. The coalbed methane (CBM) potential and CO_2 storage capacity of the Santa Terezinha Coalfield, Paraná Basin, Brazil –3d modelling, and coal and carbonaceous shale characteristics and related desorption and adsorption capacities in samples from exploration borehole CBM001-ST-RS. Energy Explor Exploit. 2013;31:485–527.
6. Ciotta M, Peyerl D, Zacharias LGL, Fontenelle AL, Tassinari C, Moretto EM. CO_2 storage potential of offshore oil and gas fields in Brazil. Int J Greenhouse Gas Control. 2021;112:103492.
7. Bachu S. Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change. Energy Convers Manage. 2000;41:953–70.
8. Chadwick RA, Arts R, Bernstone C, May F, Thibeau S, Zweigel P. Best practice for the storage of CO_2 in saline aquifers. Keyworth, Nottingham: British Geological Survey; 2008.
9. IEA-GHG. IEA greenhouse gas R&D programme: CCS Site characterisation criteria. Cheltenham, UK: IEA-GHG; 2009.

10. Smith M, Campbell D, Mackay E, Polson D. CO_2 aquifer storage site evaluation and monitoring: Understanding the challenges of CO_2 storage: results of the CASSEM project. Edinburgh, UK: Scottish Carbon Capture and Storage (SCCS); 2011.
11. Godoi JMA, Matai PHLdS. Enhanced oil recovery with carbon dioxide geosequestration: first steps at Pre-salt in Brazil. J Pet Explor Prod. 2021;11:1429–41.
12. Brasil. PL 1425/2022 Brasilia: Brasil. https://www25.senado.leg.br/web/atividade/materias/-/materia/153342 (2022).
13. Brasil. PL 4516/2023 Brasilia: Brasil. https://www.camara.leg.br/propostas-legislativas/2388242 (2023).
14. Empresa de Pesquisa Energética. Evaluation of underground storage of natural gas (UNGS) in Brazil. Rio de Janeiro, Brazil: Empresa de Pesquisa Energética; 2023.
15. Milani EJ, Rangel HD, Bueno GV, Stica JM, Winter WR, Caixeta JM, et al. Bacias sedimentares brasileiras: cartas estratigráficas [Brazilian sedimentary basins: stratigraphic maps]. Boletim de Geociencias da PETROBRAS. 2007;15:183–205.
16. Milani EJ, Thomaz Filho A. Sedimentary basins of South America. In: Cordani UG, Milani EJ, Thomaz Filho A, Campos DA, editors. Tectonic evolution of South America. 31. Rio de Janeiro, Brazil: In-Fólio Produção Editorial; 2000. p. 389–449.
17. ANP. Agência Nacional do Petróleo Gás Natural e Biocombustíveis. Encarte de consolidação da produção 2022. Boletim da produção de petróleo e gás natural. Agência Nacional do Petróleo Gás Natural e Biocombustíveis [National Agency for Petroleum, Natural Gas and Biofuels. Production consolidation booklet 2022. Oil and natural gas production bulletin. National Agency for Petroleum, Natural Gas and Biofuels]; 2022.
18. ANP. Agência Nacional do Petróleo Gás Natural e Biocombustíveis. GeoANP – mapa de dados georreferenciados [National Agency for Petroleum, Natural Gas and Biofuels. GeoANP – georeferenced data map]; http://geo.anp.gov.br/mapview (2023).
19. SGB. Siagas – Sistema de Informações de águas subterrâneas: SGB - Serviço Geológico do Brasil (former CPRM) [Siagas – Sistema de Informações de águas subterrâneas: SGB - Serviço Geológico do Brasil (former CPRM)]; https://siagasweb.sgb.gov.br/layout/ (2023).
20. IEA-GHG. Development of storage coefficients for CO_2 storage in deep saline formations. Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme; 2009.
21. EPA. Safe Drinking Water Act (SDWA). Washington DC: United States Environmental Protection Agency; 2010.
22. Li Y and Pang Z. Hydrogeochemical characteristics of deep saline aquifers in sedimentary basins in China and implications for CO_2 geological storage with emphasis on total dissolved solids (TDS) and water type. Greenhouse Gases: Sci Technol. 2017;7:53–64.
23. Goodman A, Hakala A, Bromhal G, Deel D, Rodosta T, Frailey S, et al. U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. Int J Greenhouse Gas Control. 2011;5:952–65.
24. Klapperich RJ, Liu G, Stepan DJ, Jensen MD, orecki CD, Steadman EN, et al. IEAGHG investigation of extracted water from CO_2 storage: potential benefits of water extraction and lesson learned. Energy Procedia. 2014;63:7173–86.
25. Ketzer JMM, Machado CX, Rockett GC, Iglesias RS. Atlas brasileiro de captura e armazenamento geológico de CO_2. Porto Alegre, Brazil: EDIPUCRS; 2016. p. 95.
26. de Oliveira SB, Weber N, Yeates C, Tassinari C. Geological screening for onshore CO_2 storage in the Rio Bonito Formation, Paraná Basin, Brazil. J Maps. 2023;19:1–9.
27. Rockett GC, Machado CX, Ketzer JMM, Centeno CI. The CARBMAP project: matching CO_2 sources and geological sinks in Brazil using geographic information system. Energy Procedia. 2011;4:2764–71.
28. Weber N. Armazenamento geológico de carbono em reservatórios não convencionais na Formação Irati da Bacia do Paraná: estimativas de capacidade de injeção de CO_2 e custos associados São Paulo [Geological carbon storage in unconventional reservoirs in the Irati Formation of the Paraná Basin: estimates of CO2 injection capacity and associated costs São Paulo]. Sao Paulo, Brazil: University of São Paulo; 2020.
29. Abraham-A RM, Tassinari CCG. CO_2 storage algorithms involving the hybrid geological reservoir of the Irati Formation, Parana Basin. Int J Greenhouse Gas Control. 2021;112:103504.
30. Abraham-A RM, Tassinari CCG. Carbon dioxide storage efficiency involving the complex reservoir units associated with Irati and Rio Bonito Formations, Paraná Basin, Brazil. AAPG Bull. 2023;107:357–86.
31. de Oliveira SB, Rocha HV, Tassinari CCG. 3D geochemical characterization of organic-rich shales of the Irati Formation, Paraná Sedimentary Basin: new perspective for CO_2 geological storage in southeastern Brazil. Int J Greenhouse Gas Control. 2022;114:103563.
32. Rocha HV. Armazenamento geológico de CO2 em folhelhos enriquecidos em matéria orgânica da Formação Irati, Bacia do Paraná, Brasil [Geological storage of CO_2 in shales enriched in organic matter from the Irati Formation, Paraná Basin, Brazil]. [PhD thesis]. São Paulo, Brazil: University of São Paulo; 2021.
33. Holz M, França AB, Souza PA, Iannuzzi R, Rohn R. A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. J South Amer Earth Sci. 2010;29:381–99.
34. Abraham-A RM, San Martín Cañas S, Miranda IFS, Tassinari CCG. Assessment of CO_2 storage prospect based on physical properties of Rio Bonito Formation rock units. Energy Geosci. 2024;5:100163.
35. Abraham-A RM, Tassinari CCCG, Taioli F, Rocha HV, da Silva OC. Reservoir quality evaluation as a measure to forecast hydrocarbon and CO_2 storage prospects in Irati and Rio Bonito Formations, Paraná Basin. Results Geophys Sci. 2023;14:100059.
36. Weniger P, Kalkreuth W, Busch A, Krooss BM. High-pressure methane and carbon dioxide sorption on coal and shale samples from the Paraná Basin, Brazil. Int J Coal Geol. 2010;84:190–205.
37. Ketzer JM, Iglesias R, Einloft S, Dullius J, Ligabue R, de Lima V. Water–rock–CO_2 interactions in saline aquifers aimed for carbon dioxide storage: experimental and numerical modeling studies of the Rio Bonito Formation (Permian), southern Brazil. Appl Geochem. 2009;24:760–67.

38. Lima Vd, Einloft S, Ketzer JM, Jullien M, Bildstein O, Petronin J-C. CO_2 Geological storage in saline aquifers: Paraná Basin caprock and reservoir chemical reactivity. Energy Procedia. 2011;4:5377–84.
39. Melo AH, Magalhães AJC, Menegazzo MC, Fragoso DGC, Florencio CP, Lima-Filho FP. High-resolution sequence stratigraphy applied for the improvement of hydrocarbon production and reserves: a case study in Cretaceous fluvial deposits of the Potiguar basin, northeast Brazil. Mar Pet Geol. 2021;130:105124.
40. Quintella CM, Meira M, Miyazaki SF, da Costa Neto PR, de Souza GGB, et al. Brazilian potential for CCS for negative balance emission of CO_2 from biomass energy. Energy Procedia. 2011;4:2926–32.
41. Wechi Benedet G, Diederichs Prado KC, Draeger R, Angelkorte GB, Lins de Mello AC. GHG emissions offset of a combined-cycle natural gas-fired thermopower plant in Northeastern Brazil. Dyna. 2021;88:200–210.

Nathália Weber

Nathália Weber is a specialist in CO_2 storage, with a degree in Petroleum Engineering and a master's in energy, currently pursuing a PhD in mechanical engineering at the University of São Paulo. She works as director of CCS Brasil and Manacá CCS, researcher at the Research Centre for Greenhouse Gas Innovation, and board member of the Society for Low Carbon Technologies.

Saulo Oliveira

Saulo Oliveira is a geologist with a PhD from the University of São Paulo, and is currently a professor at the Instituto de Geociências - USP. His research is focused on 3D modeling applied to mineral deposits and geological storage of CO_2.

Allan Cavalari

Allan Cavalari is a petroleum engineering student at the University of São Paulo (USP), researching well integrity, reservoir management and GIS, applied to carbon capture and storage. He is a mechanical technician, with experience in Computer Numerical Control (CNC) and industrial operation, and worked as president of the Society of Petroleum Engineers' Student Chapter of USP for 2 years.

Isabela Morbach

Isabela Morbach is a specialist in economic law from Fundação Getúlio Vargas (FGV/SP). She holds an LLM in Financial Law and a PhD in energy, both from the University of São Paulo. She was a visiting scholar at the Center for Environmental Policy at Imperial College London in 2019. Currently, she is a lawyer and Director of CCS Brasil.

Colombo C. G. Tassinari

Colombo C. G. Tassinari is a Graduated in geology is full professor and former director of Institute of Energy and Environment (University of São Paulo) and coordinator of the "CO_2 Geological Storage Research Group". He belongs to the Brazilian Academy of Sciences. Has experience in the field of Geosciences on the CO_2 geological storage and isotopic geology in oil exploration.

Julio Meneghini

Julio Meneghini is a Full Professor at the Polytechnic School of the University of São Paulo, specialized in Computational and Experimental Fluid Dynamics, and Scientific Director of the Research Centre for Greenhouse Gas Innovation. He holds a PhD in Aerodynamics from the University of London and an Imperial College Diploma and is a Full Member of the Brazilian Academy of Sciences and the Academy of Sciences of São Paulo State.

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