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# Leading the way: Brazil's pioneering steps toward Direct Air Capture (DAC) deployment in South America

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**Abstract**

The DAC.SI project is a pioneering initiative in Brazil aimed at advancing Direct Air Capture (DAC) technologies for large-scale $CO_2$ removal and climate change mitigation. The present work describes the deployment and operationalization of three DAC units with varying technological readiness levels: the DAC Test Bench, operational since September 2023, focused on performance testing and adsorbent development at the laboratory scale; the DAC 15TA, operational since April 2024, the first fully functional system with a nominal $CO_2$ removal capacity of 15 tons per year; and the upcoming DAC 300TA experimental plant, scheduled for commissioning in November 2024, designed for experimental deployment with an estimated $CO_2$ removal capacity of 300 tons per year. The project involves extensive testing of adsorbents, evaluation of $CO_2$ capture performance, system integration studies, and an assessment of the potential for $CO_2$ mineralization in Brazilian basalts, all currently underway. Future steps of the project will focus on identifying suitable regions in Brazil for DAC deployment, including research into $CO_2$ reactivity with basalt for enhanced mineralization and geological storage. Additionally, key areas of focus will include the optimization of energy use, exploring waste heat recovery and infrastructure sharing to reduce operational costs and improve the decarbonization potential of the DAC systems. In conclusion, the DAC.SI project represents a critical first step toward advancing DAC technologies, demonstrating their scalability, and positioning Brazil at the forefront of global efforts to mitigate climate change. Through these efforts, the project contributes to the development of effective and cost-efficient Negative Emissions Technologies, paving the way for a sustainable, low-carbon future.

*Keywords:* Direct Air Capture; Carbon Dioxide Removal; Negative Emissions Technologies; Carbon Capture, Utilization and Storage; Brazil DAC Technology

## 1. Introduction

Achieving climate goals requires a comprehensive strategy that includes significant decarbonization efforts through Carbon Capture, Utilization, and Storage (CCUS) projects, alongside the global deployment of Negative Emissions Technologies (NETs) [1]. To meet global targets, an annual $CO_2$ removal capacity of 10 $GtCO_2$ is needed by 2050, factoring in the specific contributions of NETs to greenhouse gas (GHG) reductions [2,3]. Given that there is no universal solution, it is crucial to direct resources toward Research, Development, and Innovation (RD&I) while implementing a diverse range of NETs tailored to the Nationally Determined Contributions (NDCs) of each country, as outlined by the United Nations Framework Convention on Climate Change (UNFCCC).

Carbon Dioxide Removal (CDR) strategies are specifically designed to address both historical $CO_2$ production and Scope 3 emissions [4,5]. In this context, Direct Air Capture (DAC) is an innovative CDR technology that directly removes $CO_2$ from the atmosphere, providing an engineered solution to mitigate climate change [1,4]. When paired with geological carbon sequestration, this process is known as Direct Air Carbon Capture and Storage (DACCS). However, the initial demonstration of DAC technology, which began in 2010, has primarily been driven by a small group of startups [6,7]. As a result, DAC remains in the early stages of development and requires broader dissemination of technological knowledge, along with the sharing of data on technical performance, financial costs, and environmental impacts [8,9].

According to the International Energy Agency (IEA), there are currently 27 operational DAC plants worldwide, capturing nearly 0.01 Mt $CO_2$ per year, with plans for around 130 additional DAC facilities in various stages of development [7]. These plants, located in Europe, North America, Japan, and the Middle East, mostly operate at small-scale capacities [3,4,7]. At present, only a small number of proposed technologies have reached the pilot plant stage, achieving a Technology Readiness Level (TRL) of 6 or higher, and only a few have secured commercial agreements for the sale or storage of the captured $CO_2$ [9]. The majority of DAC process portfolios are at earlier stages of development, ranging from proof-of-concept and modeling (TRL 1-2) to laboratory-scale experiments (TRL 3-4) or small-scale lab pilots (TRL 5). Therefore, it is crucial to invest in de-risking DAC technology and reducing implementation costs, which will allow DAC to mature quickly and contribute meaningfully to the overall CDR portfolio [3].

### *1.1. Brazil's Opportunities in CDR*

Currently, CDR policy initiatives are predominantly centered in the Global North, particularly in developed nations [10]. Given the increasing population growth, rising $CO_2$ emissions, and expanding economic influence of the Global South, it is crucial to prioritize the development of DAC technologies in these regions. Advancing DAC technology in the Global South is essential for fostering a comprehensive and equitable global response to the urgent challenges of climate change, particularly considering the heightened vulnerability of many countries in these areas.

In this context, Brazil emerges as a potential leader in the development of DAC technology in the Southern Hemisphere. With a population of 215.3 million and a Gross Domestic Product (GDP) of $1.9 trillion, Brazil is the largest economy in South America and ranks among the most significant globally. The country’s vast Amazon rainforest (60% of its land area inside Brazil), abundant clean energy resources, and geological potential for underground $CO_2$ storage—such as mineral carbonation in basaltic rocks—offer distinct advantages [11,12]. Moreover, Brazil is recognized for its substantial use of biofuels (with 10–15% biodiesel in diesel blends and 27% anhydrous ethanol in gasoline), a significant share of renewables in electricity generation (87.9%), and energy resources (47.4%) [13]. Recent regulations, such as the Future Fuels Law (“*Combustível do Futuro*”), the New Industry in Brazil (*Nova Indústria Brasil*) program, and the regulations for Low-Carbon Hydrogen and Carbon Capture, Utilization, and Storage (CCUS), along with previous initiatives like RENOVABIO, pave the way for technological advancements and innovative low-carbon solutions in Brazil.

Currently, Brazil is the largest emitter of greenhouse gases (GHG) in Latin America. On October 27, 2023, the Brazilian Government presented an updated Nationally Determined Contribution (NDC) to the UNFCCC [14]. This updated NDC establishes a clear goal to significantly reduce net GHG emissions, targeting a 48.4% reduction by 2025 and a 53.1% reduction by 2030, relative to 2005 levels (2.56 $GtCO_2e$). This commitment highlights Brazil's dedication to achieving net-zero GHG emissions by 2050. In this context, our work aims to highlight Brazil's pioneering steps towards the first DAC deployment in South America.

*1.2. DAC.SI Project*

The project, known as DAC.SI (Direct Air Capture System Integration), is developed through a collaborative effort between Repsol Sinopec Brasil (RSB) and the Institute of Petroleum and Natural Resources (IPR) at the Pontifical Catholic University of Rio Grande do Sul (PUCRS), Brazil. The DAC.SI project, launched in 2022, is a pioneering initiative in Brazil aimed at exploring Direct Air Capture (DAC) technologies. This research seeks to deepen the understanding of DAC technologies and their potential role in mitigating climate change, with the objective of enhancing Brazil's capacity to remove greenhouse gases from the atmosphere. In addition, the project focuses on evaluating system integration strategies, optimizing $CO_2$ removal processes, and identifying suitable regions for the deployment of Negative Emissions Technologies (NET) across the country.

In Fig. 1**,** the global distribution of Direct Air Capture (DAC) pilot and experimental plants is illustrated, highlighting operational facilities and their respective locations. The figure also identifies Brazil's first DAC unit, located in Rio Grande do Sul at the Institute of Petroleum and Natural Resources (IPR) at PUCRS, signifying a key advancement in the region's carbon capture initiatives.

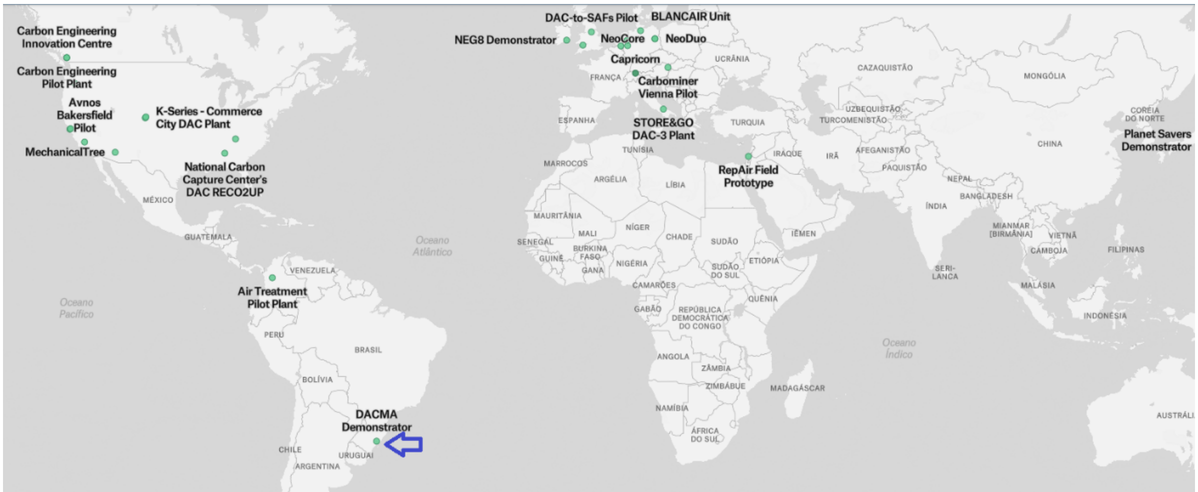


Fig. 1. DAC Coalition Mapping: Global Deployment of Direct Air Capture Pilot and Experimental Plants

Source: https://daccoalition.org/

## 2. Materials and Methods

The project's initial experimental activities were organized into the following stages: i) installation of laboratory equipment, including the DAC test bench, ii) commissioning and testing of the first DAC reactor (DAC 15TA); iii) initiation of the deployment of the DAC experimental plant (DAC 300TA), and iv) characterization of the performance and chemical and isotopic composition of the gas captured by the DAC 15TA unit.

*2.1. DAC Technology Evaluation*

The primary expected outcomes of the project include the deployment, testing, and validation of three DAC units developed by the German startup DACMA GmbH. These units differ in scale and technological readiness levels:

- DAC Test Bench (Fig. 2): Operational since September 2023, this unit focuses on performance testing and the development of adsorbents at a laboratory scale.
- DAC 15TA (Fig. 3): Operational since April 2024, this unit represents the first operational DAC system with a single reactor, designed to achieve a nominal $CO_2$ removal capacity of 15 tons per year.
- DAC 300 TA - Experimental Unit (Fig. 4): Planned for commissioning in November 2024, this unit will be the first experimental DAC system in Brazil. It will feature 20 reactors arranged in 5 units of 4 reactors each, with an estimated nominal $CO_2$ removal capacity of 300 tons per year.

A brief description of the equipment is provided in Section 3: Results and Discussions.

## *2.2. DAC.SI Project Structure*

The DAC.SI project is structured into four main work packages (WPs): WP1 focuses on the commissioning and testing of the DAC experimental unit integrated with solar energy, WP2 is dedicated to the screening and development of adsorbent materials, WP3 involves process simulation and system engineering, and WP4 aims to map and identify suitable areas for DAC technology deployment in Brazil. The proposed organizational structure is designed to facilitate the management of specialized teams, including engineers, chemists, geologists, and project managers. It accommodates various types of activities, such as strategic, computational, and experimental tasks, while also supporting the implementation of agile management strategies to effectively oversee activities and deliverables. The project's organizational structure is presented in Fig. 2.

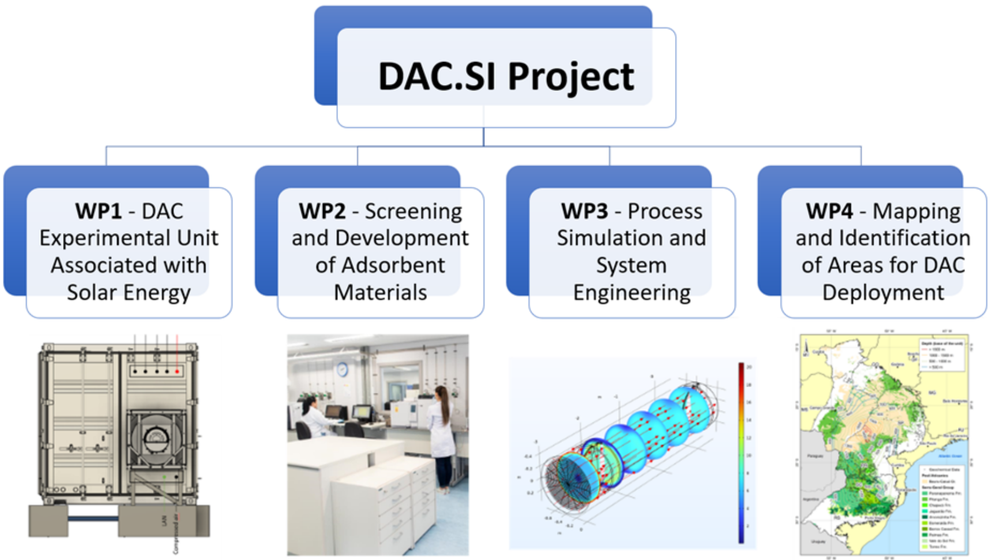


Fig. 2. Organizational structure of the DAC.SI project, highlighting the four main work packages (WPs)

The project aims to achieve the following specific RD&I objectives: i) commission and operate DAC plants within the Brazilian context, ii) assess the technological performance of DAC units integrated with solar energy, iii) characterize, test, and evaluate adsorbent materials, iv) determine the quality of the gas and water produced in the process, v) conduct process simulation and integration studies of DAC with geological $CO_2$ storage, vi) analyze the environmental performance (via Life Cycle Assessment) and cost aspects of DACCS technologies, and viii) map and identify geographically favorable areas for DACCS deployment in Brazil, including studies on $CO_2$ reactivity with basalt. Additionally, the project aims to advance in areas such as process optimization, techno-economic analysis, environmental impact assessments, and carbon accounting, verification, and auditing of DAC technologies.

### *2.3. DAC Key Performance Indicators*

The project is evaluated based on a series of key performance indicators (KPIs) that assess the technological, economic, and environmental feasibility of deploying DAC as a Negative Emissions Technology (NET) in Brazil. These KPIs, presented in Table 1, provide critical insights into the system's efficiency, cost-effectiveness, environmental impact, and scalability.

Table 1. Key performance indicators to be evaluated for Direct Air Capture (DAC) systems

| Indicator | Unit/Metric | Description |
|---|---|---|
| Effective Capture Capacity | $tCO_2$/year | Amount of $CO_2$ captured annually in Brazil |
| Purity of $CO_2$ Captured | $\%CO_2$ | Percentage of $CO_2$ in the captured gas |
| Levelized Cost of $CO_2$ Captured | $\$/tCO_2$ | Cost per ton of $CO_2$ captured |
| Energy Consumption | kWh × $tCO_2$ | Energy required for each ton of $CO_2$ captured |
| Effective Removal Capacity | $tCO_2$ removed/$tCO_2$ captured | Ratio of $CO_2$ removed per $CO_2$ captured unit via Life Cycle Assessment |
| Water Consumption | $tH_2O/tCO_2$ | Amount of water consumed per ton of $CO_2$ captured (water footprint) |

The KPIs, outlined in Table 1, are essential for evaluating the technical, economic, environmental, and resource impacts of DAC systems. These metrics, which include capture capacity, $CO_2$ purity, cost-effectiveness, energy consumption, removal efficiency, and water usage, are crucial for determining DAC's potential to contribute to Brazil's decarbonization goals. They also help assess DAC's integration with the carbon economy and its ability to operate sustainably within Brazil’s energy and environmental frameworks, ensuring the technology can be deployed at scale and meet the country’s climate commitments.

### *2.4. $CO_2$ Characterization*

The chemical and isotopic characterization of the gas captured by the DAC 15TA unit was performed at the accredited laboratories (ISO/IEC 17025) of the Institute of Petroleum and Natural Resources (IPR) at PUCRS. Gas chromatography analysis was conducted using a Shimadzu GC-2014 equipped with a methanator, a flame ionization detector (FID), and a 100-μL sampling loop to determine the $CO_2$ concentration in each sample. In addition, stable carbon isotope analysis ($\delta^{13}C$) was performed using a gas chromatograph coupled with a Delta V Plus isotope ratio mass spectrometer from Thermo Fisher Scientific. The stable isotope results ($\delta^{13}C$) are reported in per mil (‰).

## 3. Results and Discussions

### *3.1. DAC Test Bench*

The DAC Test Bench, illustrated in Fig. 3, is a gas adsorption measurement instrument to general studied of $CO_2$ adsorption and capable of measuring the breakthrough curves of $CO_2$ adsorbents. Its main function is to study the DAC processes through the temperature-vacuum swing adsorption (TVSA) method at a bench scale with a maximum quantity of 5 to 50 g of adsorbent per batch.

The key components of the DAC test bench equipment, includes a vacuum pump, heating system, reactor, valves, flow controller, buffer tank, electric box, and heat exchanger for regulating gas flow, pressure, and temperature during adsorption and desorption processes. This equipment can be used for both the characterization and optimization of adsorption and desorption of different materials. Various parameters can be adjusted and analyzed, such as adsorption time, flow rate during adsorption (air flow), desorption pressure, desorption temperature, and desorption time. The current application range will not be disclosed for strategic and confidentiality reasons.

The DAC test bench equipment can be applied in a lab-scale unit to test new adsorbent materials. This includes screening potential new adsorbents, performing longevity and degradation testing, and supporting process-informed adsorbent design through smart development. Additionally, it provides valuable support for the performance testing of new materials developed by companies, startups, and spinoffs, following an open innovation model.

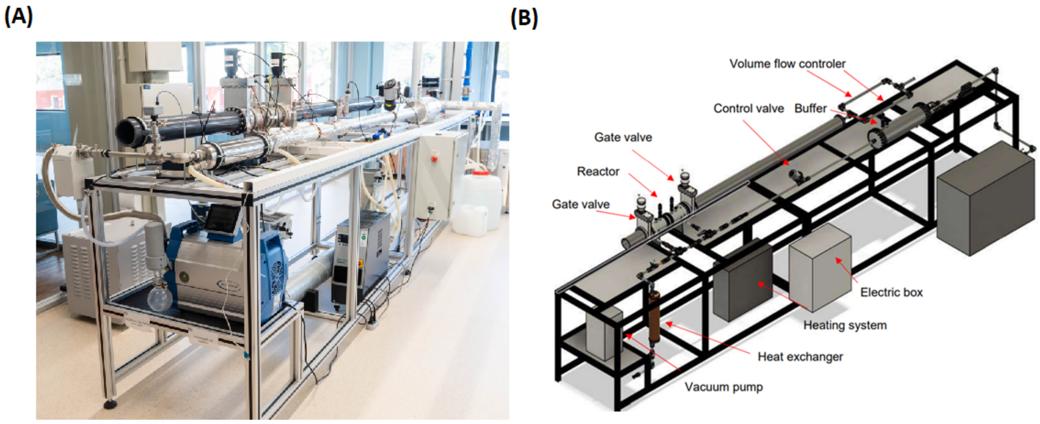


Fig. 3. DAC Test Bench Setup. (A) Photograph of the equipment and (B) diagram showing the detailed components

*3.2. DAC 15TA*

The DAC 15TA (Fig. 4) represents a scale-up from the DAC Test Bench and serves as the first reactor of the DACMA technology, designed to capture $CO_2$ from ambient air using the TVSA process. This system builds upon the earlier DAC Test Bench by scaling up its capacity and advancing the technology readiness level, enabling more robust and representative $CO_2$ capture operations and enabling more extensive $CO_2$ capture. The DAC 15TA integrates the principles of TVSA, employing cycles of temperature and vacuum variations to adsorb and desorb $CO_2$. It also acts as an intermediate step toward deploying the DAC 300TA Experimental Unit. Notably, the filter (contactor) geometry tested in the DAC 15TA is the same applied in the next DAC generation. The current adsorbent material will not be disclosed for strategic and confidentiality reasons.

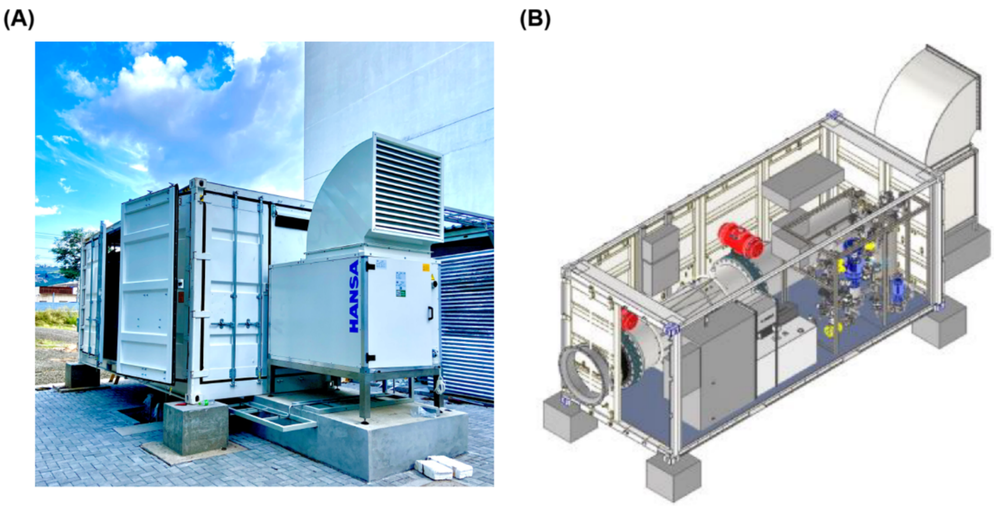


Fig. 4. DAC 15TA single reactor. (A) photograph and (B) diagram of the equipment

The equipment is installed within a 20ft shipping container, housing the reactor along with all electrical, pneumatic, and logical components. Key features include the central reactor, filter/contactor, pneumatic valves, heating system, vacuum pump, heat exchanger, ventilator, and air conditioning unit. Dedicated control panels manage energy supply, pneumatic functions, and reactor operations, ensuring seamless integration for efficient $CO_2$ capture and desorption processes. The reactor is equipped with $CO_2$, pressure, humidity, and temperature monitoring systems at both the inlet and outlet, as well as a $CO_2$ output sensor to measure the purity of the captured $CO_2$. The system is designed to export all operational data to an online data cloud and features a supervisory system for fully remote operation. Supporting peripheral equipment, including a demineralizer, air compressor, water storage tanks, a water pump, and a wastewater tank, is installed outside the container in a utility house to ensure the efficient operation of the DAC 15TA system.

The equipment has been operational since April 2024, and to date, the following activities have been completed: development of standard operating procedures (SOPs) and safety protocols, establishment of a baseline cycle and stability study, saturation tests of the adsorbent, and preliminary $CO_2$ capture tests, including chemical and isotopic characterization. The planned experiments for the DAC 15TA unit include parameter screening, KPI determination, optimization studies, and performance analysis under varying environmental conditions throughout all four seasons. Additionally, the unit will test new adsorbents to obtain KPIs and optimize the working capacity to 15 tons per year. The system currently operates during regular university hours, 10 hours per day, with cycle times ranging from 50 to 100 minutes. Fig. 5 presents an example of the DAC 15TA experimental profile, illustrating the system's performance during an operational cycle.

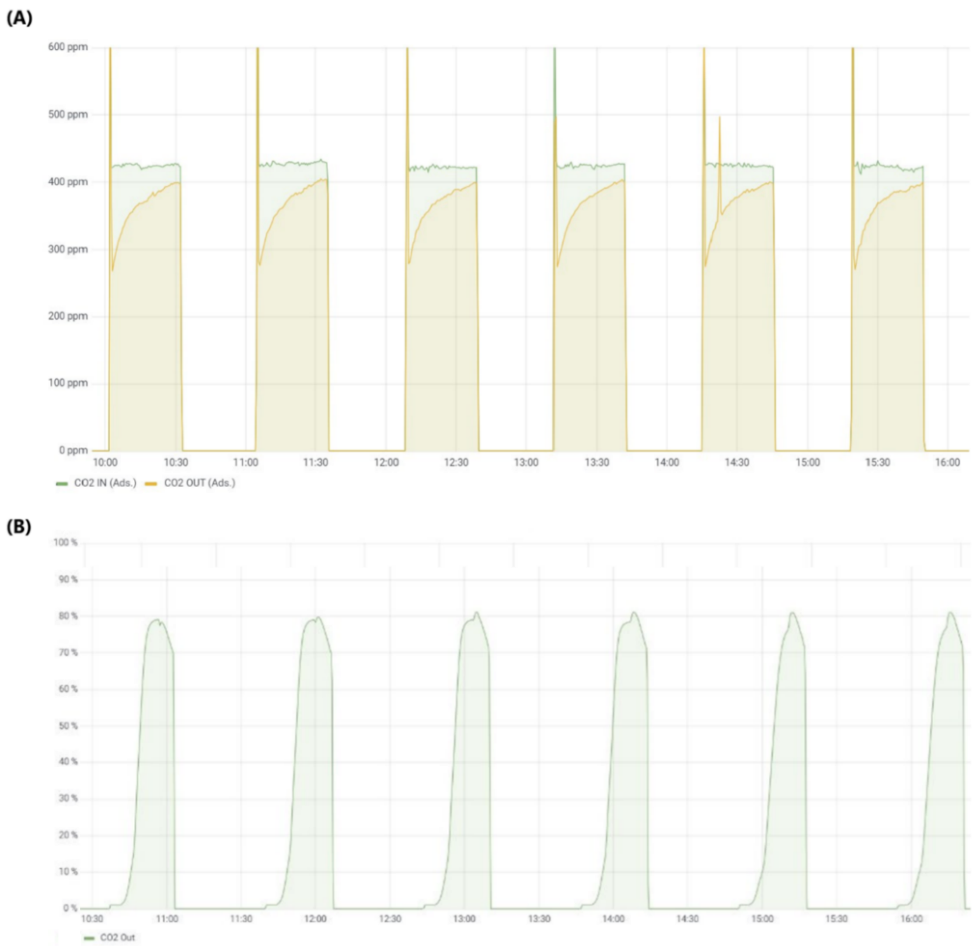


Fig. 5. DAC 15TA $CO_2$ adsorption (Fig. 5a) and desorption (Fig. 5b) profiles

Fig. 5 illustrates the $CO_2$ adsorption (Fig. 5a) and desorption (Fig. 5b) profiles across six cycles during an entire working day, showcasing the system's performance in the $CO_2$ capture process. The captured $CO_2$ is further characterized through gas chromatography and stable isotope analysis. Overall, the $CO_2$ output purity ranges from 80% to 91%. Additionally, the stable isotope signature, ranging from $\delta^{13}C$ = -9.2‰ to -7.6‰, is consistent with atmospheric $CO_2$, unequivocally confirming that the source of the $CO_2$ is atmospheric air.

Overall, the equipment has been running for over 180 days without any signs of degradation in the adsorption bed. Fig. 6 presents a period of the control chart, demonstrating that the equipment delivered by DACMA can operate over an extended period while maintaining consistency in the following aspects: working capacity (dimensionless on the graph), energy consumption, and water requirements. As an enhancement, a $CO_2$ mass sensor will be implemented in December 2024 to improve measurement sensitivity and support the validation of the system's capture capacity.

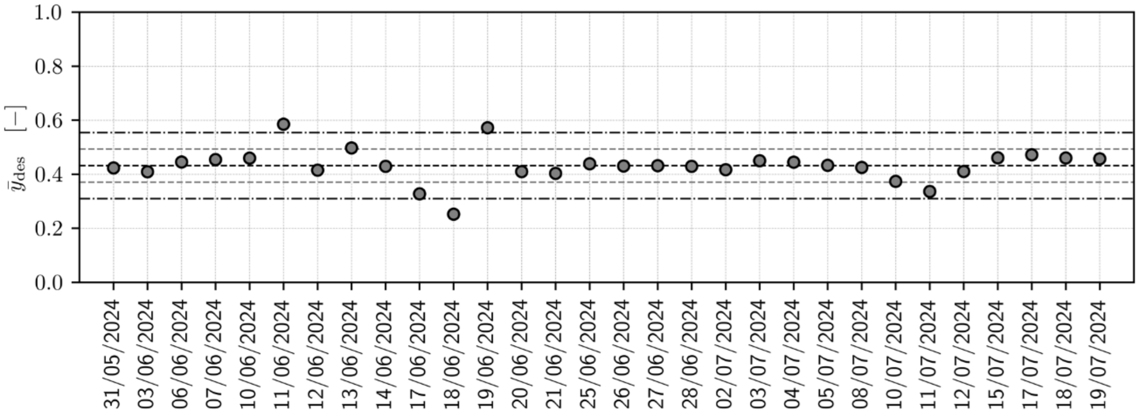

Fig. 6. DAC 15TA operational control chart showing $CO_2$ production over time

### 3.3. DAC 300 TA - Experimental Unit

The DAC 300TA (Fig. 7) is a scaled-up version of the DAC 15TA and marks Brazil's first DAC Experimental Unit to be tested and validated in a representative environment. This system builds on the lessons learned from the DAC 15TA by increasing its capacity and advancing the technology readiness level, enabling more robust and representative $CO_2$ capture operations. The DAC 300TA utilizes the principles of TVSA, employing cycles of temperature and vacuum variations to adsorb and desorb $CO_2$. It also serves as a baseline for future upscaling to a DAC Pilot Operation in Brazil.

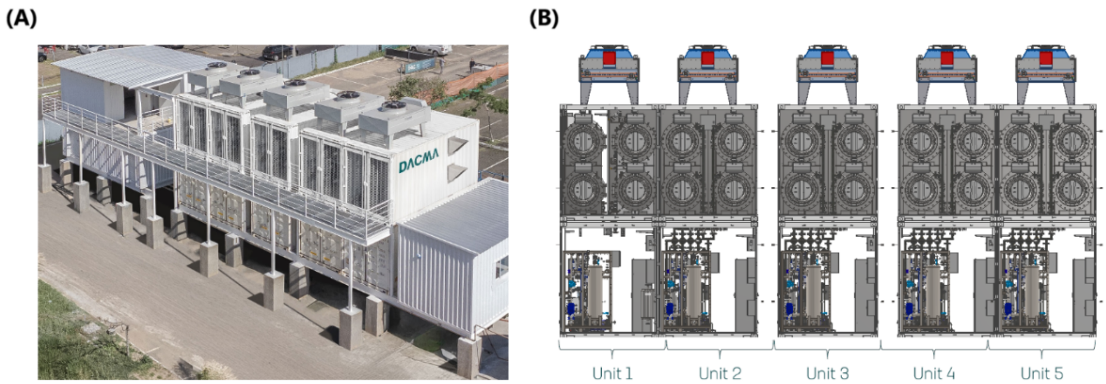

Fig. 7. DAC 300TA Experimental Unit. (A) photograph and (B) diagram of the equipment.

Planned for commissioning in November 2024, the DAC 300TA system will feature 20 reactors, organized into 5 units, each consisting of 4 reactors. Unlike the DAC 15TA, where all components were housed in a single container, each of the DAC 300TA's five units is divided into: (A) an upper reactor container and (B) a lower peripheral container. The equipment is installed within a 20-foot shipping container, which houses the reactors along with all electrical, pneumatic, and control components. Each of the 5 units can be operated individually (independently of the others), allowing for the use of different experimental parameters and adsorbents. This configuration enhances the R&D potential associated with the equipment.

Key features of the DAC 300TA include the central reactor, filter/contactor, pneumatic valves, heating system, enhanced vacuum system, heat exchanger, ventilator, and air conditioning unit. Dedicated control panels manage energy supply, pneumatic functions, and reactor operations, ensuring seamless integration for efficient $CO_2$ capture and desorption processes. The reactor is equipped with $CO_2$, pressure, differential pressure, humidity, and temperature monitoring systems at both the inlet and outlet, as well as a $CO_2$ output sensor to measure the purity of the captured $CO_2$. The DAC 300TA also includes a $CO_2$ mass sensor for each of the 5 units, as well as an additional sensor to monitor the total $CO_2$ production of the Experimental Unit. The system is designed to export all operational data to an online data cloud and features a supervisory system for fully remote operation. Supporting peripheral equipment, including a demineralizer, air compressor, water storage tanks, a water pump, and a wastewater tank, is installed outside the container in a utility house to ensure the efficient operation of the DAC 300TA system.

The expected technical performance of the DAC 300TA unit at its current development stage includes a nominal $CO_2$ capture capacity of 300 tons per year (±15%), water consumption of 2 tons per ton of captured $CO_2$, a minimum $CO_2$ purity of ≥97%, and a total energy requirement of 1289 kWh per ton of $CO_2$. This total includes 398 kWh per ton for electrical components and 891 kWh per ton for thermal energy. The key activities planned for the DAC 300TA include the development of standard operating procedures (SOPs) and safety protocols, establishment of a baseline cycle and stability study, and validation of the reproducibility and robustness across the five units and 20 reactors. These activities will assess the effectiveness of the DAC manufacturing process. Additionally, a long-term operational test will be conducted to evaluate the system's stability and efficiency over extended periods. The ultimate goal is to validate the DAC 300TA working capacity and ensure the system's optimal performance.

After completing all validation stages, IPR aims to become a key support hub for the design and validation of new technologies and materials for DAC processes. The development pipeline will start at the DAC Test Bench in the laboratory, progress through the single reactor of the DAC 15TA, and ultimately be tested in the DAC 300TA Experimental Unit. In this way, IPR-PUCRS plans to implement a comprehensive development pipeline (Fig. 8) for testing and scaling adsorbent materials, transitioning from laboratory (LAB) to fabrication (FAB). This will serve as a hub for DAC technologies, fostering an open innovation environment to advance and optimize $CO_2$ capture solutions.

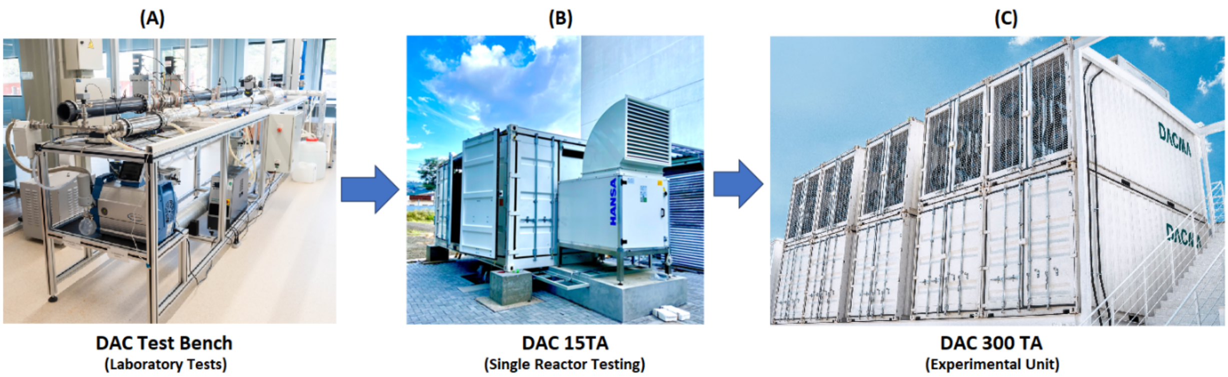


Fig. 8. From Lab to Fabrication: the DAC development and testing pipeline

## 4. Conclusion

The DAC.SI project marks a significant milestone in advancing Direct Air Capture (DAC) technologies in Brazil, with the primary goal of enhancing the country's capacity to mitigate climate change. By focusing on the development of Negative Emissions Technologies (NET), the project aims to identify and deploy scalable DAC solutions across Brazil, contributing to the nation's long-term decarbonization efforts.

The deployment of DAC systems is progressing through well-defined stages. Starting with the installation and commissioning of the DAC test bench, followed by the operational launch of the DAC 15TA unit in April 2024. The DAC 15TA, with a nominal $CO_2$ removal capacity of 15 tons per year, has undergone a first round of testing to evaluate adsorbents and the chemical and isotopic composition of captured $CO_2$, with preliminary results presented. In parallel, the upcoming DAC 300TA experimental plant, planned for commissioning in November 2024, will mark a critical step in scaling up DAC technology and optimizing performance at a larger scale.

The project's broader objectives include the optimization and integration of DAC and Carbon Capture and Storage (CCS) technologies in Brazil. Key activities include characterizing adsorbents, evaluating the synergy between DAC and geological $CO_2$ mineralization, and conducting region-specific studies to identify areas suitable for DACCS deployment, with a focus on $CO_2$ reactivity with basalt for enhanced mineralization. Additionally, the project will explore opportunities to reduce energy demand by sharing infrastructure and utilizing waste heat, further enhancing DAC's decarbonization potential.

By advancing these technologies, the project will not only contribute to Brazil's decarbonization but also position the country as a global leader in DAC innovation. These efforts pave the way for the large-scale deployment of DAC systems, providing valuable insights and data that will accelerate the development of cost-effective, sustainable solutions for climate change mitigation.

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