A Feasibility Analysis of a Small Scale DIY Direct Air Capture Implementing a Moisture Swing System

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Abstract

Amid the urgent need to address the escalating challenges of climate change, this paper evaluates the feasibility of an innovative concept—a compact, household-level Moisture Swing Carbon Capture (MSCC) device employing Ion Exchange Resins (IER) as the absorption medium. This personal device is designed to empower homeowners and communities to effectively capture carbon dioxide (CO2) from both dilute external air and localized concentrated sources, thereby facilitating reductions in personal carbon footprints. Central to the machine is the selection, preparation, and fine-tuning of IER, engineered to ensure optimized efficiency in both CO2 absorption and desorption under varying moisture conditions. A versatile, adaptable system is needed for a diverse array of settings, from individual households and rooftops to educational institutions and community spaces to start small in the large step forward in the global pursuit of effective and accessible carbon capture solutions.

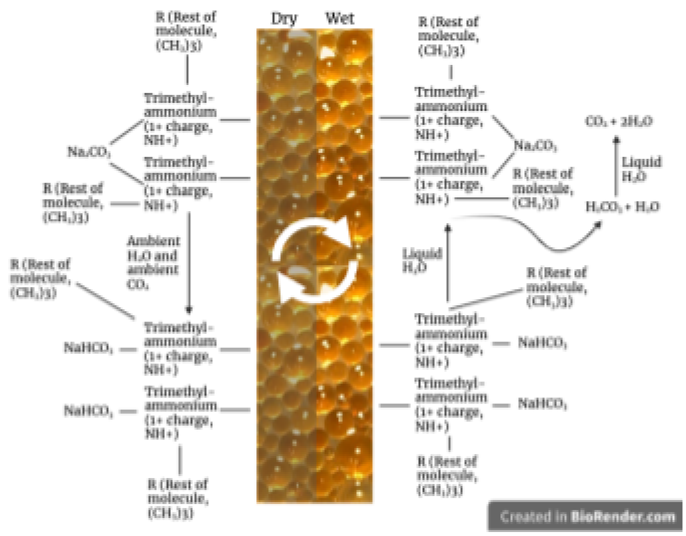

Fig. 1 *Adsorption principle of the ion exchange resin.* Created with BioRender.com.

1. Introduction

In recent years, the escalating levels of greenhouse gasses, notably carbon dioxide (CO2), have led to a concurrent rise in the Earth's ambient temperature. This global warming phenomenon has dire consequences, manifesting in catastrophic environmental damage and increasingly severe weather events, as extensively documented (World Weather Attribution, 2021). Mitigating these consequences necessitates the reduction of greenhouse gas emissions, a widely acknowledged imperative.

However, it has become increasingly evident that merely curbing emissions is insufficient to meet climate goals. Climate predictions indicate that we must also actively remove CO_2 from the atmosphere to restore environmental equilibrium (Vitillo et al., 2022). This imperative underscores the need for the development of low-cost, energy-efficient, and readily deployable Direct Air Capture (DAC) units. These units should be designed to be modular, cost-effective, require minimal maintenance, consume low levels of power, and have the option of being built in a DIY manner.

Among the various carbon removal methodologies, the Moisture Swing Carbon Capture (MSCC) method emerges as a promising solution, distinguishing itself from the conventional Temperature Swing Carbon Capture (TSCC) approach. MSCC offers a distinct advantage due to its capacity to spontaneously extract CO_2 from the atmosphere when dry and release it when exposed to moisture, thus establishing a regenerating cycle with minimal energy input (Wang, Lackner and Wright, 2023). MSCC uses the evaporative energy of water in contrast to large amounts of energy in the form of heat used in the TSCC approach.

The MSCC device uses a simple sensor setup that measures the increase of CO_2 ppm levels after the resin regeneration stage where the resin has been submerged in a beaker of water. Working principle at the heart of this paper leverages Anion Exchange Resins (AERs) to facilitate the moisture swing cycle. The resins are chemically bonded by crosslinking with quaternary ammonium cations (abbreviated to quat). The quats are further enhanced with sodium carbonate to enable the efficient capture and release of CO_2.

This paper will document the steps and process of building a low-cost DIY MSCC machine, along with the fundamental science behind the process, in an easy-to-understand format that welcomes citizen scientists, researchers, or just tinkerers. This paper will only briefly cover the adsorption of the CO_2, and spend more time on the regeneration of the CO_2 saturated resin. The main point of this paper is to understand the feasibility of such MSCC devices on a smaller, localized scale.

2. Materials

2.1 Sorbent. Sorbent material was prepared for the device in a household setting using readily available equipment. The sorbent material, the IER, was sourced (DuPont™ Water Solutions, AMBERLITE™ IRA900 Cl Ion Exchange Resin). In the experimental procedure, 5 grams of the ion exchange resin are initially placed into a bag. A small beaker is then filled to capacity with distilled water, and the resin-filled bag is submerged into the beaker. The beaker, with the resin bag inside, is subsequently positioned within the middle of a slow cooker, ensuring that the beaker is completely surrounded by water in the slow cooker to allow for proper heat transfer. The slow cooker is activated and maintained at a temperature of approximately 85 degrees Celsius for a duration of 48 hours, set to the low heat setting.

At approximately the 48-hour mark, the preparation of a 0.5 molar sodium carbonate solution is initiated by dissolving 2.15 grams of sodium carbonate in 50 milliliters of distilled water. Following the 48-hour resin conditioning process, the resin bag is removed and rinsed thoroughly with distilled water. Immediately after rinsing, the resin bag is immersed in the freshly prepared 0.5 M sodium carbonate solution.

Two hours after the resin is introduced into the sodium carbonate solution, the bag is withdrawn, and the previous solution is discarded. The resin is rinsed once again with distilled water. A new sodium carbonate solution is prepared using the same methodology, and the resin bag is placed into this solution. These last four steps (immersing the bag, removing it, discarding the solution, and rinsing) are iterated five to six more times to ensure the complete replacement of chloride ions with carbonate ions within the resin (Wang, Lackner and Wright, 2011).

Following the ion exchange process, the resin is allowed to air dry for a period of 24 hours. The resin was then placed in a resin bag before subsequent testing and analysis. This comprehensive procedure is designed to facilitate the transfer of chloride ions from the resin to carbonate ions.

3. Device Construction

3.1 Overview. A hermetically sealed prototype low-cost device was prepared to test the DIY sorbent. The CDR (Carbon Dioxide Removal) machine is composed of a resin wetting system (achieved resin submersion), a CO_2 sensor, a beaker holding water, a waterproof box with three holes, wires, and an Arduino microcontroller. Additionally, a 3D-printed fan chamber was produced to facilitate the adsorption on the resin. This low component count is applicable for a home setting and can be made by anyone. While not optimized for efficiency, this test chamber, also referred to as a device in this paper, provides insights into household carbon removal feasibility.

3.2 Chamber. An IP-67 waterproof container was sourced (Home Depot, Ezy Storage 18L/19Qt Waterproof Clear Latch Tote IP-67). An analysis of the IP-67 rating shows that the container is waterproof up to 1 meter deep submersion (C&T Solution Inc., 2023). Furthermore, it shows that an IP-67 restricts dust particles from ingressing. These ratings should be efficient for an airtight container, but nonetheless, tests were carried out in the chamber to check its efficiency as an airtight test chamber in the next three paragraphs.

3.2.1 Container testing setup. A hole was produced with a drill in the container to allow a 3 inch segment of silicone tubing to slide into the hole. The outsides of the hole were then hermetically sealed with hot glue to prevent CO_2 escape. A valve was outfitted upon the end of the tubing segment to stop the flow of CO_2 from the CO_2 supply. The CO_2 for this initial test was supplied from a household carbonated water machine, supplied by SodaStream. A rather long segment of silicone tubing was placed from the nozzle of the SodaStream to the valve. A CO_2 sensor was placed in the exact middle of the chamber. Another hole was produced in the side of the box to allow for the wires of the sensor to protrude and be hooked up to a microcontroller on the outside to obtain sensor readings. The hole surrounding the wires was again hermetically sealed with hot glue. Further information on the sensor system shall be explained in later paragraphs.

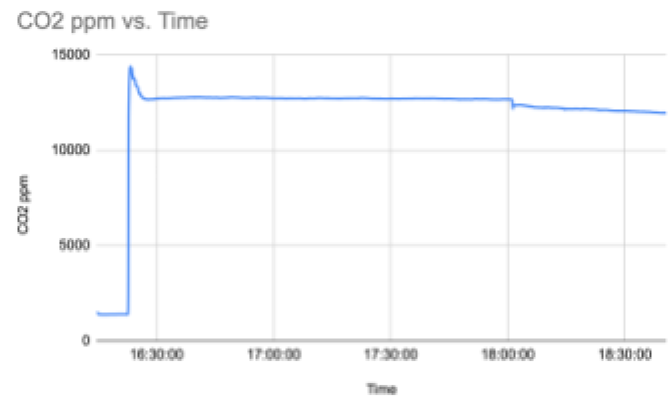

Fig. 2 *CO_2 leakage in the hermetically sealed test chamber supplied with CO_2 from a SodaStream.*

3.2.2 Container hermetic testing.

The valve on the chamber was opened to allow the CO_2 from the SodaStream to enrich the chamber. The SodaStream was pulsed and CO_2 entered the chamber. The sensor was subsequently turned on and the readings were produced on a computer. The test ran for approximately 2 hours and 20 minutes.

3.2.3 Container hermetic testing results.

The results were recorded from the sensor and put into a Google spreadsheet. A graph was produced showing the relationship of time vs. CO_2 levels (Figure 2). The graph concluded that the IP-67 container that was chosen can withstand multiple hours with CO_2 contained and show minimal decrease and leakage in CO_2 levels. This container proves adequate for a prototype carbon removal system. Further additions to the chamber will be made to improve the CO_2 release efficiency, described herein.

3.3 Sensor and data logging.

The sensor used in the above tests was an SCD30 (Amazon, extralife SCD30 Quality Sensors Module for and RH/T Measurements I2C Modbus PWM, green, black). This sensor can be purchased for approximately 30 dollars, proving to be a sufficient price for home use and mass produced carbon removal machines. The SCD30's CO_2 readings have an accuracy of ±(30 ppm + 3% MV) @400-10000 ppm, which is exceedingly accurate for its low price (Sensirion AG, 2023). Furthermore, this sensor contains humidity and temperature sensors to allow for humidity and temperature compensations.

3.3.1 Sensor interfacing.

The SCD30 was interfaced with to retrieve the humidity, temperature, and CO_2 ppm levels. The sensor was wired up to a low-cost Arduino microcontroller (Amazon, ELEGOO UNO R3 Board ATmega328P with USB Cable(Arduino-Compatible) for Arduino) via the I2C protocol. This method of sensor hookup requires notably four wires between the sensor and the Arduino microcontroller: VCC, GND, SDA, and SCL. Between the Arduino microcontroller and the SCD30, an I2C level shifter was used to convert between the 5v levels of the Arduino to the 3.3v levels of the SCD30. The code used herein can be obtained from a GitHub repository (Nicholson, 2023).

3.3.2 Sensor calibration. Sensor calibration was achieved for proper function. The sensor was calibrated in this paper by placing the sensor outside and exposing it to the approximate 400 ppm levels of CO_2 in the ambient air for less than a minute. A different script was uploaded to the sensor for calibration (Seidle, 2023).

3.4 Fan chamber. An external micro fan chamber was constructed separately from the main release chamber. It was constructed out of two 3D printed parts that slid into each other. Two fans were subsequently placed on either end of the chamber to draw in air and to take out air. The resin bag can be placed inside this chamber to allow

3.5 Resin wetting. To permit regeneration of the resin, a resin bag dipping device was produced to interface with the existing chamber. The dipping mechanism was constructed of a nine volt geared hobby motor acting as a winch, fishing line, a 3D printed reel, and hot glue to attach the motor to the chamber's lid. The 3D printed reel was subsequently attached to the motor's shaft and a hole was made for the wires of the motor to exit the container. Up and down usage of the winch is enacted by touching the leads of the motor to a nine volt battery. Different directions of the winch can be generated by switching the polarity of the battery.

4. Experimental Methods

4.1 Overview. A test of the resin regeneration was conducted to prove the feasibility and ease of moisture swing carbon capture and release.

4.2 Testing. The resin bag underwent a two-hour period within the fan chamber before being connected to the regeneration system's winch. Positioned below the winch, a beaker of distilled water facilitated the regeneration process. Subsequently, the test chamber was sealed, and a ten-minute warm-up period was allowed for the sensor in the closed system. Data from the sensor was streamed onto the Arduino IDE's serial monitor. After ten minutes, the resin was submerged in the water for two minutes,

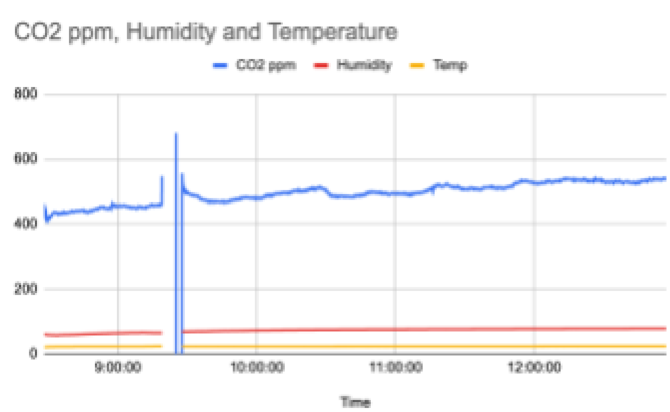

Fig. 3 *CO_2, humidity, and temperature over time of the resin regeneration test.*

initiating regeneration. Post-submersion, the winch raised the resin back up and the monitoring of CO_2 levels was initiated. The test persisted for an additional four hours and fifteen minutes, all the while data was continually streamed at 2 second increments to the Arduino serial monitor.

5. Results

5.1 Data gathering. Sensor data was displayed and documented via the Arduino IDE's serial monitor. This data was then formatted and transferred to a Google Spreadsheet. Utilizing the spreadsheet's graphing function, a CO_2 ppm versus time graph was generated (Figure 3).

5.2 Data analysis. The resin regeneration test was deemed successful based on the observed increase in CO_2 ppm post-resin submersion. An anomalous early spike in the graph, possibly stemming from a sensor error, remains unaddressed. Employing a Python script (Nicholson, 2023), CO_2 capture in grams was computed. The calculated captured CO_2 in the fan chamber and subsequent release amounted to 0.004 grams. The computation underwent can be simply summarized: captured CO_2 in grams was calculated by finding the percent of the CO_2 in the air inside the chamber. The percent was then multiplied by the volume of the box to find liters of CO_2. Lastly, the weight of CO_2 per liter was calculated by finding the density of grams/liter of CO_2.

6. Further Discussion

6.1 Overview. The Python script used for CO_2 quantification also indicated that a single tree exhibits 13,770 times greater efficiency than the described machine. Recognizing this vast efficiency gap between trees (the common efficiency benchmark) and the CDR machine underscores the need to assess the viability of small-scale DIY CDR for citizen scientists and homeowners.

6.2 Household and small scale CDR feasibility. Further analysis using the Python script highlighted crucial metrics. Assuming this current unmodified and unoptimized device operates without enhancements—completing a cycle in 4.5 hours, running continuously for a year, costing ten dollars to produce—it would need to be 50,000 times more efficient to be as cost-efficient as trees in reducing atmospheric CO_2. Enhancing this machine to such a degree poses significant challenges. Considering these obstacles, pursuing the DIY moisture swing direct air capture machine seems impractical until improvements in resin efficiency and cost are achieved. The absence of documented resins capable of holding their weight in CO_2 complicates this pursuit. Alternative household direct air capture methods like algal CO_2 scrubbers and biochar producers may prove more promising until resin efficiency significantly improves.

6.3 DIY CDR machine feasibility.

The construction of the moisture swing carbon capture device occurred within typical household limitations, predominantly in a kitchen and a bedroom workshop. The most challenging aspect was crafting an effective resin, involving a 12-hour soak in near-boiling water with chemical solution replacement needed every 2 hours. Identifying a reliable kitchen appliance accessible to homeowners—such as a slow cooker—presented temperature regulation challenges compared to lab-grade equipment. In hindsight, a lab setting may have bolstered resin efficiency. My perspective as a researcher leans toward caution regarding DIY CDR machines in household settings, foreseeing potential subpar outcomes. Pursuing the production of DIY CDR machines without lab-grade equipment, materials, and supplies may yield less efficient CO_2 scrubbing. Simpler approaches like an algae photo-bioreactor might offer more feasible solutions for citizen scientists and others seeking efficient CO_2 capture, as mentioned above.

7. Working Principles

7.1 Resin.

The resin, which is made out of polystyrene and crosslinked with divinylbenzene, is covalently bonded to the functional group, which is a trimethylammonium cation. This functional group is categorized under quaternary ammonium cations (abbreviated to quat) and can hold a negatively charged ion. In the resin's dry and empty state, the ion bonded to two quats is a carbonate ion (CO_3^{2-}). The resin was exposed to ambient moisture in the form of H_2O in the air and CO_2 in the air and the formation of two bicarbonate ions (HCO_3^-) on two different quats occurred, hence capturing the CO_2. To remove the CO_2 from the resin to regenerate it for reuse, water was added. The water reacted with the HCO_3^- to create carbonic acid (H_2CO_3). The carbonic acid dissociated in the water to become carbonate (which bonded back to the quat), CO_2, and H_2O. The CO_2 was not captured for storage, but could have been. The cycle was not repeated but easily could be.

The reactions of which can be summed up in these equations:

(1) $CO_3^{2-} + CO_2 + H_2O \text{ (ambient)} \rightarrow 2\ HCO_3^-$
(2) $2\ HCO_3^- + H_2O \text{ (from liquid water)} \rightleftharpoons H_2CO_3 + CO_3^{2-} + H_2O$
(3) $H_2CO_3 \rightleftharpoons H_2O + CO_2$

Eq. 1 *The CO_2 was adsorbed with the help of surrounding moisture. The carbonate was converted into two bicarbonate ions.*

Eq. 2 *The regeneration process was started. Water was added to the two bicarbonates to create carbonic acid (H_2CO_3) and the original carbonate, which subsequently bonded back with the quats.*

Eq. 3 *The regeneration process was finished. The carbonic acid rapidly dissociated into water and CO2. The liquid water stayed behind and accumulated with the other water to allow a high-purity stream of CO2.*

The working principle is explained further in literature, including benefits of the use of resin with the trimethylammonium instead of other mediums (Wang, Lackner and Wright, 2023).

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