

Optimizing Artificial Trees for Carbon Capture: Harnessing Advanced Adsorbents in Artificial Trees to Combat Climate Change

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Abstract:

This research explores using affordable, small-scale artificial trees for carbon capture, utilizing silica gel, zeolite, and alumina functionalized with amine-based compounds (TEOA, MEA, and a MIX of both). With global CO₂ emissions rising alarmingly, finding accessible, cost-effective carbon capture technologies is critical. At a low production cost of **\$24** per unit, these systems present an alternative to large-scale industrial solutions by capturing CO₂ directly from urban areas. Through four trials, CO₂ absorption rates were tested over six hours, with silica, particularly functionalized with the MIX, demonstrating the highest initial capture rates. However, while effective in short-term absorption, these materials showed saturation over time. Highlighting the need for greater material stability and reusability. With an estimated cost of **\$300** per ton of CO₂ captured, these devices, although small, offer an economically stable path for decentralized carbon capture, addressing a gap in urban sustainability. Unlike large direct-air capture systems such as Climeworks, which require massive infrastructure, these compact units could be deployed across residential areas, creating a network of CO₂ sequesters capable of localized air purification. This approach brings carbon capture technology closer to communities and enhances accessibility by reducing infrastructure and operational demands. Ultimately, this research highlights the potential of these small-scale units to contribute to global carbon sequestration efforts. Providing a sustainable and economically viable solution for densely populated regions, with further refinement promising even greater environmental impact.

Question:

How effective are silica gel, zeolite 13X, and alumina, functionalized with amine-based compounds (TEOA, MEA, and a MIX), in capturing CO₂ within a small-scale artificial tree system, and how do these materials compare in terms of absorption efficiency, stability, and scalability for decentralized carbon capture solutions? Can small-scale artificial trees provide an affordable and efficient solution for urban CO₂ capture?

Introduction:

CO₂ is the main driver of global warming. The rapid accumulation of Carbon Dioxide (CO₂) in the atmosphere is one of the main global issues we must face. CO₂ and other greenhouse gases are emitted during fossil fuel consumption to produce industrial materials. To reduce these, we must transform our energy systems (Our World in Data). Originally, CO₂ emission was slow until the 21st century, when over 35 billion tonnes are emitted yearly (Our World In Data). Global Temperatures have raised 0.08°C per decade since 1880, with a more rapid warming of 0.32°F (0.18°C) per decade since 1981 (LINSEY et al., 2024). The average surface temperature has risen by about 1.1°C since the 1800s (United Nations, n.d.).

Global sea levels have risen by about 20 centimeters since the 20th century due to thermal expansion and melting of the polar ice caps, which are driven by greenhouse gases (IPCC, 2019). The oceans absorb 30% of CO₂ emitted into the atmosphere through diffusion, which forms carbonic acid. This causes seawater pH to lower, leading to ocean acidification and affecting marine life by disturbing marine ecosystems and food webs (Doney 2009) (Sabine). The pH of surface ocean waters has decreased by 0.1 units, corresponding to a 30% increase in hydrogen ion concentration (IPCC, 2014). The Increase in hydrogen ion concentration reduces the availability of carbonate ions, which are crucial for marine organisms like corals, mollusks, and some plankton to build their calcium carbonate shells and skeletons. In turn, this weakens ecosystems, disrupts marine food webs, decreases biodiversity, and threatens the livelihoods of human communities dependent on these ecosystems for food, coastal protection, and economic activities such as fisheries and tourism

The World Health Organization estimates that from 2030 to 2050, climate change will cause approximately 250,000 additional deaths from heat stroke (WHO, 2018). This especially concerns children, the elderly, and the working class. By 2030, it is estimated that it will cost the U.S. \$100 billion annually for reduced productivity (Cerullo, 2023).

The American Lung Association reports that decreased ozone levels due to climate change could result in thousands of premature deaths. This is because of increased respiratory issues, including asthma and chronic obstructive pulmonary disease (Jacob 2009). For the average person, this can mean more

frequent hospital visits, leading to spending on healthcare and a decline in daily health. In the U.S. alone, \$790 billion or 5% of GDP is lost on air pollution, while only 2.5 billion is being spent on fighting air pollution.

Climate change affects agricultural productivity, leading to food shortages and malnutrition. The Food and Agriculture Organization states that by 2050, climate change could reduce global food production by 10% (FAO 2018).

Elevated CO₂ levels can reduce the nutrient content of foods such as rice and wheat. By 2050, the protein content of these crops can decrease by up to 8% (Myers 2014).

Carbon capture is a process designed to prevent carbon dioxide from being released into the atmosphere by capturing it at its source or from the atmosphere. This technology is crucial to our fight against climate change. CO₂ is captured from Industrial power sources before being released into the atmosphere, transported to storage via pipelines, and stored in Deep geological formations. The global carbon capture and storage capacity was around 40 million metric tons of CO₂ per year (CCS 2020). The Cost of capturing CO₂ varies widely depending on the technology and source of emission, ranging from \$20 to \$120 per ton of CO₂ (IEA 2020).

While carbon capture offers potential for mitigation, it isn't being implemented due to several notable drawbacks. Carbon capture technology costs are high, making it less economically viable. Developing the necessary CO₂ transport and storage infrastructure is another major challenge, requiring significant resources and coordination.

Increased CO₂ emissions lead to global warming, which fuels the frequency and severity of natural disasters, such as wildfires, floods, droughts, and hurricanes. The U.S. National Centers for Environmental Information (NCEI) report that climate-related disasters in the U.S. alone have caused over \$2.780 trillion in damages between 1980 and 2024 (NCEI 2024)

Silica gel has a high surface area, ranging from 300 to 800 m²/g, which can absorb large amounts of CO₂; the high surface area increases its capacity to capture and hold CO₂ (Ruthven, 1984). Silica gel is thermally stable at high temperatures, making it suitable for industrial implementation and ensuring structural integrity and adsorption (XU 2018). The storage of this gel is significantly low; silica gel can be easily regenerated by applying heat or reducing pressure, allowing the CO₂ to be released. Economic feasibility and Reusability is crucial for optimizing storage, as they help reduce the amount of space required (Choi 2009). Silica gel is relatively inexpensive, widely available, and used in many packing items. Silica gel typically ranges from \$1.50 to \$3.00 per kilogram. Zeolite 13X is priced between \$1.00 and \$1.95 per kilogram. Prices for activated alumina range from around \$2.00 to \$4.00 per kilogram. All of these are easily modified via amine-based solutions.

The Artificial Tree, proposed by Klaus Lackner, is designed to mimic the natural process of trees absorbing CO₂ from the air; the structure itself will have a large surface area of absorbent material such as silica gel to capture CO₂ directly. The air passing over the silica gel will capture the CO₂ molecules. The combination of Artificial trees along with silica gel enhances the efficiency of CO₂ capture; the high surface area and adsorption capacity ensure more CO₂ can be captured per unit area of Artificial trees (Choi 2009).

Each Artificial Tree can capture approximately 1 ton of CO₂ per day, about 365 tons of CO₂ per year (Lackner 2010). Deploying 100 million artificial trees could theoretically remove about 36.5 billion tons of CO₂ annually. This is close to global CO₂ emissions of 36.4 billion tons (Global Carbon 2019). Current estimates for Artificial trees using Direct Carbon Capture (DCC) range from 100 to 600 dollars per ton; as Technology advances, these costs will decrease (Fasihi 2019). Energy consumption for DCC is estimated to be 1.5 to 2.5 MWh per ton of CO₂, which can be easily maneuvered through the use of renewable energy, like solar, to minimize carbon footprint (Socolow 2011). Direct extraction of carbon dioxide would allow for carbon management without a need for change in infrastructure (Lackner 1999).

Current CO₂ emissions are around 36.4 billion tons per year; deploying 100 million artificial trees using DCC technology would cost between \$3.65 trillion and \$21.9 trillion annually, with the cost per ton of CO₂ captured ranging from \$100 to \$600. To restore atmospheric CO₂ to pre-industrial levels, an estimated 1 trillion tons of CO₂ would need to be removed, costing between \$100 trillion and \$600 trillion. These estimates do not include the additional infrastructure, maintenance, or energy costs, though renewable energy could mitigate some operational expenses.

Climeworks is a leading DCC company operating power plants with the concept of Artificial Trees; their orca plant in Iceland captures 4000 tons of CO₂ per year, demonstrating a large-scale deployment without infrastructure (Climeworks 2021). Carbon engineering pilot plant in Canada captures 1 ton of CO₂ per day, scaling up to 1 million tons by 2026 (Carbon Engineering 2021). By experimenting with amine-functionalized versions and testing smaller, scalable designs, we can explore a new pathway for improving efficiency use and enhancing economic feasibility compared to large-scale infrastructure. Focusing on optimizing various adsorbent materials for artificial trees instead of a more expensive material. A mature tree will absorb 22 kilograms (48 pounds of carbon) per year on average (Stancil 2015).

Captured CO₂ can enhance oil recovery, making DCC more viable. EOR projects can store 0.2 to 0.4 tons of CO₂ per barrel of oil produced (IEA 2020). CO₂ captured by artificial trees can be converted into synthetic fuels, helping reduce reliance on fossil fuels and contribute to a circular carbon economy (Keith 2018).

Hydrogen Production uses renewable energy to split water into hydrogen and oxygen through electrolysis, facilitating green hydrogen. Hydrogen can react with captured CO₂ to create synthetic hydrocarbons, such as methanol or synthetic fuels (Linde n.d.). Incorporating this process can be valuable for cleaner fuel production, enabling a carbon-neutral cycle. This can mitigate CO₂ emissions by supporting the development of sustainable energy systems by reducing reliance on fossil fuel, which makes up 74% of total emission

CO₂ hydrogenation is the process of turning captured CO₂ into synthetic fuels, such as methanol or methane. This process becomes more reliant on CO₂, creating a circular carbon economy. The process involves combining CO₂ with hydrogen in a reactor using catalysts like nickel or copper, creating carbon-neutral fuels (Ye 2019). This contributes to the long-term sustainability of carbon capture systems, making CO₂ an asset rather than a storage challenge, aligning with current global emissions reduction goals.

The Fischer-Tropsch process is essential to carbon capture research because it converts captured CO₂ and hydrogen into long-chain hydrocarbons. The process converts a mixture of carbon monoxide (CO) and hydrogen (H₂) using metals like iron or cobalt as catalysts. This reaction takes place at high temperatures and pressures, producing long-chain hydrocarbons. In carbon capture, CO₂ is reduced to CO and combined with H₂, producing carbon-neutral synthetic fuels (Bahri n.d.). These can be turned into fuels like diesel and jet fuel, Which can be used in transportation and industry.

Materials

In this experiment, the materials include basic safety equipment such as gloves, goggles, and a lab coat, as well as chemicals like ethanol alcohol (95%), triethanolamine (TEOA), and monoethanolamine (MEA). The absorbent materials used are silica gel, Zeolite 13X, and alumina, which will be functionalized with the amines to enhance their CO₂ capture properties. The methods involve observing CO₂ levels (the dependent variable) throughout the experiment. To measure these levels quantitatively, a CO₂ meter will be used to record the data, providing accurate measurements of the CO₂ captured by the various absorbent materials. This approach allows for clear tracking of the changes in CO₂ concentration, helping to assess the effectiveness of each material in carbon capture.]

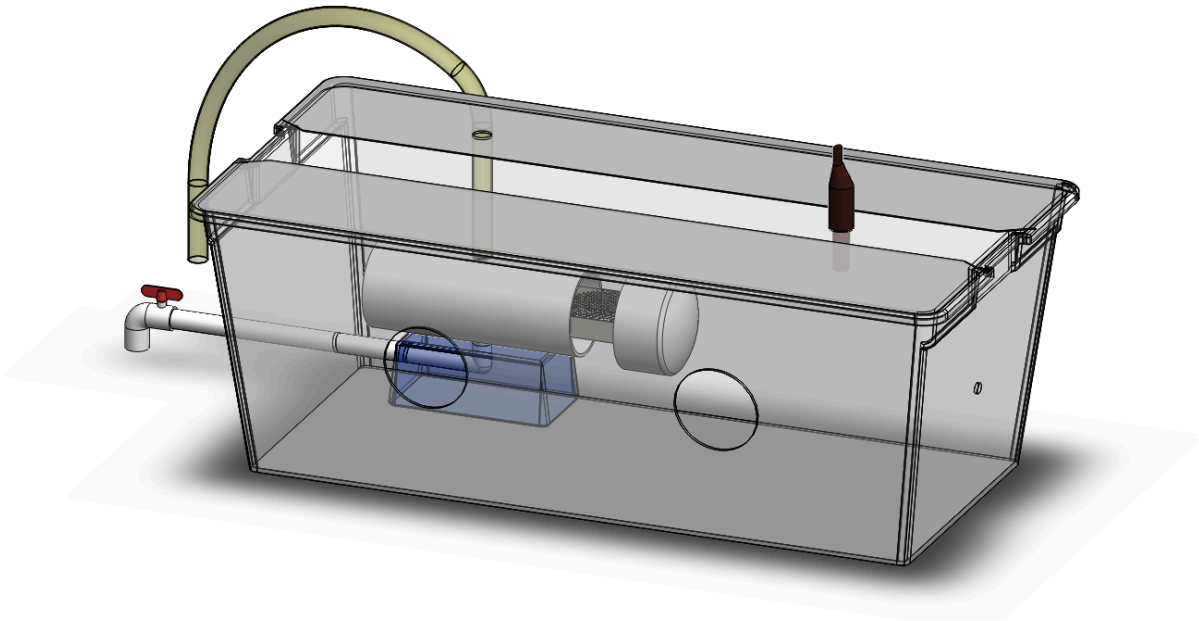


Figure 1: Shows a CAD model of the whole setup for a better view. **Images created by Pretom Chowdhury, unless said otherwise.**



Figure 2: Two holes were drilled into the container's lid. The lid was sanded down to create a rough texture on the indents. Chalk was applied on the top to create an airtight seal once the lid was open, ensuring CO₂ did not escape. Start by obtaining a clear plastic storage container measuring 35 inches in length, 17 inches in width, and 13 inches in height.



Figure 3: Aerial view of the box. Water tube and CO₂ placed in their respective holes.

Create two openings in the container's lid: one with a diameter of 1.125 inches for the CO₂ meter, which will monitor CO₂ levels inside the container, and another with a diameter of 0.625 inches for the water tube that will supply water to the artificial tree and will be secured with glue. On the sides of the box measuring 17 inches, drill a hole with a diameter of 0.5 inches; on the opposite 17-inch side, drill a hole with a diameter of 0.875 inches. The 0.5-inch hole is intended for the tube attached to the CO₂, while the 0.875-inch hole is for the water outlet pipe, allowing water to leave the container. Using glue, secure the CO₂ tank tube and the pipe in their respective holes. A 0.5-inch hole was drilled on the container's side, and the CO₂ tank tube was placed in the hole.

Cad Model:



Figure 4: Gloves taped into the two 4-inch holes on the 35-inch side of the container. These openings allow for the attachment of gloves, which are secured with tape. The gloves enable the opening and closing of the artificial tree during the experiment

Artificial Tree

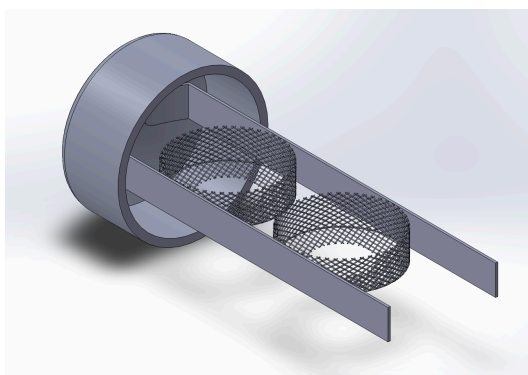
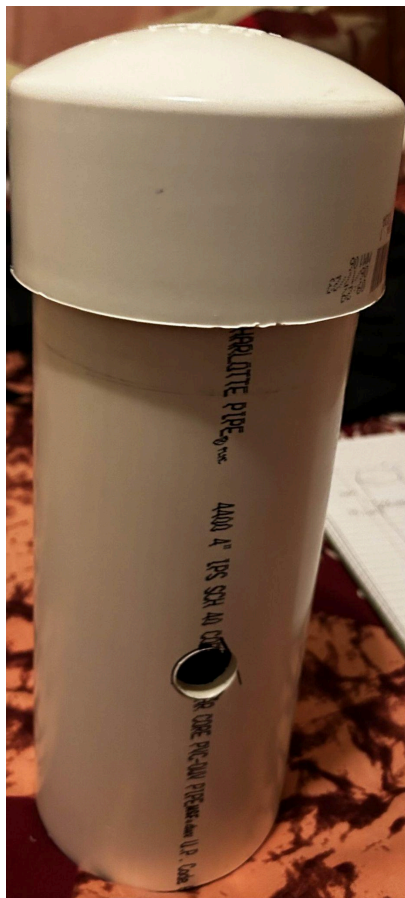


Figure 5 a b: Shows the design of the artificial tree in C.A.D and a photograph

First, select a PVC cap that matches the diameter of a 4-inch PVC pipe. Next, obtain two metal sheets, each measuring 10 inches in length, 1.25 inches in height, and 0.1 inch in width. Secure these sheets to the PVC cap using screws. Then, take a half-inch diameter PVC pipe, 10 inches long, and drill holes throughout its length. Glue this pipe centrally onto the cap. Using metal wire mesh, form a hollow cylinder with a 3.5-inch radius and a 1-inch height. The cost of this design was **\$24**.

Additionally, cut a wire mesh circle with a 3.5-inch radius featuring a central hole 2 inches in diameter. Attach this circle to one end of the cylinder to create a platform for absorbent disks. Construct four such platforms. Finally, these platforms, nuts, and bolts are attached to the metal sheets on the cap. This assembly constitutes the top part of the tree, designed to slide into the tree's bottom part. (Shown Above)

Amine functionalized Disks

Get Silica gel, Zeolite 13X, and Alumina. They must be powdered; grind them into a fine powder if they aren't. Ensuring the substances are clean, dry, and organized in different containers. Dissolve the chosen amine compound into a suitable solvent. The amine compounds that were used in this experiment

were triethanolamine (TEOA) (99%), Monoethanolamine (MEA) (99%), and a mixture of the two. The solvent used was ethyl alcohol (95%). The concentrations used were 20%, of each solution. To make a 20% mix, 20 mL of the amine compound is used for every 82 mL solvent. For the mixture, 10 mL of amine and 82 mL of solvent were used. Store the mixture in flasks for later use. A fume hood and proper safety equipment were worn throughout the use of chemicals. Mix the various solutions in the amine solution, ensuring a homogenous distribution. Allow the substances and solution to mix for at least 24 hours. After fully functionalizing, wash the amine-based substances with distilled water to remove any amine by-products and air dry the product.

After the silica gel had been functionalized and mixed with casting resin, a ratio of 40% resin to 60% substance; for this experiment, a ratio of 10 grams of substance was used, and 4 grams of resin was placed. The mixture was placed into a disk mold with a diameter of 4". After the resin hardened, remove the mold from the petri dishes. After removing the Petri dishes from the mold, drill 16 holes, each with a diameter of 1 millimeter. Sand down the absorbent disk to expose the pores, allowing CO₂ to be captured by the absorbent disks. Shown in Figure 6.



Figure 6: Represents the disks in the tree after it has been sanded down and holes have been drilled.

Data Collection:

A **Vernier Go Direct CO₂ Gas Sensor** was used to measure the amount of CO₂ in the confined space. The container initially contained approximately 30,000 ppm of CO₂. After each 6-hour trial, the machine was closed to create a vacuum seal. Boiling hot water was later pumped through the system to release the CO₂ from the discs, and the amount of CO₂ released was determined through titrations. The

slope formula was used to figure out the absorption rate per hour. To figure out tons per year, use the equation: **Annual CO₂ Capture=Hourly CO₂ Absorbed (mg)×24 hours/day×365 days/year.**

Hypothesis:

The null hypothesis (H₀) states that the artificial tree utilizing amine-functionalized silica gel, zeolite, and alumina will not absorb significantly more CO₂ than traditional carbon capture methods under the same experimental conditions. Conversely, the alternative hypothesis (H₁) suggests that the artificial tree with these materials will absorb significantly more CO₂ compared to conventional carbon capture technologies in a similar setup.

Results:

Trial 1: Silica			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	2798.334	2506.332	6457.668
2 nd hour	1462.000	2631.000	5883.002
3 rd hour	1005.666	1442.664	3484.668
4 rd hour	836.666	1465.000	2373.666
5 rd hour	754.332	1478. 000	1706.666
6 rd hour	736.334	1477.664	1004.332
Trial 2:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	2016.666	2704.000	6736.000
2 nd hour	1145.333	2397.664	6087.002
3 rd hour	907.668	1280.336	3903.000
4 rd hour	734.666	1353.000	2625.666
5 rd hour	629.000	1207.000	2088.666

6 th hour	608.666	1315.665	1312.666
Trial 3:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1904.664	2995.334	6244.000
2 nd hour	1670.336	2535.000	5895.668
3 rd hour	1208.332	1688.668	2599.000
4 th hour	1256.336	1516.332	2424.000
5 th hour	1251.000	1426.000	2309.665
6 th hour	1272.332	1374.000	1672.000
Trial 4:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1463.000	2491.668	6618.666
2 nd hour	1392.668	2217.000	5851.000
3 rd hour	1389.332	1642.332	3380.688
4 th hour	1307.000	1590.332	2816.666
5 th hour	1274.668	1267.332	1520.000
6 th hour	1163.332	1239.332	1320.000

Figure 7: CO₂ absorption rates for TEOA 20%, MEA 20%, and MIX 20% with Silica over six hours across four trials. MIX 20% showed the highest initial capture (up to 6736 PPM), declining sharply, while MEA 20% maintained more stable, moderate absorption. All Data collected and handled by **Pretom Chowdhury**

Trial 1: Zeolite

	TEOA 20%	MEA 20%	MIX 20%
1 st hour	2798.334	5010.029	1589.334
2 nd hour	1462.000	4525.040	1561.000
3 rd hour	1005.666	2852.720	1473.000
4 rd hour	836.666	1490.322	1406.666
5 rd hour	754.332	1355.813	1411.000
6 rd hour	736.334	1256.666	1254.666
Trial 2:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1898.668	4872.000	1955.664
2 nd hour	1710.332	3959.668	1724.332
3 rd hour	1440.668	3795.666	1531.664
4 rd hour	1398.668	3016.332	1482.668
5 rd hour	1239.668	1651.334	1884.332
6 rd hour	1140.334	1631.334	1774.332
Trial 3: Zeolite			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1791.000	4817.336	1621.668
2 nd hour	1531.668	4351.000	1595.332
3 rd hour	1402.332	2743.000	1509.332
4 rd hour	1148.664	1433.002	1523.332

5 rd hour	1297.000	1303.666	1231.664
6 rd hour	1272.332	1238.334	1250.334
Trial 4: Zeolite			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1710.336	4723.332	1801.332
2 nd hour	1453.332	4623.000	1599.332
3 rd hour	1291.000	2506.000	1534.000
4 rd hour	1207.332	2059.332	1380.000
5 rd hour	1257.002	1420.668	1227.000
6 rd hour	1253.332	1263.334	1292.332

Figure 8: CO₂ absorption rates for TEOA 20%, MEA 20%, and MIX 20% using Zeolite as the base over six hours across four trials. MEA 20% displayed the highest initial absorption (up to 5010 PPM), declining gradually, while MIX 20% and TEOA 20% showed moderate and steady absorption throughout.

Trial 1: Alumina			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1071.334	2199.668	2675.336
2 nd hour	723.000	1361.000	2647.000
3 rd hour	706.666	1340.668	2281.668
4 rd hour	642.666	1322.664	1507.000
5 rd hour	674.334	1262.000	1387.668
6 rd hour	653.666	1235.000	1234.668
Trial 2			

	TEOA 20%	MEA 20%	MIX 20%
1 st hour	985.627	2023.695	2461.309
2 nd hour	765.160	1252.120	2435.240
3 rd hour	750.133	1233.415	2099.135
4 th hour	691.253	1216.851	1386.440
5 th hour	691.253	1161.040	1276.655
6 th hour	601.373	1136.200	1135.955
Trial 3:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1007.054	2067.688	2514.816
2 nd hour	679.620	1279.340	2488.180
3 rd hour	664.266	1260.228	2144.768
4 rd hour	604.106	1243.304	1416.580
5 rd hour	603.874	1186.280	1304.408
6 rd hour	614.446	1161.200	1160.588
Trial 4:			
	TEOA 20%	MEA 20%	MIX 20%
1 st hour	1004.767	2089.685	2541.569
2 nd hour	686.850	1292.950	2514.650
3 rd hour	671.333	1273.635	2167.585
4 rd hour	650.533	1256.531	1431.650

5 th hour	640.617	1198.900	1318.285
6 th hour	621.483	1173.250	1172.935

Figure 9: CO₂ absorption rates for TEOA 20%, MEA 20%, and MIX 20% over six hours using Alumina as the base material. MIX 20% consistently showed the highest initial absorption (up to 2675 PPM), gradually declining over time. MEA 20% demonstrated moderate but steady absorption rates, while TEOA 20% had the lowest, showing stable but limited CO₂ capture across trials.

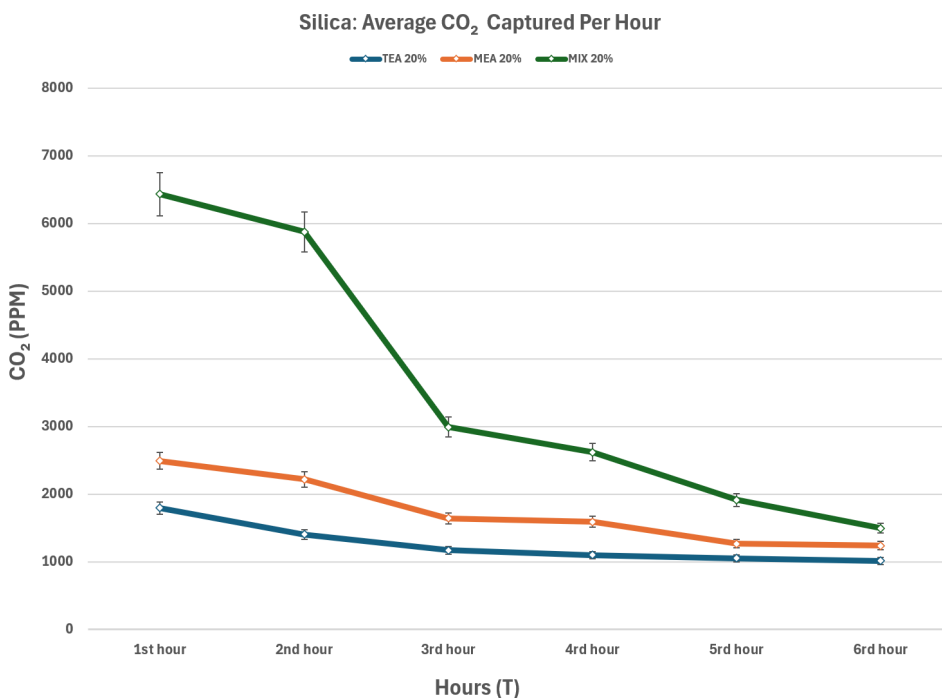


Figure 10: Average CO₂ absorption rates for Silica functionalized with TEA 20%, MEA 20%, and MIX 20% over six hours. MIX 20% showed the highest initial absorption rate, capturing 6431.333 PPM of CO₂ in the first hour, but demonstrated a rapid decline in efficacy, dropping to 1496 PPM by the sixth hour. In contrast, MEA 20% maintained a more stable absorption rate, capturing 2491.668 PPM in the first hour and 1239.332 PPM by the sixth hour. TEA 20% showed the lowest but steady absorption rates, starting at 1794.7767 PPM and gradually decreasing to 1014.7767 PPM by hour six.

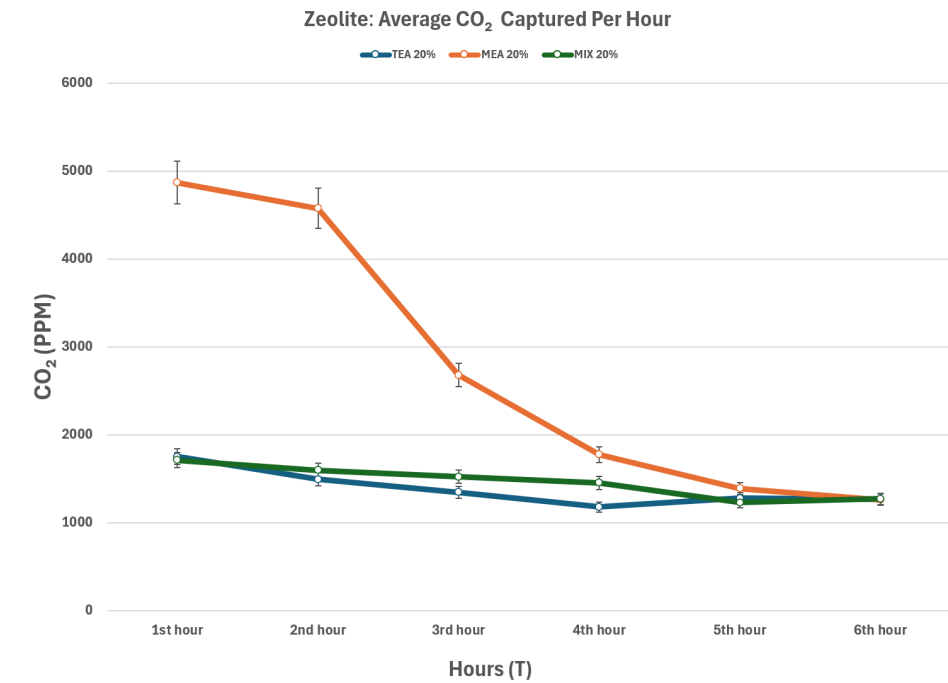


Figure 11: The graph displays the CO₂ absorption rates of Zeolite functionalized with 20% TEOA, MEA, and a MIX over six hours. MEA 20% shows the highest initial rate at 4866.7 PPM, rapidly declining to around 1260 PPM by the sixth hour. TEOA 20% and MIX 20% start lower, at 1750.7 PPM and 1711.5 PPM, respectively, gradually declining to similar levels around 1260–1271 PPM by hour six. This indicates that MEA 20% captures CO₂ more effectively in the short term but levels off over time, while TEOA and MIX maintain steadier, lower rates throughout.

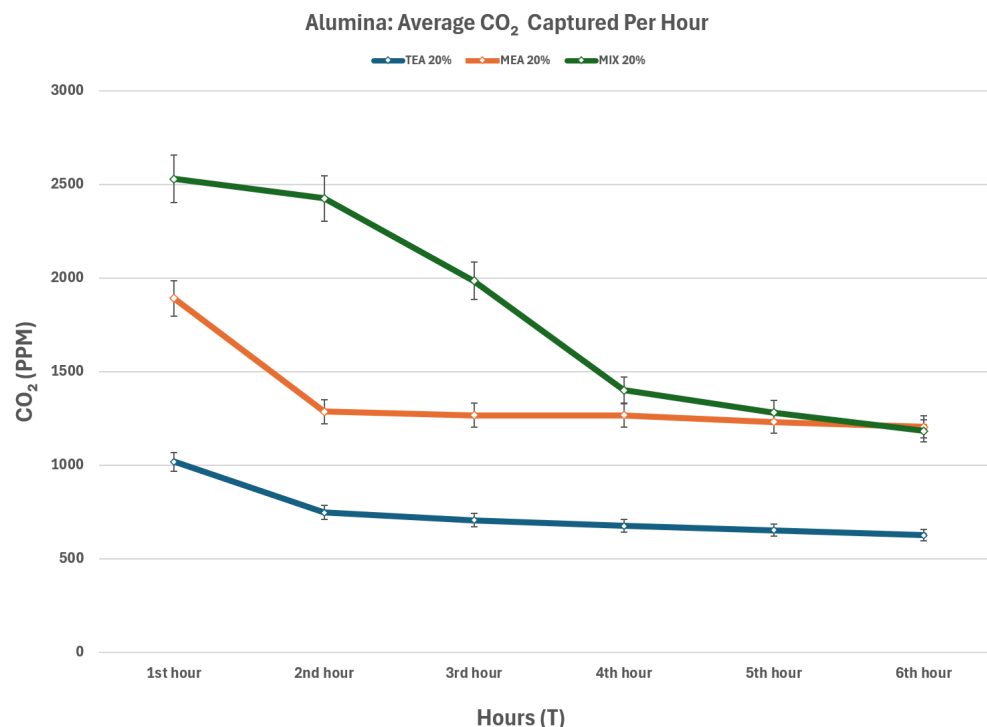


Figure 12: Average CO₂ capture per hour for alumina functionalized with 20% concentrations of TEA, MEA, and MIX, measured over six hours. MIX 20% demonstrated the highest initial CO₂ absorption rate at 2528.36 PPM in the first hour, followed by a rapid decline, reaching 1181.19 PPM by the sixth hour. MEA 20% maintained a more consistent absorption rate, starting at 1891.29 PPM and gradually reducing to 1204.13 PPM by the sixth hour, indicating greater stability over time. TEA 20% had the lowest initial absorption rate at 1017.20 PPM, declining steadily to 625.51 PPM by the sixth hour. Error bars represent standard deviation across trials, illustrating variability in absorption performance.

Anova: Two-Factor Without Replication						Anova: Two-Factor Without Replication						Anova: Two-Factor Without Replication								
SUMMARY	Count	Sum	Average	Variance		Count	Sum	Average	Variance		SUMMARY	Count	Sum	Average	Variance					
1st hour	3	10717.78	3572.593	6250712		1st hour	3	8328.849	2776.283	3277705		1st hour	3	5436.851	1812.284	575588.9				
2nd hour	3	9493.113	3164.371	5669599		2nd hour	3	7663.852	2554.617	3061238		2nd hour	3	4454.975	1484.992	733880.5				
3rd hour	3	5800.62	1933.54	892976.1		3rd hour	3	5547.692	1849.231	524492.3		3rd hour	3	3954.696	1318.232	410906.2				
4rd hour	3	5309.999	1770	602569.8		4th hour	3	4404.491	1468.164	89255.34		4th hour	3	3340.842	1113.614	148811.2				
5rd hour	3	4233.721	1411.24	201843.7		5th hour	3	3894.574	1298.191	6649.745		5th hour	3	3161.985	1053.995	121868.7				
6rd hour	3	3750.109	1250.036	57979.91		6th hour	3	3794.165	1264.722	34.78735		6th hour	3	3010.818	1003.606	107350.6				
TEA 20%	6	7531.666	1255.278	88803.52		TEA 20%	6	8307.665	1384.611	43235.31		TEA 20%	6	4420.598	736.7664	20627.26				
MEA 20%	6	10448	1741.333	259709.2		MEA 20%	6	16543.13	2757.188	2567503		MEA 20%	6	8142.229	1357.038	69342.25				
MIX 20%	6	21325.68	3554.279	4354119		MIX 20%	6	8782.829	1463.805	34940.12		MIX 20%	6	10797.34	1799.557	353400				
ANOVA						ANOVA					ANOVA									
Source of Variation	SS	df	MS	F	P-value	F crit	Source of Varia	SS	df	MS	F	P-value	F crit	Source of Varia	SS	df	MS	F	P-value	F crit
Rows	13778665	5	2755733	2.830895	0.07585	3.325835	Rows	6435803	5	1287161	1.894948	0.182264	3.325835	Rows	1440201	5	288040.2	3.708769	0.036951	3.325835
Columns	17616868	2	8808434	9.048682	0.00571	4.102821	Columns	7126160	2	3563080	5.245539	0.027681	4.102821	Columns	3420166	2	1710083	22.0188	0.000217	4.102821
Error	9734494	10	973449.4				Error	6792591	10	679259.1				Error	776646.5	10	77664.65			
Total	41130027	17					Total	20354553	17					Total	5637013	17				
Silica							Zeolite							Alumina						

Figure 13: Figure 9 shows the ANOVA statistical results for CO₂ absorption rates of Silica, Zeolite, and Alumina functionalized with TEOA 20%, MEA 20%, and MIX 20% over six hours. The p-values for the

columns were **0.02768** for Zeolite, **0.00571** for Silica, and **0.000217** for Alumina, indicating **statistically significant** differences in CO₂ absorption based on the type of adsorbent used.

Discussion:

In the four trials conducted for Silica, the absorption rates of CO₂ were measured over six consecutive hours. Across all trials, MIX 20% consistently demonstrated the highest initial absorption rate. For instance, in Trial 1, MIX absorbed 6457.668 PPM of CO₂ in the first hour, significantly outperforming TEA (2798.334 PPM) and MEA (2506.332 PPM). However, this initial high performance was followed by a rapid decline in absorption efficiency, with MIX dropping to 5883.002 PPM in the second hour and further down to 1004.332 PPM by the sixth hour. This steep decline suggests that while MIX 20% is highly effective for short-term CO₂ capture, it saturates quickly, limiting its effectiveness for long-term absorption.

In contrast, MEA 20% demonstrated more consistent absorption throughout the trials. Although it initially did not capture as much CO₂ as MIX 20%, MEA maintained relatively steady absorption rates over time. For example, in Trial 3, MEA absorbed 2995.334 PPM in the first hour and continued to capture 1374.000 PPM by the sixth hour, showcasing its ability to sustain CO₂ capture more effectively over longer periods. TEA 20%, meanwhile, showed moderate absorption rates, generally falling between MIX and MEA. However, TEA's performance fluctuated between trials, particularly in Trial 2, where its first-hour absorption dropped to 2016.666 PPM, compared to 2798.334 PPM in Trial 1, indicating that TEA may be more sensitive to external variables.

Silica has the potential to be a CO₂ absorbent. The data in Figure 1 Indicates that MIX 20% is highly efficient for rapid, short-term CO₂ capture but loses effectiveness quickly, making it less suitable for extended use when using silica-based materials. MEA 20%, on the other hand, shows the most reliable long-term performance, maintaining steady absorption rates over several hours. TEA 20% offers a balance between the two, with moderate and somewhat variable performance across the trials. Future research should focus on optimizing the long-term performance of MIX 20%, by adjusting the concentration or modifying its application to improve stability over extended periods.

Throughout the trials for Zeolite 13X, MEA 20% consistently demonstrated the highest CO₂ absorption, particularly in the first hour. For example, in Trial 1, MEA absorbed 5010.029 PPM of CO₂ in the first hour, significantly outperforming TEOA (2798.334 PPM) and MIX (1589.334 PPM). However, after the first hour, a noticeable decline was observed in the absorption rates for all three chemicals. In Trial 2, MEA dropped from 4872.000 PPM to 3959.668 PPM in the second hour, though it remained the most efficient absorbent overall, showing better retention of CO₂ capture throughout the trials.

Zeolite TEOA 20%, while not as efficient as MEA, demonstrated moderate performance, maintaining steady absorption over time. In Trial 3, TEOA absorbed 1791.000 PPM in the first hour and 1272.332 PPM by the sixth hour, showcasing a gradual but consistent decline. On the other hand, MIX 20% consistently had the lowest absorption rates, starting with 1589.334 PPM in Trial 1 and experiencing a steady decline across all trials. Despite this, MIX showed a relatively steadier drop than TEOA, which remained the least effective solution across the six-hour duration.

The data from the Zeolite trials indicate that MEA 20% is the most effective absorbent for CO₂ capture, maintaining the highest initial absorption rates and consistent performance over time. TEOA 20% balanced initial absorption and steady retention, while MIX 20% was the least effective. Future research could explore optimizing MEA concentrations and further refining the experimental setup to improve the consistency and performance of CO₂ capture.

In the four trials conducted using Alumina, the CO₂ absorption capabilities were measured over six hours. Across all trials, MIX 20% consistently demonstrated the highest initial absorption rates, absorbing 2675.336 PPM of CO₂ in the first hour of Trial 1, followed by MEA 20% with 2199.668 PPM, and TEOA 20% with 1071.334 PPM. However, after the first hour, a noticeable decline in CO₂ absorption was observed for all three chemicals. MIX 20%, which performed the best initially, fell to 2647.000 PPM in the second hour of Trial 1 and continued to decline steadily throughout the trials.

Zeolite MEA 20% consistently outperformed TEOA 20% across all trials, particularly in the first few hours. For example, in Trial 2, MEA absorbed 2023.695 PPM in the first hour compared to TEOA's 985.627 PPM. Despite this, MEA also experienced a steady drop in absorption over time, with significant reductions by the fourth and fifth hours. TEOA 20% had the weakest overall performance, starting with the lowest absorption rates and gradually declining throughout each trial.

Across all trials for Alumina, MIX 20% consistently demonstrated the highest initial absorption rates, absorbing 2675.336 PPM of CO₂ in the first hour of Trial 1, followed by MEA 20% with 2199.668 PPM, and TEOA 20% with 1071.334 PPM. However, after the first hour, a noticeable decline in CO₂ absorption was observed for all three chemicals. MIX 20%, which performed the best initially, fell to 2647.000 PPM in the second hour of Trial 1 and continued to decline steadily throughout the trials.

Alumina MEA 20% consistently outperformed TEOA 20% across all trials, particularly in the first few hours. For example, in Trial 2, MEA absorbed 2023.695 PPM in the first hour compared to TEOA's 985.627 PPM. Despite this, MEA also experienced a steady drop in absorption over time, with significant reductions by the fourth and fifth hours. TEOA 20% had the weakest overall performance, starting with the lowest absorption rates and gradually declining throughout each trial.

By Trial 4 for Alumina, all chemicals showed lower initial absorption rates than Trial 1, with MIX 20% absorbing 2541.569 PPM in the first hour, down from 2675.336 PPM in the first trial. This

trend of declining absorption across trials suggests potential material saturation or experimental variability, indicating that further optimization is needed to improve the consistency and efficiency of the process.

When used with alumina, alumina MEA 20% and MIX 20% showed better initial CO₂ absorption than TEOA 20%. However, the rapid decline in absorption after the initial hours suggests that while these solutions have strong initial performance, they may not maintain efficacy over longer periods. Future research should focus on optimizing the stability and longevity of these solutions to enhance CO₂ absorption over extended periods. Adjusting amine concentrations or increasing the surface area of the absorbent materials could further improve their performance.

Climeworks, one of the leaders in carbon capture technology, uses a direct air capture (DAC) system that primarily relies on amine-functionalized filters similar to the ones used in this experiment. Climeworks reports capturing around 900 tons of CO₂ annually with large-scale facilities such as Iceland's "Orca" plant. Their system captures CO₂ at approximately 1,000 kg CO₂ per day per module (Rivero 2024), indicating a significantly larger scale compared to the smaller experimental setup used in this study. Climeworks utilizes solid sorbents that are also amine-based, and the captured CO₂ is released by heating the filter to about 100°C.

Carbon Engineering uses a different approach with liquid solvent-based direct air capture technology, which absorbs CO₂ into a solution where it forms a carbonate. Based in Canada, their facility is reported to capture 1 million tons of CO₂ annually (Carbon Engineering 2022). This method, though effective, involves significantly more complex infrastructure and higher operational costs compared to smaller, solid-based systems like the ones tested here.

In the experiments with silica sorbents, the performance varied between 736 mg(TEA) (Mg=PPM) and 6,457 mg (MIX) of CO₂ captured per hour. In comparison, Climeworks' system, which uses a similar amine-based solid sorbent system, captures around 1 kg (1,000,000 mg) per hour. However, it's important to note that Climeworks' design is much larger and involves considerable infrastructure. Given the smaller and cheaper design of the experimental setup, the silica sorbents show promising potential for scalability if the design is expanded.

Zeolite has been widely studied for its adsorption capabilities, and the experimental data here indicate CO₂ absorption ranging between 736 mg (TEOA) to 5,010 mg (MEA) in the first hour. Zeolites are used in some carbon capture systems due to their high surface area and affinity for CO₂. However, they are generally outperformed by advanced amine systems, like those used by Global Thermostat, another DAC company that uses zeolites in combination with amines to capture CO₂. Their hybrid approach captures thousands of tons of CO₂ annually, showing how zeolites can be integrated into larger systems to enhance performance.

Alumina-based sorbents demonstrated lower overall absorption capacity than silica and zeolite, with a maximum of around 2,675 mg (MIX) in the first hour. Although alumina is not commonly used as a primary sorbent in commercial DAC systems, it has been explored as a supporting material due to its thermal stability. The performance in these experiments suggests that while alumina may not be the most effective standalone sorbent for CO₂ capture, its durability and cost-effectiveness could make it useful in hybrid systems, especially when paired with more active sorbents like amines ((Lara & Romeo, 2017)

The results of this study suggest that smaller, modular carbon capture machines, such as those tested with silica, zeolite, and alumina-based materials, offer a practical and scalable solution for carbon sequestration in urban environments. Given that these designs are significantly smaller and cheaper than large-scale industrial carbon capture infrastructure, their deployment throughout neighborhoods could create a decentralized network of carbon-capturing units. This approach could remove carbon dioxide directly from residential areas, improving air quality and contributing to localized climate mitigation efforts.

Additionally, the decentralized nature of this approach allows for flexible implementation across various environments. By placing these smaller machines in residential neighborhoods, near schools, parks, and industrial zones, it would be possible to directly reduce the carbon footprint in areas where emissions are generated. The cumulative effect of multiple units could rival or even exceed the CO₂ capture capacities of larger installations when scaled across a city or region. For example, a network of 100 small machines deployed in a dense urban area could remove significant amounts of CO₂ daily, comparable to larger industrial plants, while also providing localized benefits (Shadman 2022)

The experimental setup was designed for small-scale application, with each unit capturing CO₂ at rates that would necessitate networked deployment for meaningful impact. For example, a single silica-based unit absorbed an average of 4000 mg CO₂ per hour, as shown in figure 10. Assuming consistent performance (factoring in saturation over time), deploying 100 units could capture approximately 400 grams of CO₂ per hour or around 3.8 metric tons annually if operated continuously. For widespread urban application, deploying 100 units would cost approximately \$2400. Operational costs for disc replacement every 6 months add up to \$3.60 annually per unit. This is due to the gradual decline in absorption over time, making frequent replacements less necessary.

If 100 small machines are placed across residential areas, industrial zones, and high-traffic areas, they can help to reduce CO₂ concentrations in air pollution hotspots, contributing to cleaner air and healthier environments. Assuming the cost of operating smaller machines is significantly lower than large-scale projects (as production and installation are cheaper), the cost per ton of CO₂ captured could be reduced. Initial estimates suggest it could fall below \$100 per ton, making it a more viable option for widespread urban use.

The operational costs for the carbon capture system, based on discs priced at \$1.80 for every 4 discs, with replacements required every two months, amount to \$3.60 per year (operational costs). Using data from the Silica TEA 20% trial, the system captures approximately 0.01167 tons of CO₂ annually.

Using the equation $\frac{\text{Operational cost}}{\text{CO}_2 \text{ Captured per ton}} = \text{Total cost}$. By dividing the total operational cost by the amount of CO₂ captured annually, this equation clearly measures cost-effectiveness per ton captured, enabling a direct comparison with larger carbon capture systems. The cost per ton of CO₂ captured is approximately \$308.48 without a higher surface area disc. This is within the typical \$100 to \$600 per ton achieved by larger industrial carbon capture systems. This machine's strength lies in its low upfront costs, reusability of materials, and potential for decentralized use in residential or urban settings where large-scale infrastructure might be feasible.

The artificial tree design presents significant potential for scalable deployment in urban and industrial settings, directly addressing localized CO₂ emissions. To maximize its efficiency and reduce operational costs, several strategies can be employed. Enhancing the surface area of absorbent disks, potentially through 3D printing or microstructural modifications, could significantly improve CO₂ absorption rates. This would allow each unit to capture more CO₂ without requiring additional materials or larger physical footprints. Furthermore, introducing hybrid sorbents combining silica, zeolite, and alumina with advanced materials could enhance absorption capacity and longevity. Optimizing the functionalization process with more stable and reactive amine compounds could further reduce saturation rates and extend the reusability of the sorbents.

Improving the regeneration efficiency of the system is another critical area for development. The current boiling water method could be enhanced by integrating waste heat recovery systems or renewable energy sources, such as solar thermal panels, to lower energy consumption. Deploying units in an automated networked configuration with smart sensors to monitor CO₂ levels and trigger regeneration cycles as needed could further optimize energy use and minimize maintenance costs. These advancements would significantly enhance the cost-effectiveness and environmental sustainability of the design.

Biological integration offers another promising avenue for future research. Incorporating bioengineered materials, such as algae-based systems, and artificial trees could allow captured CO₂ to be used for photosynthesis or converted into valuable bioproducts. This approach would promote a circular carbon economy, transforming the captured CO₂ into an asset rather than a storage challenge. The system could evolve into a versatile tool for tackling carbon emissions by exploring these technological and biological integrations.

Conclusion:

This research aimed to evaluate the effectiveness of silica gel, zeolite, and alumina as adsorbent materials for CO₂ capture in artificial trees, comparing their performance under controlled conditions. Four trials collected and analyzed data on the CO₂ absorption rates of each material when functionalized with amine-based compounds—TEOA, MEA, and a MIX of both. My findings highlight the potential of these materials to serve as cost-effective alternatives to larger-scale carbon capture systems, with notable variability in performance across the adsorbents and chemical functionalizations. Zeolite 13X consistently demonstrated the highest initial absorption rates, particularly when paired with MEA 20%, while silica and alumina showed moderate performance. However, a common trend observed across all trials was the decline in absorption rates after the first few hours, indicating the potential for saturation or material limitations.

While the smaller-scale design performed at a lower capacity than industrial systems like those employed by Climeworks and Carbon Engineering, it offers a more affordable and scalable approach for urban deployment. The relatively low production and operation costs and the flexibility to deploy these units in urban areas make them a promising tool for localized carbon capture. With future optimizations in material longevity, surface area, and chemical functionalization, artificial trees utilizing silica, zeolite, and alumina-based materials could significantly contribute to global carbon capture efforts. Thus, we reject the null hypothesis and accept the alternative hypothesis, confirming that these adsorbent materials can be viable candidates for efficient CO₂ capture in small-scale, decentralized applications.

Future improvements to the modular artificial tree design could focus on recycling and reusability to further reduce costs and environmental impact. By incorporating recyclable materials or developing more efficient chemical regeneration protocols, the absorbent disks could have extended lifespans, reducing the frequency and cost of replacements. Additionally, designing smaller, portable units could expand the technology's application to dynamic environments such as public transportation hubs or construction sites, significantly broadening its impact.

Cost reductions through mass production and collaboration with government and industry stakeholders would further enhance the accessibility of these units. Economies of scale could make this technology affordable for residential deployment, allowing communities to install artificial trees in neighborhoods, schools, and parks. Incentives such as government subsidies or carbon credit programs could encourage widespread adoption and transform this technology into a practical tool for localized carbon capture.

Integrating this system with renewable energy sources, such as wind or solar power, could enhance operational efficiency and sustainability. The design could maintain its low environmental footprint by ensuring that the energy required for regeneration and maintenance is carbon-neutral. With

these advancements, modular artificial trees could become a cost-effective and scalable solution for combating climate change, contributing to a decentralized network of carbon capture systems with global impact.

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