Cyanobacteria & Atmospheric Carbon Capture: The Design and Potential of the CynoFilter, by Akshay Kotibhaskar

1. Abstract

Climate change and the rise in atmospheric carbon dioxide (CO_2) levels have necessitated the development of effective and scalable carbon capture technologies. This paper explores the integration of cyanobacteria, photosynthetic microorganisms, as a nature-based solution to sequester atmospheric CO_2. *Cyanobacteria's* innate ability to perform photosynthesis efficiently positions them as an ideal candidate for biological CDR (Carbon Dioxide Removal) systems.

This research presents the **CynoFilter**, a fully designed modular filtration system that immobilizes cyanobacteria in a sodium alginate matrix to maximize CO_2 absorption. The complete structural and functional model has been developed, incorporating engineered enhancements such as optimized gas exchange, controlled environments, and modular scalability. While experimental validation has not yet been conducted, a structured testing methodology has been outlined, detailing the required sensors, cyanobacterial strains, equipment, and evaluation framework.

Additionally, extensive research into existing studies has been conducted to determine the most effective strains for CO_2 sequestration, their carbon fixation rates, and their viability in the proposed system. Following testing, the next stage will involve refining the design based on findings and developing a working prototype for real-world implementation. By integrating biological efficiency with engineered solutions, the CynoFilter offers a promising approach for atmospheric CO_2 reduction while laying the foundation for future experimental validation and scalability.

2. Introduction

2.1 Climate Change and the Need for Carbon Capture

Over the past century, anthropogenic activities such as industrialization, deforestation, and the burning of fossil fuels have caused a sharp rise in CO_2 concentrations, from pre-industrial levels of 280 ppm to over 410 ppm today **[1]**. This escalation has led to a global increase in temperatures, rising sea levels, and ecosystem disruption. The IPCC projects that CO_2 concentrations must be reduced to below 350 ppm to stabilize global temperatures and limit warming to 1.5°C above pre-industrial levels **[2]**.

Existing carbon capture approaches fall into two categories: engineered systems, such as chemical absorption and geological sequestration, and nature-based solutions (NBS) like afforestation and soil carbon sequestration. While engineered systems can achieve high efficiency, they are often resource-intensive and costly **[3,4]**. Conversely, NBS are more sustainable but frequently face scalability constraints **[5]**. This paper explores a hybrid approach: leveraging the biological efficiency of *cyanobacteria* within an engineered modular system to provide a scalable and cost-effective carbon sequestration solution.

2.2 Research Question and Objectives

The purpose of this study is to design, plan, and optimize a bioengineered filtration system, the CynoFilter, that utilizes *cyanobacteria* to capture atmospheric CO_2. The system has been fully conceptualized, incorporating a modular hexagonal tray design, a sodium

alginate immobilization matrix, and enhancements such as forced airflow and optimized lighting conditions.

While experimental testing has yet to be conducted, this research establishes a detailed methodology for future validation, including:

- **Selection of *cyanobacterial* strains** based on existing research, analyzing their carbon fixation rates and environmental resilience.
- **Specification of required sensors and equipment** to measure CO_2 uptake, oxygen output, and system efficiency.
- **Development of a structured testing framework** to assess strain viability, system durability, and potential for large-scale deployment.

Additionally, a comparative analysis of existing studies on *cyanobacteria*-based carbon capture has been conducted, identifying key performance metrics and informing the selection of strains and system parameters for optimal efficiency. After testing, insights will be used to refine the design and transition toward the development of a working prototype.

By bridging biological efficiency with engineered solutions, the CynoFilter aims to provide a sustainable and scalable method for atmospheric CO_2 removal. This research lays the foundation for future experimental validation, industrial applications, and potential large-scale deployment.

3. Scientific Background

3.1 The Carbon Sequestration Potential of Cyanobacteria

Cyanobacteria are ancient photosynthetic microorganisms that have played a crucial role in atmospheric CO_2 regulation for over 2.5 billion years **[6]**. Their ability to convert CO_2 into organic biomass using oxygenic photosynthesis makes them a promising tool for carbon dioxide removal (CDR) **[7]**. Unlike terrestrial plants, which are limited by space, nutrient availability, and slow growth rates, *cyanobacteria* are highly adaptable, with some strains thriving in extreme environments such as deserts and polar regions **[8]**.

A key advantage of *cyanobacteria* is their carbon-concentrating mechanisms (CCMs), which allow them to actively uptake CO_2 and convert it into bicarbonate, enhancing photosynthetic efficiency **[9]**. Some genetically optimized strains have demonstrated CCM efficiency improvements of over 40%, further increasing their potential for industrial-scale carbon capture **[10]**.

3.2 Efficiency Comparison: Cyanobacteria vs. Trees

Afforestation remains a widely recognized carbon sequestration strategy, but trees require decades to reach maturity and their efficiency is constrained by environmental factors. A mature tree absorbs approximately 22 kg of CO_2 per year **[11]**.

By contrast, *Synechococcus elongatus* PCC 7942 has been shown to fix CO_2 at rates of approximately 5.4 g CO_2 per g biomass per day under optimized conditions **[12]**. Over one year, 1 kg of *Synechococcus elongatus* biomass could sequester up to 1,971 kg of CO_2, making it nearly 90 times more effective than a tree on a per-mass basis. Additionally, a $2m^2$ unit of immobilized *cyanobacteria* in an engineered bioreactor could match the CO_2 capture of an entire acre of trees **[13]**.

3.3 Immobilization in Sodium Alginate for Optimized Performance

Sodium alginate, a biopolymer derived from brown algae, has been widely studied for its ability to encapsulate microbial cells while allowing gas exchange **[14]**. When crosslinked with calcium chloride, it forms a semi-permeable gel matrix that stabilizes *cyanobacteria* and protects them from environmental stressors such as pH fluctuations and microbial contamination **[15]**.

Studies have demonstrated that immobilization improves carbon sequestration efficiency. Encapsulated *Synechocystis sp. PCC 6803* maintained CO_2 fixation rates 20–30% higher than free-living cells over extended periods **[12]**. Similarly, immobilized *Spirulina platensis* sustained productivity at 85–90% efficiency even under fluctuating environmental conditions **[13]**.

While previous studies have applied *cyanobacteria* immobilization in photobioreactors for liquid-phase CO_2 absorption, its application for direct atmospheric carbon capture remains unexplored. The CynoFilter introduces a novel approach by developing a modular system that immobilizes *cyanobacteria* in sodium alginate to capture airborne CO_2 efficiently **[16]**.

3.4 Key Challenges and Considerations

While *cyanobacteria* present significant potential for CDR, several challenges must be addressed for large-scale deployment:

- **Contamination Risks** – *Cyanobacteria* often compete with other microorganisms such as algae, fungi, and bacteria, which can reduce their efficiency. Immobilization in alginate provides a partial barrier, but additional measures such as HEPA filtration may be required **[17]**.
- **Environmental Sensitivity** – Optimal growth conditions vary between strains, with many requiring temperatures between 25–35°C. Deviations can reduce CO_2 fixation rates by up to 50% **[18]**.
- **Toxin Production** – Some *cyanobacteria* produce secondary metabolites that may impact long-term system stability. Selecting non-toxic strains and incorporating regular monitoring can mitigate this risk **[19]**.
- **Scalability and Energy Costs** – Most *cyanobacteria*-based CO_2 capture systems rely on liquid-phase photobioreactors, which require continuous aeration and high energy inputs. The CynoFilter aims to address this by using passive air filtration, but further testing is required to validate its real-world efficiency **[16]**.

4. Design of the CynoFilter

The CynoFilter is intended to be a modular, scalable filtration system designed to maximize CO_2 capture efficiency. The design draws inspiration from natural systems and incorporates several engineering principles to enhance performance. However, it is important to note that – while we have developed a life-size model - this design is currently conceptual and will require iterative testing and refinement, as well as the construction of a functional prototype shortly.

4.1 Hexagonal Tray Design

The choice of a hexagonal structure is inspired by the geometry of honeycombs, which are proven to be the most efficient way to partition a plane into regions of equal area with

minimal total perimeter, as formalised in the honeycomb conjecture and rigorously proven by Hales (1999). This property ensures a high surface-area-to-volume ratio and structural efficiency **[18]**. A hexagonal design provides the following advantages:

- Maximized Surface Area: The greater surface area facilitates increased gas exchange and CO_2 exposure.
- Material Efficiency: Hexagonal grids minimize the use of materials while maintaining structural integrity.
- Scalability: Individual hexagonal trays can be stacked or replaced, enabling modular scalability.

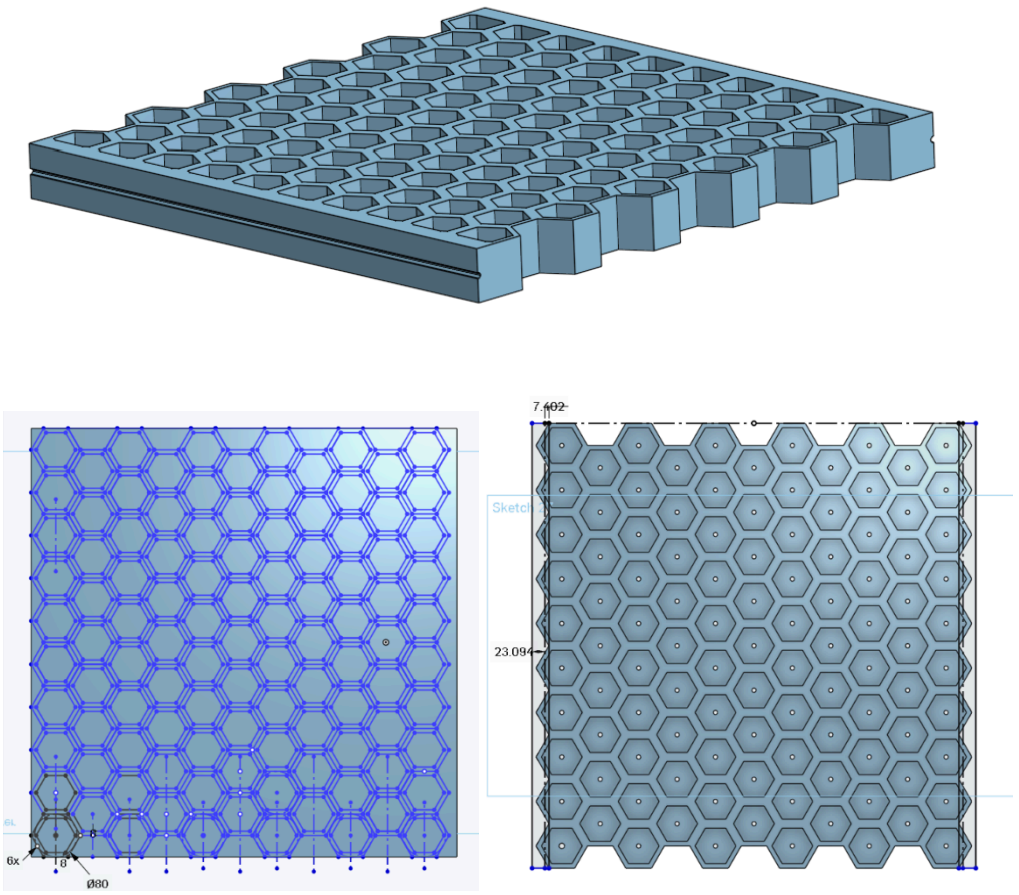

Fig 1: CAD Rendered Tray Design

To address manufacturing challenges, the hexagonal design was adjusted to fit within an 800x800 mm square casing for ease of production and assembly. Each side of the structure can now be produced in batches, and components can slide into place, providing a seamless build and replacement system.

Research in bioreactor design highlights that hexagonal compartments optimize gas diffusion and microbial activity compared to rectangular or circular alternatives **[19]**. The square casing simplifies production and reduces costs without compromising efficiency.

4.2 Sodium Alginate Matrix

Each hexagonal compartment is filled with a sodium alginate matrix encapsulating the cyanobacteria. Sodium alginate ensures:

- Controlled Environment: Allows nutrient and gas exchange while protecting cyanobacteria from mechanical stress **[4]**.
- Durability: Maintains structural stability over prolonged use.

4.3 Filters

The outer shell of the CynoFilter is equipped with high-efficiency particulate air (HEPA) filters at both ends to prevent the ingress of harmful pathogens. This design ensures:

- Controlled Environment: By blocking airborne bacteria, fungi, and viruses, the HEPA filters maintain a sterile environment, preventing rapid population decline of the cyanobacteria.

Example Model: The "Portable Air Purification System" by Zandair[1], for instance, utilizes HEPA filters to effectively remove airborne pathogens, ensuring a contaminant-free environment **[16]**.

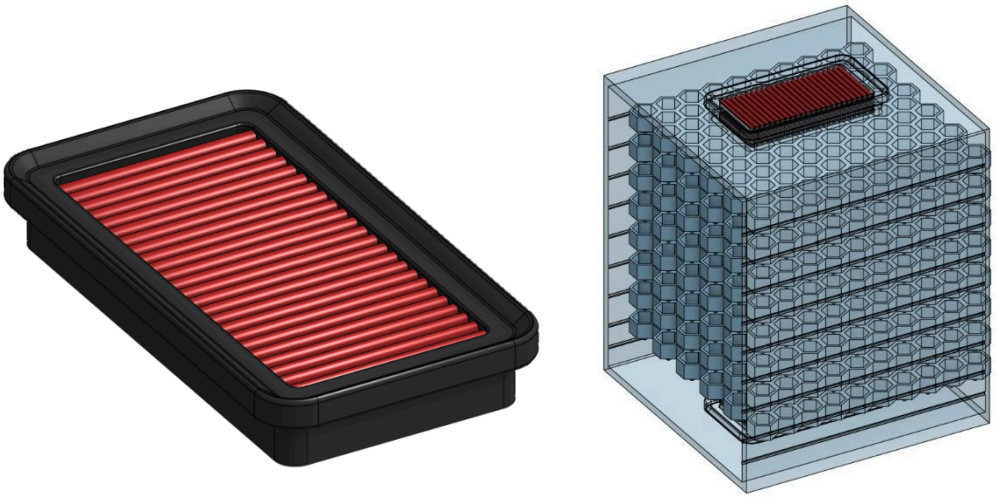

Fig 2: HEPA Filters

4.4 Membranes

To securely house the *cyanobacteria* and sodium alginate matrix within each hexagonal module, an ultra-fine membrane is placed beneath each layer to retain the solution.

Additionally, since certain *cyanobacteria* strains may produce trace amounts of toxins over time, this membrane prevents such substances from contaminating lower layers, thereby maintaining overall system efficiency. However, acknowledging inevitable long-term membrane deterioration, the trays are designed for periodic replacement to ensure sustained performance.

Example Model: Research on immobilizing yeast and bacterial cells in alginate microbeads coated with silica membranes has demonstrated the effectiveness of such membranes in retaining encapsulated solutions and preventing leakage **[15]**.

4.5 Modularity and Replacements

The trays are designed to slide into pre-grooved slots within a square modular housing, ensuring ease of manufacturing, assembly, and maintenance. Each tray can be replaced individually without disrupting system operation **[10]**.

[1] ZANDAIR™ 100P Portable Air Purification System

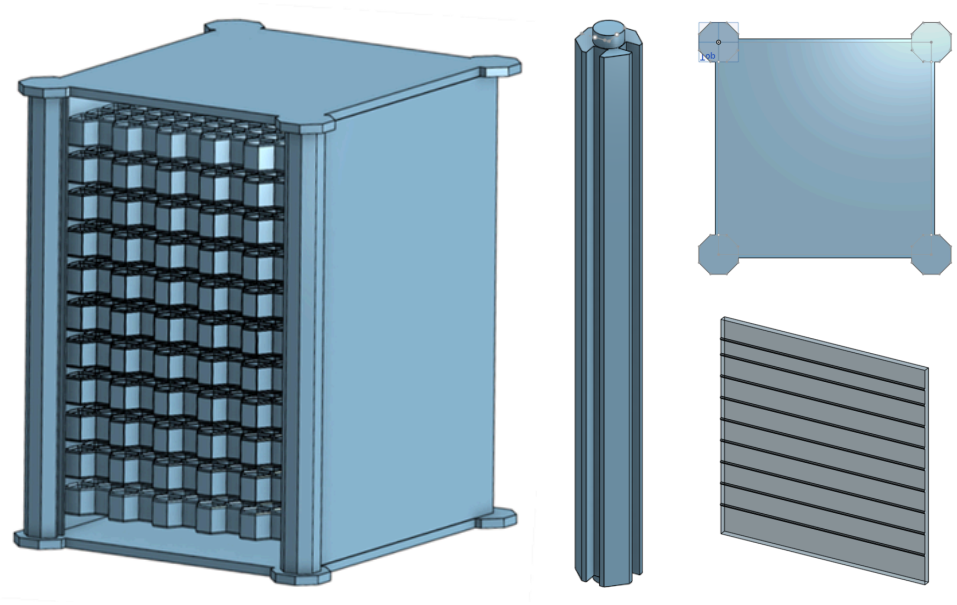

Fig 3: Assembly Components

4.6 Additional Enhancements

The current design of the *CynoFilter* , while productive, is not our final destination. There are an abundance of supplemental features we intend on incorporating into future designs. The most notable of which are the following:

- **Forced airflow system**
  - To optimize CO_2 exposure across the trays, air channels, integrated into the system, ensure uniform distribution of the inflowing gas, while maintaining low energy requirements.
  - Airflow models in similar bioreactors have shown that directed, uniform gas flow significantly improves mass transfer rates, enhancing overall CO_2 sequestration **[11]**.

- **Blue and Red LEDs**
  - LEDs are included for supplemental lighting to enhance photosynthesis, particularly under low-light conditions.
  - Research indicates that cyanobacteria achieve optimal photosynthetic efficiency under blue and red wavelengths of light **[11]**.

- **Cross Linking Agents**
  - To improve the mechanical strength and permeability of the alginate matrix, cross-linking agents such as polyethylene glycol (PEG) and chitosan coatings can be incorporated.
  - Research shows that PEG enhances the durability of alginate gels, while chitosan coatings improve structural integrity and reduce contamination risks **[4]**.

5. Testing the Efficiency of Cyanobacteria Strains

To validate and optimize the CynoFilter's CO_2 sequestration capabilities, we have developed a two-phase testing strategy. The first phase will compare the CO_2 sequestration efficiency of different *cyanobacteria* strains, identifying the most effective strain for use in

the CynoFilter. The second phase will test the CynoFilter prototype itself, assessing its real-world CO_2 capture efficiency under both controlled and external conditions.

5.1 Equipment and Materials

The following materials and instruments are required for the experiments:

Handheld Gas Sensors

Accurate measurement of CO_2 consumption and O_2 production is critical for assessing *cyanobacteria* performance. The following sensors serve as examples of suitable devices:

- CO_2 Sensors:
    - Temtop M10 Air Quality Monitor – Measures CO_2 levels along with PM2.5, temperature, and humidity, providing a cost-effective solution at $89.99. **[23]**
    - INKBIRDPLUS Indoor Air Quality Monitor – Offers detailed CO_2 tracking with a full-color LCD, available for $79.99. **[28]**
- O_2 Sensors:
    - AlphaSense O2-A2 Oxygen Sensor – Provides high-accuracy oxygen content measurements and is priced at $70.00. **[22]**
    - AlphaSense O2-A3 Oxygen Sensor – Offers a more affordable alternative at $82.00. **[22]**

Estimated Cost for Sensor Procurement

Depending on the selected models, the total cost for the required CO_2 and O_2 sensors is estimated to range from $149.99 to $171.99. The Eton College Biology Department has agreed to fund the purchase of these sensors, ensuring that we have access to reliable monitoring tools for the experiments.

Other Lab Materials

- Sodium Alginate Powder – Used to immobilize *cyanobacteria* in a stable matrix for gas exchange analysis. **[12]**
- Agar Plates & Nutrient Media – Required for culturing *cyanobacteria* strains under controlled conditions. **[24]**
- Incubator – Provides a stable temperature and light environment for optimal *cyanobacteria* growth. **[9]**
- Standard Glassware (Test Tubes, Bungs with Double Delivery Tubes) – Used to set up respiration experiments, measuring gas exchange in sealed systems. **[25]**

All necessary laboratory equipment and materials—aside from the handheld sensors—are already available in the Eton College laboratory. Additionally, the Culture Collection of Algae and Protozoa (CCAP) has agreed to provide *cyanobacteria* strains at no cost, with only shipping fees required.

5.2 Experimental Design: Phase 1 – Comparing Cyanobacteria Strains

Objective:

To determine which *cyanobacteria* strain exhibits the highest CO_2 sequestration efficiency, providing the best candidate for use in the CynoFilter.

Procedure:

1. Immobilization in Sodium Alginate:
    - *Cyanobacteria* cultures will be mixed with a 2% sodium alginate solution, then added dropwise into a 3% calcium chloride solution, forming gel beads. **[12]**
    - This method has been widely validated for enhancing microbial stability and gas exchange efficiency. **[24]**
2. Respiration Chamber Setup:
    - The *cyanobacteria*-infused beads will be placed into sealed respiration chambers, mimicking standard aerobic respiration experiments. **[25]**
    - Each chamber will be connected to a CO_2 and O_2 sensor, allowing real-time gas concentration monitoring.
3. Environmental Conditions:
    - The chambers will be maintained under controlled light and temperature conditions inside an incubator, ensuring consistent exposure to CO_2. **[9]**
4. Data Collection:
    - CO_2 concentration (ppm) and O_2 production (%) will be recorded at six-hour intervals for two weeks, tracking sequestration efficiency over time. **[26]**
5. Comparative Analysis:
    - Gas exchange rates will be used to rank each *cyanobacteria* strain by efficiency, identifying the best-performing candidate for the next phase. **[27]**

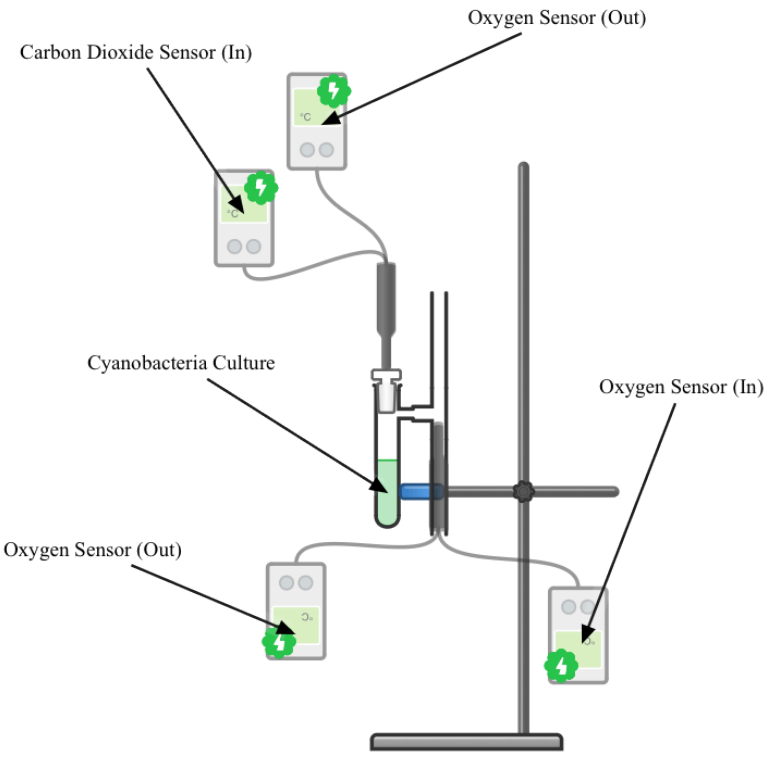

Fig 4: Experiment Design

5.3 Experimental Design: Phase 2 – Testing the CynoFilter

Objective:

To evaluate the real-world CO_2 capture efficiency of the CynoFilter prototype, proving that it is a viable method for carbon sequestration in urban environments where *cyanobacteria* do not naturally occur.

Procedure:

1. The CynoFilter will be assembled using the selected strain, embedded in an optimized sodium alginate matrix. **[12]**
2. The system will be tested in two environments:
    - Controlled Lab Setup – Replicating atmospheric CO_2 levels in a closed chamber.
    - Field Deployment – Installed in an urban setting to analyze real-world air purification potential.
3. CO_2 and O_2 sensors will measure sequestration rates, and results will be compared against the baseline strain performance from Phase 1.

By demonstrating significant CO_2 reduction in urban conditions, where *cyanobacteria* would not typically survive, this phase will confirm that the CynoFilter is an effective and deployable solution for carbon capture.

5.4 Expected Outcomes and Feasibility

Predicted Results:

- *Synechococcus elongatus PCC 7942* is expected to demonstrate the highest CO_2 fixation rate at 5.4 g CO_2 per g biomass per day. **[9]**
- Sodium alginate immobilization is projected to increase sequestration efficiency by 20–30%, as reported in similar studies. **[12]**
- The CynoFilter is expected to capture 50–80% of available CO_2 in a controlled setting.

Scientific Feasibility:

- Established Methods: Similar studies have confirmed that immobilized *cyanobacteria* outperform free-living cultures in CO_2 sequestration. **[12]**
- Replicability: The respiration chamber setup follows standard aerobic respiration experimental designs, ensuring feasibility within our available resources. **[25]**
- Time-Efficiency: Given *cyanobacteria*'s rapid growth rate, meaningful results can be obtained within 2–3 weeks, aligning with expectations from past research. **[9]**

5.5 Concluding Remarks

This testing methodology ensures a rigorous, scientifically valid experimentation process while remaining feasible with our available resources. By first identifying the most efficient *cyanobacteria* strain, we can empirically determine the best candidate for the CynoFilter, optimizing its efficiency before scaling up to real-world testing.

With financial support from the Eton College Biology Department, strain sourcing from CCAP, and access to a fully equipped lab, our study is logistically sound, scientifically justified, and achievable within a short timeframe. The results will provide critical data for advancing the CynoFilter as a scalable CO_2 sequestration technology.

6. Research Analysis, Conclusion & Future Development

Since direct testing has not yet been conducted, we must delve into existing research on *cyanobacteria*-based CO_2 sequestration to support the CynoFilter's feasibility. By evaluating efficiency metrics, optimization strategies, and real-world applications, we can infer expected performance and establish a foundation for future experimental validation.

6.1 Key Findings from Literature

Studies confirm that *cyanobacteria* can fix CO_2 at significantly higher rates than terrestrial plants, making them viable candidates for scalable carbon capture.

***Cyanobacteria* Strain**	**CO_2 Fixation Rate (g CO_2/g biomass/day)**	**Key Features**
Synechococcus elongatus PCC 7942	5.4	High efficiency, rapid growth **[9]**
Synechocystis sp. PCC 6803	2.5	Robust adaptability **[12]**
Spirulina platensis	3.2 – 5.0	Commercially scalable **[13]**

Research also highlights optimization techniques that enhance sequestration efficiency. Increasing CO_2 concentration from ambient (400 ppm) to enriched (800 ppm) can improve fixation rates by approximately 30 percent **[8]**. Sodium alginate immobilization increases *cyanobacteria* stability and retention efficiency by 20 to 30 percent **[12]**. Genetic enhancements in *Synechococcus elongatus* have demonstrated CO_2 uptake improvements of up to 40 percent **[7]**.

These findings confirm that immobilized *cyanobacteria* in a controlled bioreactor environment, as planned in the CynoFilter, represents a viable alternative to conventional carbon capture technologies.

6.2 Comparative Performance Against Conventional CO_2 Capture

While chemical scrubbing remains the dominant approach in industrial carbon capture, biological methods offer a lower-energy, scalable alternative. Recent studies have shown that large-scale cultivation of *cyanobacteria* is a viable industrial strategy for CO_2 mitigation, with specific implementations designed to absorb flue gases directly from power plants **[21]**.

Method	**CO_2 Capture Efficiency**	**Energy Requirement**	**Scalability**
Amine Scrubbing	85–95%	High	Industrial Scale **[3]**

Biochar Sequestration	30–50%	Moderate	Land-limited **[5]**
Cyanobacteria-based Sequestration	60–80%	Low	Easily Scalable **[13]**

The CynoFilter's passive CO_2 uptake, low maintenance requirements, and scalability make it a strong candidate for urban and industrial integration **[21]**.

6.3 Real-World Case Studies

The AlgaePARC Project in the Netherlands demonstrated that large-scale cyanobacteria bioreactors could sequester up to 250 tons of CO_2 per hectare per year **[19]**. This large-scale deployment serves as a strong validation of cyanobacteria's potential for carbon sequestration and industrial integration. Further studies have reinforced this, testing large-scale cyanobacteria cultivation for biofuel production and direct CO_2 capture, showing that these systems can be feasibly deployed in high-emission zones **[20]**.

While these projects prove the effectiveness of *cyanobacteria*, they rely on photobioreactors that require continuous aeration, high water volumes, and carefully maintained nutrient inputs, making them viable only in industrial-scale settings. The CynoFilter takes this principle and makes it more efficient, adaptable, and accessible. Instead of requiring large water bodies or complex infrastructure, it immobilizes *cyanobacteria* within a compact, modular system, allowing for deployment in urban, industrial, and even mobile environments. By using passive CO_2 absorption rather than forced aeration, the CynoFilter reduces operational costs while maintaining high sequestration efficiency, making it a significantly more scalable and flexible solution.

Where industrial-scale photobioreactors are confined to specific large-scale applications, the CynoFilter's modular design allows for widespread implementation, from small-scale urban deployments to industrial carbon mitigation systems. This versatility, combined with its low-maintenance structure, positions it as a next-generation approach to biological carbon capture, leveraging the proven effectiveness of *cyanobacteria* while eliminating the barriers that have prevented wider adoption.

6.5 Future Developments

To transition from concept to implementation, the following steps are planned:

- Pilot testing will be conducted to validate CO_2 sequestration rates in a controlled laboratory setting.
- The first field deployment will take place in urban and industrial locations to assess real-world performance.
- System optimization will involve refining strain selection, immobilization efficiency, and structural design based on test results.

By combining biological efficiency with engineered modularity, the CynoFilter presents a sustainable, scalable solution for atmospheric carbon capture. Future testing will provide empirical validation, paving the way for widespread deployment and further technological advancements.

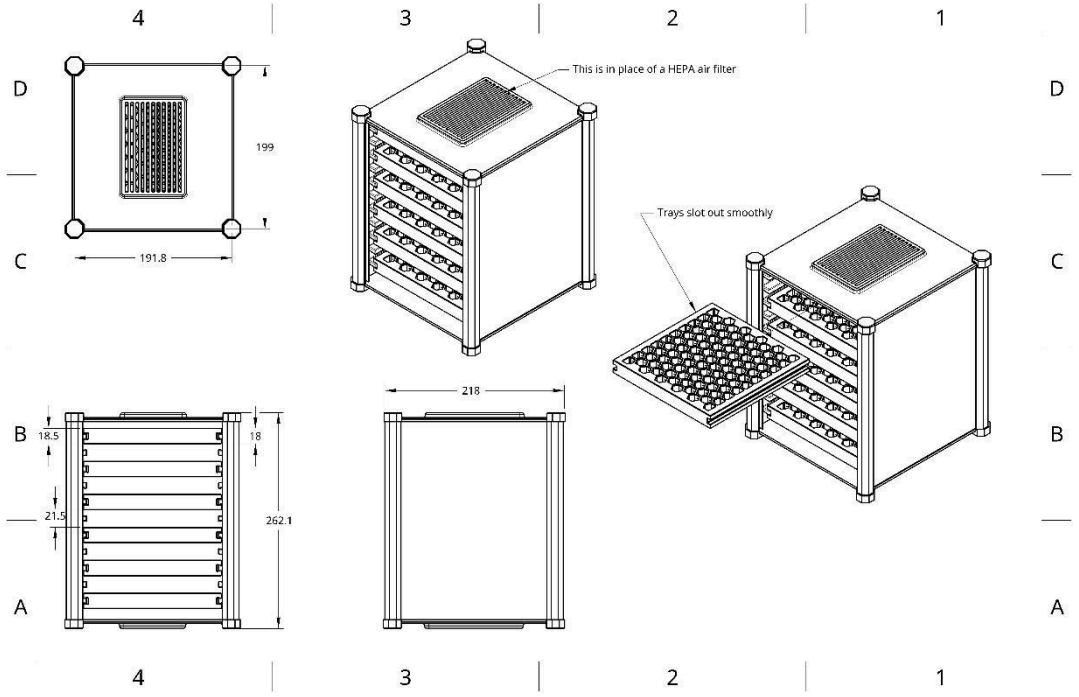

Fig 5: Complete Design Sketch

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