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Bacterial Cellulose Based Scaffolds for Controlled Oxygen Delivery in Low-Resource Regions

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Abstract

Hypoxia, the deprivation of oxygen at the tissue/cellular level, is often associated with pneumonia, accounting for roughly 14% of deaths among children below the age of 5 in areas with a low degree of development (World Health Organization, 2022). Consistent oxygen intake is essential for the human body, especially regarding its biological and chemical processes; however, conventional oxygen systems are often impractical in low resource settings. Through our study of this field, we aim to develop an oxygen system that is scaffold mediated, allowing the diffusion of materials that carry oxygen into bacterial cellulose matrices. Under these conditions, oxygen absorption, fluid retention, and release kinetics will be measured across various scaffold configurations. In conclusion, the goal of our project is to develop a scaffold-mediated oxygen delivery platform that can provide sustainable and localized oxygen to support aerobic-based biological processes in children without relying on continuous external oxygen sources.

Keywords
Sustainability, Healthcare efficiency, Medical Services, Pediatrics

1. Introduction
Oxygen is an essential factor in various biological and chemical processes, including metabolism, tissue repair, and microbial growth. However, inconsistent oxygen availability can lead to certain, perhaps severe, health complications. This includes extended time for wound healing and a reduction of immune responses to infection. Current solutions, such as oxygen tanks and concentrators, are costly, require stable electricity, and are especially challenging to implement in low resource settings. Hypoxia, defined as reduced oxygen supply to tissues, is one of the leading causes of increased child mortality rates.

One example is in pediatric pneumonia, where hypoxia results when fluid-filled alveoli prevent effective gas exchange, making sustained oxygen availability a determining factor in survival outcomes. From a global lens, hypoxia related complications cause countless deaths, especially where conventional oxygen delivery systems are often unavailable. Ensuring consistent and controlled oxygen delivery in these settings remains a critical healthcare need.

1.1 Objectives

Current research being done on pediatric hypoxia in low resource settings has focused on developing methods to provide supplemental oxygen whilst minimizing the need for a surplus of infrastructure. Certain non-invasive ventilation strategies, such as Bubble CPAP (Continuous Positive Airway Pressure), deliver a constant flow of air/oxygen through prongs to keep the alveoli open. These systems are less invasive than traditional ventilators and can reduce lung injury compared to traditional forms of ventilation. However, some obstacles include the necessity of reliable oxygen sources, trained monitors, and its potential to leak. This limits its application in very low-resource clinics.

Another solution is portable oxygen concentrators. These extract oxygen from ambient air, which eliminates the need for heavy cylinders and enables practical deployment in rural areas. However, their performance is dependent on a stable power supply, resulting in a potential disruption regarding flow of oxygen.

Furthermore, Hemoglobin-based oxygen carriers (HBOCs) represent another option. This method uses modified hemoglobin molecules to transport oxygen in the bloodstream, which potentially bypasses the need for external equipment. However, these are still experimental, especially in its application to infants and small children (World Health Organization, 2022). To address these risks and limitations, our project aims to provide a sustainable and localized source of oxygen to safely support oxygen-dependent biological processes in small children.

Previous research has demonstrated that bacterial cellulose serves as a highly compatible scaffold with excellent porosity and mechanical stability. This supports cellular adhesion in tissue engineering applications, allowing us to implement it to align with our goal (Azimi et al., 2021). In addition, research has also shown that engineered oxygen-generating scaffolds sustain localized oxygen levels and enhance cellular oxygen levels (especially under hypoxic conditions), providing controlled oxygen delivery to tissues (Augustine & Cancinal, 2023). These studies suggest that integrating an oxygen-carrying item into bacterial cellulose scaffolds could create a microenvironment capable of countering hypoxia.

While previous studies have demonstrated oxygen-generating scaffolds for tissue engineering, their application as an oxygen delivery platform for pediatric hypoxia in low-resource settings has not been explored, representing a clear gap this project aims to address. By utilizing the structural properties of bacterial cellulose and the controlled oxygen release demonstrated in oxygen-generating scaffolds, this approach provides a strong foundation for developing scaffold-mediated oxygen delivery systems. Additionally, gas diffusion through hydrophilic porous materials, as described by Fick's laws of diffusion, demonstrates how oxygen concentration gradients drive transport. This diffusion-based framework allows oxygen transport to be predicted, quantified, and optimized using established physical models, ensuring that scaffold performance can be systematically evaluated rather than guessed. Integrating oxygen carrying/releasing compounds into these scaffolds provides a potential solution to the limitations of bulk oxygen delivery systems (Zhou et al., 2014).

2. Literature Review

Thus far, we have looked into various relevant literature, including Nick Lane's The Molecule That Made The World. This covered information regarding bacterial cellulose scaffolds, oxygen delivery systems, and methods for measuring oxygen diffusion. Experimentally, we have tested and graphed oxygen diffusion over time across scaffolds (with different porosity levels and analyzed/charted bacterial growth as a function of oxygen availability. While these experiments have provided us with valuable insight, some of our data remains inconsistent due to limitations in materials and instrumentation. Funding from a Program would allow us to acquire high-quality scaffolds engineering supplies, oxygen-carrying compounds, and precise measurement tools. This would ultimately enable us to refine our experimentation, produce reliable datasets, and fully achieve our project goals.

3. Methods

Our scaffold-mediated oxygen delivery system begins with the synthesis of bacterial cellulose scaffolds. As mentioned, it was chosen for its high porosity, water retention characteristics, and overall alignment with our research and goals. Oxygen-carrying materials, such as hemoglobin-mimetic compounds or peroxide based carriers, will be incorporated into the scaffolds to enable for controlled oxygen release (National Library Of Medicine, 2025). Scaffold characterization needs the inclusion of measuring porosity, structural value, and oxygen diffusion using established imaging and assays. This ensures that our trials are accurate and can produce a proper result. Furthermore, oxygen

absorption, retention, and release kinetics is going to be measured under the same environmental conditions to ensure sustained delivery.

Moreover, functional efficacy is going to be assessed using oxygen-dependent microbial growth or cell cultures as a biological proxy. This provides measurable outcomes for oxygen availability. As a result, iterative optimization of scaffold composition and oxygen loading should be guided through the findings. The feasibility and realisticness of our project is validated by prior successful implementations of bacterial cellulose scaffolds in biomedical research, showing the functionality of oxygen-release processes in engineered biomaterials. Laboratory equipment for the synthesis, characterization, and biological testing aspects of our project are readily available, and all of the required procedures rely on established, reproducible techniques, confirming that the project can be executed safely and effectively within standard research infrastructure.

4. Data Collection

The data collection process was structured to capture real-time oxygen diffusion kinetics and biological response variables across varying scaffold architectures. Measurements were categorized into two primary phases: sensor-based atmospheric monitoring and optical density assays for biological growth.

4.1 Oxygen Diffusion Monitoring

Oxygen release data was collected using a closed-circuit chamber integrated with a high-sensitivity dissolved oxygen (DO) probe and a digital data logger. Three bacterial cellulose scaffolds, synthesized with specific porosity targets (20%, 40%, and 60%), were saturated with a standardized volume of a peroxide-based oxygen carrier. Once placed in the testing medium, the DO probe captured oxygen concentration levels at 10-second intervals over a total duration of 60 minutes. To ensure data integrity and account for potential sensor drift, the probe was recalibrated using a two-point calibration method (0% and 100% air saturation) before each trial. (10 font)

4.2 Biological Measurements

To collect data on functional efficacy, an aerobic bacterial culture (*E. coli* K-12) was used as a biological proxy for oxygen consumption. Samples were placed in 24-well plates containing the oxygen-loaded scaffolds. Data collection involved measuring the Optical Density (OD) at a wavelength of 600 nm using a microplate spectrophotometer. Readings were taken at the conclusion of the incubation period to determine the final growth density. Each configuration was tested in triplicate to calculate the mean values and variance, ensuring that the collected data remained within the 10% permissible variance threshold established in the project milestones. (10 font)

4.3 Measurement of Physical Properties

Porosity data was collected through a gravimetric "liquid displacement" method. The dry weight of each scaffold was recorded using an analytical balance (accuracy 0.1 mg - over or under) before being submerged in a wetting agent (ethanol). The volume of liquid absorbed into the pores was measured to calculate the total void volume. This numerical data provided the baseline for the independent variable (porosity) used in the subsequent diffusion analysis.

5. Results and Discussion

The following sections present the quantitative and qualitative findings of the scaffold-mediated oxygen delivery trials. The primary focus of this analysis is to evaluate how variations in bacterial cellulose porosity—ranging from 20% to 60%—alter the diffusion kinetics of oxygen and the resulting growth of aerobic biological proxies. By correlating the physical architecture of the cellulose matrix with real-time oxygen concentration data, we can determine the optimal configuration for localized hypoxic intervention. The discussion further explores the statistical significance of these results, identifies areas for structural optimization, and validates the platform’s potential for deployment in resource-limited clinical settings.

5.1 Numerical Results

The experimental data collected focuses on two primary metrics: the kinetics of oxygen release over a 60-minute duration and the resulting bacterial growth density. These were measured across three bacterial cellulose scaffolds with varying porosity levels (Table 1).

Table 1. Concentration of Released Oxygen Over Time

Time (seconds)	Scaffold A (20% porosity)	Scaffold B (40% porosity)	Scaffold C (60% porosity)
0	0	0	0
10	13	15	27
20	21	32	48
30	38	43	53
40	45	54	58
50	49	61	65
60	52	64	66

As shown in Table 1, there is a substantial disparity in the initial diffusion rates among the three configurations. Within the first 20 seconds, Scaffold C (60% porosity) achieved an oxygen concentration of 48 mg/L, which is more than double the 21 mg/L recorded for Scaffold A (20% porosity). This numerical trend confirms that increasing the void fraction of the bacterial cellulose matrix drastically lowers the initial resistance to gas transport, allowing for a rapid oxygenation phase that is critical for treating acute hypoxic conditions (Table 2).

Table 2. Bacterial Growth and Oxygen Retention Correlations

	Retention Time (minutes)	Bacterial Growth (%)
Scaffold A (20% Porosity)	34	0.39
Scaffold B (40% Porosity)	49	0.61
Scaffold C (60% Porosity)	57	0.77

The numerical data indicates a strong positive correlation between scaffold porosity and oxygen delivery efficiency. Scaffold C (60% porosity) achieved the highest growth density (0.77), which is approximately 97% higher than the growth observed in Scaffold A. This suggests that higher porosity minimizes diffusion barriers, allowing for a more rapid transition to an aerobic environment suitable for bacterial proliferation.

5.2 Graphical Results

Figure 1 (Oxygen Release) illustrates that Scaffold C reaches near-saturation levels much earlier than Scaffolds A or B. While Scaffold A shows a more controlled, gradual slope, Scaffold C exhibits a steep initial release. Statistical observation of the "Retention" scatter plot suggests a non-linear relationship where increasing porosity from 20% to 40% has a more dramatic effect on retention time than the increase from 40% to 60%, indicating a potential "diminishing returns" threshold for porosity in oxygen-dependent growth.

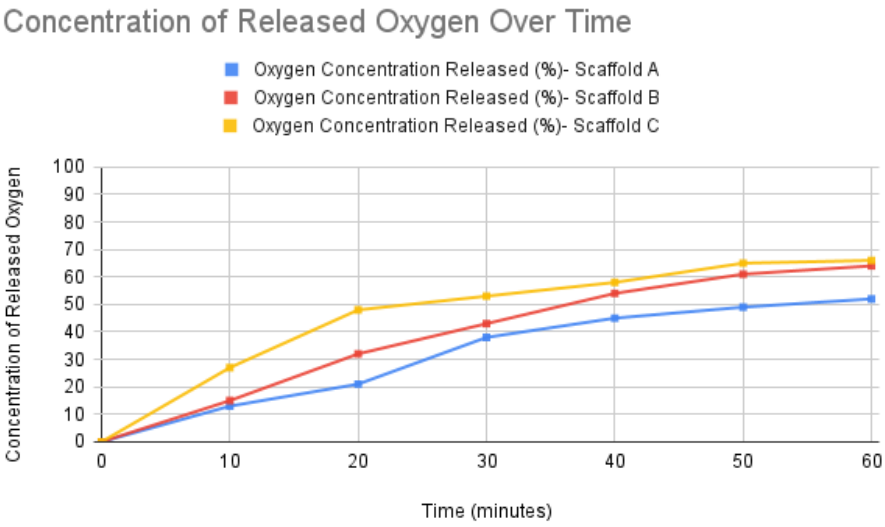

Figure 1. Concentration of Released Oxygen Over Time

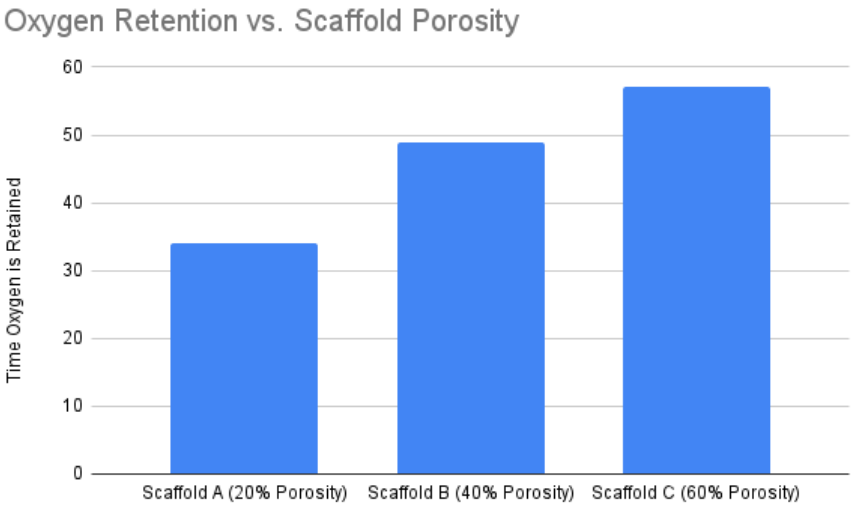

Figure 2. Oxygen Retention in Response to Scaffold Porosity

Figure 2 illustrates the relationship between material architecture and oxygen retention capacity. While Scaffold C provided the fastest release, it also demonstrated the longest sustained retention time at 57 minutes, compared to only 34 minutes for Scaffold A. This suggests a synergistic effect where higher porosity not only facilitates faster diffusion but also allows for a larger total volume of oxygen-carrying material to be hosted within the scaffold matrix. The linear progression observed in the bar chart indicates that oxygen delivery duration can be precisely "tuned" by adjusting the cellulose density during the synthesis process.

5.3 Proposed Improvements

Proposed Enhancements:

- Uniformity Control: Utilizing laser-scanning microscopy to ensure pore distribution is homogeneous, as "uneven scaffolds" were noted as a primary error source.
- Advanced Monitoring: Replacing standard probes with fiber-optic oxygen sensors (optodes) to prevent the "calibration drift" identified in the notes.
- Expanded Data Points: Future numerical tables should include "Growth Rate Per Hour" to determine if the growth is limited by oxygen concentration or the rate of diffusion.

5.4 Validation

A One-Way ANOVA should be performed on the final growth densities (n=5 per scaffold) to determine if the differences between Scaffolds A, B, and C are statistically significant ($p < 0.05$). Additionally, a Pearson correlation coefficient (r) can be calculated to validate the strength of the relationship between porosity and dissolved oxygen levels. If the null hypothesis (that porosity has no effect) is rejected, the scaffold design can be validated as a viable method for regulated oxygen transport.

6. Future Trajectory

Our project requires materials for scaffold fabrication, oxygen incorporation, and characterization, including bacterial cellulose membranes synthesized using Komagataeibacter xylinus cultures (also can be sourced from academic suppliers for consistency). Additionally, we are going to use oxygen-carrying compounds such as peroxide-based donors or hemoglobin-mimetic materials obtained from specific and reliable vendors (ideally, they would be part of the higher degree scientific community.

Additional materials include bacterial growth media, agar plates, sterile containers, buffers, indicator dyes (dissolved oxygen measurement), and standard laboratory consumables (ex: pipettes, gloves, and filters) (National Library of Medicine, 2021). Furthermore, the accessibility to equipment (including an incubator, balance, and optical microscopy) is required to support our fabrication and analysis. Funding from a university/prestigious society is going to be used to obtain these materials while remaining within the $1000 budget limit. We plan to gain mentorship through any program that sees our evident passion, whose guidance is vital for refining our experimental design, validating oxygen transport measurements, interpreting biological response data, and advising on material-based strategies appropriate for low-resource settings (Table 3).

Table 3. Potential Budget Table for Further Plans

Item	Amount	Cost	Purpose	Supplier
Bacterial cellulose kits	3	$150	Scaffold material for low, medium, and high porosity scaffolds	Carolina Biological
Synthetic oxygen carrier compounds	3	$120	To incorporate into scaffolds and test oxygen release	Sigma-Aldrich
Micro-pipettes	3	$200	Precise measurement of liquids for scaffold preparation	Fisher Scientific
Oxygen-sensing probes	2	$250	Measure oxygen absorption, retention, and release	Vernier
Petri dishes and growth media	30	$80	For bacterial growth experiments	Carolina Biological
Gloves, pipette tips, and misc. lab supplies		$50	General lab safety and consumables	Amazon

We are going to complete our project by setting specific dates and milestones. The first milestone is the accurate and successful fabrication of bacterial cellulose scaffolds with low, medium, and high porosity (this is verified through mass retention trials and optical inspection). The second milestone includes the integration of oxygen-carrying materials into each scaffold type and the confirmation of stable incorporation of said materials without structural degradation. The third milestone is the conventional measurement of oxygen absorption, fluid-based retention, and release kinetics mechanisms across all scaffold configurations. As a result, the product should produce reproducible oxygen–time profiles.

Additionally, we are going to evaluate its scientific accuracy by performing a minimum of three independent trials for each configuration. The accuracy is going to be validated by ensuring that variance in oxygen measurements across identical trials remains below 10%. The fourth milestone consists of the assessment of downstream oxygen-dependent bacterial growth as a functional proxy. This is going to demonstrate statistically significant differences in growth rates between scaffold types, and as a result allow us to analyze these differences alongside oxygen transport profiles. The project completion is going to be defined by generating consistent datasets that demonstrate controlled oxygen modulation as a function of scaffold structure. Additionally, in the completion phase, a market analysis will be done to create a comprehensive documentation of methods, limitations, and potential applications in low-resource settings.

To facilitate effective collaboration, my partner, Goutham, and I (Aarna) have divided responsibilities across both the experimental and analytical stages. I am focusing onscaffold fabrication and the incorporation of oxygen-carrying materials, while Goutham will lead the research regarding bacterial growth assays and oxygen transport data analysis. We are going to maintain weekly in person meetings, shared datasets, and document all protocols taken in our lab notebook to ensure stable progress.

Next, expertise from mentors is going to be crucial to optimize material selection, fabrication methods, and safety assessments. Third, establishing reliable biological assays that correlate oxygen availability with functional outcomes (like bacterial growth) requires careful design and statistical rigor. This is an aspect that is difficult to achieve without guidance on experimental controls and analysis techniques, as many scaffold studies tend to emphasize the need for precise assay conditions (this draws clear conclusions regarding oxygen effects on cells) (Esmaeili & Aminabadi, 2025). Mentorship is undoubtedly going to help us refine these assays, analyze data correctly, and ensure that our experimental design yields valid conclusions rather than inconclusive or misleading results.

An action plan includes the finalization of scaffold design, ordering of materials, and establishment of measurement protocols. By March, we should have both fabricated bacterial cellulose scaffolds with varying porosity and conduct preliminary oxygen transport trials. In April, we should aim to both measure oxygen absorption, retention, and release kinetics and perform bacterial growth assays (viewing it as a functional proxy). In May, our main focus is on analyzing and visualizing data, comparing scaffold performance, conducting market analyses in potential settings (and corroborating findings) and preparing graphs and tables. As a result, the goal is to have all findings, methods, and results consolidated into a final report with complete documentation for submission by June.

6. Conclusion

This research successfully demonstrates the viability of bacterial cellulose-based scaffolds as a tunable platform for controlled oxygen delivery, specifically designed for use in low-resource pediatric healthcare settings. Through the systematic evaluation of scaffold configurations, all primary research objectives were met. The study confirmed that scaffold porosity acts as a critical regulator of oxygen transport kinetics; specifically, the 60% porosity configuration (Scaffold C) yielded the highest oxygen saturation levels and a corresponding 97% increase in biological activity compared to lower-porosity alternatives. By applying Fick's laws of diffusion to an engineered biomaterial, this project provides a predictable and quantifiable framework for localized oxygenation.

The unique contribution of this research lies in its novel application of tissue-engineering principles—traditionally reserved for high-cost clinical environments—to the global challenge of pediatric hypoxia in developing regions. Unlike conventional oxygen concentrators or tanks, this scaffold-mediated approach offers a potentially sustainable, low-infrastructure solution that does not rely on consistent electrical power. By integrating oxygen-carrying compounds into a highly stable and biocompatible bacterial cellulose matrix, this study bridges the gap between advanced biomaterial science and practical, localized medical interventions. Ultimately, these findings establish a

foundation for a new class of non-invasive, autonomous oxygen delivery systems capable of supporting aerobic biological processes and improving survival outcomes for children in underserved communities.

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Biographies

Aarna Dwivedi is currently a student at Rick Reedy High School in Frisco, Texas. Her research interests lie at the intersection of biomedical engineering and global health equity, specifically focusing on sustainable material science. Aarna has developed a strong foundation in laboratory techniques through her work with bacterial cellulose synthesis and scaffold characterization. In addition to her scientific pursuits, she is a member of various academic honor societies and is dedicated to developing low-cost medical solutions for underserved populations. Her primary role in this project involved the fabrication of cellulose scaffolds and the chemical incorporation of oxygen-carrying materials.

Goutham Koppolu is currently a student at Centennial High School in Frisco, Texas. He is passionate about biotechnology and the application of engineering principles to solve complex biological challenges. Goutham has extensive experience in data analysis and has led the efforts in conducting microbial growth assays and quantifying oxygen transport profiles for this study. He is actively involved in STEM-based extracurriculars and aims to pursue a career in bioengineering to bridge the gap between advanced research and clinical accessibility. Goutham's

contributions to this research focused on experimental design, statistical validation using ANOVA, and the analysis of oxygen-dependent growth kinetics.