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Living Systems in Domestic Design: Integrating Microalgae for Air Purification through Light and Human-Centred Design

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ABSTRACT
The integration of living organisms in indoor spaces leads to an opportunity to explore alternative approaches to environmental and human-centred design. Indoor environments require solutions that address sustainable performance while also responding to human and spatial needs. This research explores the practicality of integrating **Chlorella vulgaris** into a domestic lighting product that can help reduce CO2 in an interior space. This research examines the biological requirements of microalgae, CO2 fixation, the effect of lighting, and photobioreactor design, while also considering domestic usage and user acceptance. In the paper, a theoretical quantitative analysis was performed for a proposed culture of maximum 1L volume. The findings indicated that **Chlorella vulgaris** can fix a certain amount of CO2, but it is comparatively very less to everyday CO2 accumulation in an indoor space. This research proposes that a better design opportunity is to integrate algae with an interior lighting product that works beyond the purpose of illumination and creates a connection between human-centric design and environmental processes, rather than a standalone air purification alternative. This research also aims to establish a basis for further study of the design considerations and environmental needs beyond the theoretical results.

Keywords: Chlorella vulgaris, microalgae, indoor air quality, CO_2 remediation, photobioreactor, domestic lighting, biophilic design, sustainable product design.

1. INTRODUCTION

Indoor environments are an important part of daily life, which makes the overall quality of these spaces connected to comfort, well-being, emotions, and satisfaction. There are many factors that affect **indoor environmental quality (IEQ),** which mainly include thermal conditions, lighting, sound, and air quality. These factors don't always work independently, interactions among these factors determine how users perceive their surroundings. Tang et al. (2020) studied the combination of lighting, sound, carbon dioxide (CO_2) levels, and thermal conditions and found that overall user satisfaction was affected by the combination of these factors. Moreover, a methodical review by Grasso-Cladera et al. (2025) states that indoor environmental quality can be directly associated with physical responses and psychological well-being. This clearly implies that while designing indoor environments, it's important to consider both **environmental performance and the human experience** related to that space.

As human activities continuously contribute to changes in air composition, indoor air quality becomes most relevant among the other components of IEQ when considering an occupied space. In indoor environmental conditions, CO_2 is an important parameter because it is associated with **ventilation and occupancy**. Ventilation is considered a standard approach in maintaining indoor air quality, as it allows outdoor air to enter and also removes accumulated CO_2 and other impurities. However, the increasing interest in sustainable design has promoted the exploration of alternative approaches that can work beyond conventional ways, creating an opportunity to explore biological processes for managing indoor environmental conditions.

Photosynthesis provides one such approach, as the organism takes in CO_2 as a part of the process and produces oxygen and biomass. **Microalgae** are one such species which has been scientifically studied for their ability to take in CO_2 and release a good amount of oxygen. These species can be cultivated in photobioreactor systems to support their growth. In one such scientific study, Han et al. (2023) showed the prospects of a microalgae-based photobioreactor for removing CO_2 from an indoor environment; the research paper showed that the microalgae system can interact with indoor CO_2 accumulation under controlled conditions. The species they used for this research was **Spirulina maxima.** This research paper provides scientific evidence about the potential of microalgae as an alternative approach for improving indoor air quality.

Among various species of microalgae, **Chlorella vulgaris** is being studied in the current project because it uses light to carry out photosynthesis, and researchers have shown that it can absorb CO_2 and turn it into biomass. The performance of the algae depends on the surrounding conditions, especially **the light** it receives. Esteves et al. (2020) studied the effect of various LED wavelengths on the absorption of CO_2 and production of biomass in green microalgae. The research showed that the wavelength of light can significantly influence the growth of algae. **Chlorella vulgaris** attained its highest biomass productivity and carbon capture under the **white LED**. This proves that an indoor algae-based lighting system cannot be designed without thinking about the light needed by that particular species.

There are many challenges while introducing algae into an indoor environment. Photobioreactors should provide a proper habitable environment for the growth of microalgae while also keeping aesthetic, spatial, and environmental requirements in mind. Arora et al. (2024) studied the integration of microalgae in indoor environments and highlighted the same factors as important. As in a domestic space, the biological system and these factors should coexist, maintaining functional and visual balance. Considering the fact that illumination plays a vital role in this process, **a lighting system** could be the way to bring all these different requirements together in a household project.

However, it is important to consider the light that is being used in relation to the ambience and human experience. Stokkermans et al. (2018) studied that the brightness and uniformity of a light can affect the atmosphere of a space. While Madias et al. (2023) highlight in their research paper that there is potentially a difference between the lights required for bioreactors and those meant for domestic spaces. Hence, it requires consideration of biological performance, lighting, aesthetics, indoor environmental conditions, and human experience while integrating microalgae into a domestic interior. **This research focuses on ways to integrate Chlorella vulgaris into an indoor lighting product that can help reduce the accumulated carbon dioxide within a closed space, while also considering the biological requirements and the overall human-centred experience.**

2. LITERATURE REVIEW

2.1 Indoor Air Quality and the Domestic Environment

Indoor environmental quality (IEQ) is a very important aspect, as people spend plenty of time indoors. Several factors, such as air quality, lighting, thermal conditions, etc., interact with each other and affect how a person perceives and experiences the space. Tang et al. (2020) found that these environmental factors affect the overall satisfaction of the user. Similarly, Grasso-Cladera et al. (2025) highlighted that the indoor conditions can influence users' physical and psychological well-being. Therefore, it is important to consider how the user will be affected by the system, not just whether it will be technically functional. CO_2 is continuously produced due to respiration, which leads to its accumulation in residential spaces. Factors like number of occupants, room volume, and ventilation affect the concentration of CO_2 in a space. U.S. The Environmental Protection Agency (2026) states that the indoor concentration of CO_2 can indicate the occupancy and ventilation conditions of that particular space.

Conventionally, ventilation is used to control CO_2 and maintain air quality, but increasing interest in sustainability has encouraged researching alternate approaches. Organisms like microalgae can absorb CO_2 and release oxygen and biomass during the process of photosynthesis, making them a suitable fit for exploring them as a remedy to improve air quality in indoor spaces while also considering the importance of conventional ventilation.

2.2 Microalgae and CO_2 Reduction

Most of the research about using algae to reduce CO_2 has mainly focused on their cultivation in controlled systems like **photobioreactors (PBRs)**. These systems help to create a suitable environment for algae growth, providing proper light and CO_2. The amount of carbon reduction depends on whether the cultivation system provides the proper conditions that algae need for growth.

Han et al. (2023) studied a microalgae photobioreactor using **Spirulina maxima**, proving that photosynthetic microorganisms can be used in indoor settings to help reduce carbon concentration. Moreover, the study also shows that the performance can vary with different cultivation conditions and operating parameters.

Therefore, we cannot say that a particular algae will always remove the same amount of CO_2. Factors like the **type of species, availability of light, gas transfer, CO_2 absorption, cultivation conditions, and reactor design** can influence the whole process. These factors should be considered with utmost importance, especially when designing for an indoor space where availability of these might be compromised or limited. Therefore, the study of various microalgae is necessary to figure out which species can provide desired results within the constraints of a product-scale system.

2.3 Chlorella Vulgaris and Photosynthetic Performance

Chlorella vulgaris is a green microalgae species that has been studied for its ability to convert CO_2 into biomass through photosynthesis. This particular species' performance depends largely on the light supplied to it. Esteves et al. (2020), in their research, compared the effect of red, blue, and white LED light on different species of microalgae. They found that **Chlorella vulgaris** achieved its highest biomass productivity and CO_2 reduction under the **white light**. The study reported a CO_2 fixation rate of approximately **11.4 ± 0.5 mg CO_2 L^{-1} day^{-1}** for **Chlorella vulgaris** under white LEDs, meaning that for every **1 litre of** algae culture, the algae fixed about **11.4 mg** of CO_2 in one day when grown under the **white LED light**.

Other studies show that factors like light intensity, CO_2 concentration, photoperiod, temperature etc. can affect the performance of this particular species. Some experimental studies have shown that the culture performs better under increased light intensities and extended illumination time, whereas the same extended conditions can also have a negative impact on algae growth as well. This shows that while designing the system, light cannot be added just to illuminate the culture. The algae need the right duration, wavelength, and intensity of light to grow and fix CO_2 effectively. **For a domestic product, the lighting conditions and the culture volume are different from those of laboratory-scale systems**. So, the laboratory experiment findings and numbers should be considered as a general benchmark, not as a guarantee of how much CO_2 the actual product will remove.

2.4 Photobioreactors and Indoor Integration

A **photobioreactor (PBR)** is a system that is used to cultivate microorganisms who perform photosynthesis under conditions that support their growth. A photobioreactor provides complete control over factors like light exposure, CO_2 availability, temperature, nutrient supply, and gas transfer. Changes in these conditions would directly impact the growth of algae and CO_2 fixation.

The overall design of PBR also affects the amount of light and gases reaching the algae culture. Studies on PBR designs show that the flow of gases, liquids, and mass transfer play a vital role in distributing CO_2 and nutrients throughout the culture. Hence, the geometry of the reactor needs to be considered along with its biological function.

The integration of PBR with interior spaces and architecture has been explored in different projects. Arora et al. (2024) discussed different types of photobioreactors and also looked at how they can be used as a part of buildings and spaces. For a domestic environment, the system should coexist with everyday activities and should occupy limited space. A household PBR should provide a proper environment for algae while also being visually appealing, safe to handle, and easy to maintain. The PBR would require periodic maintenance and culture replacement, so it is important to consider accessibility while designing.

Integration of a photobioreactor system with an indoor lighting product creates a good design opportunity, as the lighting component can provide illumination while supporting growth of the culture. However, the lighting requirements for algae growth are different from those of a human user. Therefore, **the product should create a balance between biological performance and aesthetics, usability, and energy consumption.**

2.5 Lighting Requirements: Algae and Humans

Light is one of the most important environmental factors that affect algae growth and photosynthesis. Its influence doesn't just depend on the amount of light provided but also on the **wavelength and duration**. Different studies on **Chlorella vulgaris** show that changes in light intensity can affect biomass production, where insufficient light can limit growth and excessive light can cause photoinhibition. Therefore, an effective lighting product is needed for a proper level of illumination.

However, the light should be designed keeping the human user and aesthetics in mind. It should provide a suitable, illuminated, and comfortable environment for the user. Stokkermans et al. (2018) found that the perceived atmosphere of a lit environment is influenced by characteristics such as brightness and uniformity.

Madias et al. (2023) state that biological and human centred lighting requirements don't always align. Therefore, the proposed product should consider and balance both algae growth and human visual comfort.

2.6 Biophilic Design and Human Experience

Biophilic design refers to incorporating natural elements and characteristics into the built environment. This is explored as an approach that brings elements of nature into indoor spaces in a way that people feel more connected to their surroundings. Zhong et al. (2022) said in their paper that biophilic design can contribute to health, well-being, and sustainability when the natural elements and architecture are meaningfully integrated.

This suggests that for the proposed product, the algae can be treated as a visible and functional part of the design rather than hiding it. The visible changes in the culture, like the colour and movement, can become a part of the product experience.

2.7 Consumer Perception and Sustainable Product Choice

The adoption of sustainable products depend on how consumers perceive it, their usefulness, appearance and not just only their environmental benefits, Joshi and Rahman (2019), found out that people may be more likely to buy a sustainable product when they care about environment and feel like that their particular purchase can make a real difference.

For a microalgae-based product it's therefore important to understand whether the user would understand its environmental function and consider it worth it when compared to a conventional lighting product. Therefore, it's important for the product to communicate its function properly while also being practical and aesthetically pleasing. Luchs et al. (2012) say that the choice of products associated with sustainability can be influenced by their aesthetic design.

2.8 Nature Inspired Product Design

Nature can also be used as an inspiration for the form, structure, and function of the product. Shu et al. (2011) say that designers can study how a certain thing works in nature and then use that principle to solve a human problem. Verma and Punekar (2020) state a similar finding but specifically related to product design. Nature can be used systematically to develop a product's form, structure, or design rather than just copying how it looks.

For the proposed product, algae is not just serving a biological function but is also translated into the physical design of the lighting system, the form, structure, and visual aesthetics. This approach helps strengthen the product as it allows the biological function and product design to be considered together rather than treating them individually.

2.9 Research Gap

The existing research shows that microalgae have the ability to provide CO_2 remediation and convert carbon into biomass through photosynthesis. Research also explored the possibility of introducing a photobioreactor in an architectural setting and the role of biophilic design and lighting on consumer perception. However, these areas are generally studied separately.

There is less focus on bringing all these aspects together in a small domestic lighting product. In particular, the relationship between the biological requirements of **Chlorella vulgaris** and those of a compact household, human emotions, product aesthetics, and practical maintenance requires further consideration. Therefore, this research focuses on the practicality of integrating **Chlorella vulgaris** into a domestic lighting product, considering both biological and human requirements. This research uses information from previous studies and calculations to study whether the product can actually work and what its limitations are theoretically.

3. METHODOLOGY

This study explores the integration of **Chlorella vulgaris** into an indoor lighting product using a literature-based feasibility and product design approach. The research was reviewed to identify the biological requirements of **Chlorella vulgaris**, CO_2 fixation rates, PBR conditions, lighting requirements, and considerations for indoor product integration. Later, these findings were used to evaluate the proposed product concept.

3.1 CO_2 Fixation Calculation

The proposed product can contain a maximum algae culture volume of approximately 1 L. To calculate its estimated CO_2 fixation capacity, a published carbon fixation rate for this particular species was taken as a reference. Esteves et al. (2020) stated a CO_2 fixation rate of approx. 11.4 ± 0.5 mg CO_2 L^{-1} day^{-1} for **Chlorella vulgaris** under white LED light.

The theoretical daily CO_2 fixation was calculated using:

Daily CO_2 fixation = CO_2 fixation rate × culture volume

For a 1 L culture:

11.4 mg CO_2 L^{-1} day^{-1} × 1 L = 11.4 mg CO_2 day^{-1}

Therefore, a 1L culture would approximately fix **11.4mg of CO_2 per day**. Moreover, this calculation was also used to find how the theoretical capacity would change with different culture volumes:

Table 1.1: Theoretical values of CO2 fixation for different culture volumes.

CULTURE VOLUME	THEORETICAL CO_2 FIXATION/DAY
1L	11.4 mg
2L	22.8 mg
3L	34.2 mg
5L	57.0 mg
10L	114.0 mg

These values just show the theoretical biological capacity of **Chlorella vulgaris** to fix CO_2; they shouldn't be interpreted as the actual amount the proposed product would remove from a room.

3.2 Comparison with Indoor CO_2 generation

To understand the performance of the product better, the calculated values were compared to the amount of CO_2 generated by occupants. Persily (2017), in their research on building occupants, shows CO_2 generation of approximately **0.0052 L/s for an average adult during office-type activity.** This refers to approximately **449 L of CO_2 per day**, or roughly **0.89 kg CO_2 per day** when converted using the density of CO_2.

This comparison is just to understand the significance of the number, not to claim that the product can actually perform the same as the calculated amount. A room is not a closed space; factors like occupancy, ventilation, room volume, and air mixing affect indoor CO_2 concentration. Therefore, we cannot establish an exact number for the performance of the algae culture.

3.3 Product Feasibility and Design Evaluation

The calculated biological capacity was taken into consideration along with its physical requirements. The proposed concept consists of a **modular algae culture chamber integrated with a lighting system**, with provisions for light exposure and passive air exchange. The product was assessed based on its culture volume, lighting requirements, maintenance, and accessibility.

The proposed design allows the algae culture to be removed for replacement and cleaning. However, the exact maintenance timeline cannot be established from the available research alone and would require the individual testing of the final prototype.

Based on the study and calculations, the proposed product is considered **a supplementary approach to indoor CO_2 management** and not a replacement for conventional ventilation. The actual performance of the product would depend on factors like light intensity, temperature, airflow, gas transfer, CO_2 availability, etc.

4. RESULTS

4.1 Theoretical CO_2 Fixation Capacity

Based on the estimated culture volume, i.e., 1 L, the theoretical CO2 fixation capacity was calculated using Esteves et al. (2020) as a reference, which came out to be **11.4 ± 0.5 mg CO_2 L^{-1} day^{-1}** for **Chlorella vulgaris** under white LED light.

Using the mean value:

11.4 mg CO_2 L^{-1} day^{-1} × 1 L = 11.4 mg CO_2/day

Therefore, the proposed **1 L** culture can fix approximately **11.4 mg** CO2 per day.

To understand how the culture volume affects this number, the same calculation was performed with the larger volumes. For example, **2L** culture can fix **22.8 mg/day,** while **5L** culture can fix **57 mg/day**. This shows how the fixation rate increases with increased volume.

However, these values are just theoretical and not the actual estimate of the true capacity of the proposed product.

4.2 Comparison with Human CO2 Generation

The theoretically calculated capacity of a 1 L culture was compared with estimated CO2 generation by human occupants. According to reports by Persily (2017), the rate is approximately **0.0052 L/s** for an adult during office-type activity, which roughly equals **449 L of CO2.**

Based on this data, there is a very large difference in scale; the amount of CO2 that one person can produce is far greater than the amount that the proposed product can fix.

4.3 Design Implications

The result shows that the proposed product should be considered as a small-scale biological system and not a complete full-scale replacement for indoor air purification. The calculation shows that it is important to design the product around realistic expectations.

The results also state that there is a need for a modular culture chamber that provides continuous air flow, illumination and maintenance system. The airflow and lighting components should be designed with proper considerations that support the biological needs.

These findings provide a scope for further evaluation of the concept, making it better in terms of its function and usability.

5. DISCUSSIONS

The findings of the research show that the proposed microalgae based lighting product has more potential as a design integration of biological and domestic functions rather than as an air treatment device. The theoretical value for CO2 fixation shows that small algae cultures have measurable biological activity, but they cannot remove the CO2 when compared with normal occupant CO2 generation. This makes the product an opportunity to integrate nature into an everyday household product rather than a replacement for conventional air treatment methods.

The research suggests that the success of the product depends on its function, lighting, and interaction with the space, not just its CO2 fixation capacity. The product gets a unique identity due to the visible algae culture and the overtime changes in making it interact with the space. At the same time, the research also shows the gap in the laboratory based studies and the performance of a compact domestic product.

Physical testing is needed to clearly establish how much CO2 can be fixed by the proposed configuration.

Overall, the research shows that **Chlorella vulgaris** can be explored in living, multifunctional products for domestic spaces based on scientific evidence while also highlighting the need to balance biological performance and the product scale constraints.

6. CONCLUSION

This research explored the possibility of introducing **Chlorella vulgaris** into a domestic lighting product. The research shows that microalgae can fix accumulated CO2 and that **Chlorella vulgaris** can be considered a suitable organism for further exploration.

The research concluded that the proposed product should be marketed as **a supplementary environmental system rather than a replacement for ventilation or air purification methods,** as the quantitative analysis proved that a small culture volume has limited capacity to fix CO2 when compared to the amount of accumulated CO2 in a closed space.

Beyond its natural function, there is an opportunity to bring a living microorganism into a domestic everyday product through visibility, lighting, and modularity. The biological process contributes to both function and user experience.

Further development requires physical prototyping and testing under realistic indoor conditions. Later research should study actual CO2 reduction, lighting performance, maintenance, energy use, and user acceptance. This further research will prove whether the product can be moved towards a practical domestic product from a theoretically feasible design.

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