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Algae-Based Systems for Indoor Air Purification: Evaluating Their Effectiveness In Reducing Indoor Pollutants

Faton Kalisi

Abstract

Algae-based systems have emerged as an innovative solution for addressing indoor air quality challenges in urban environments. Through photosynthesis, microalgae absorb carbon dioxide (CO_2) and convert it into oxygen while simultaneously reducing the concentration of hazardous pollutants such as volatile organic compounds (VOCs) and particulate matter (PM). By integrating photobioreactor (PBR) modules into building facades and indoor air filtration devices, these systems not only purify the air but also contribute to architectural sustainability. Recent studies have demonstrated that such systems can achieve significant reductions in indoor CO_2 levels, with experimental systems reducing CO_2 by approximately 55% under controlled conditions, and have the added benefit of improving respiratory health. Despite promising laboratory and pilot-scale outcomes, challenges remain regarding scalability, operational consistency under varying light and airflow conditions, and economic feasibility in real-world settings. This paper evaluates the current effectiveness of algae-based indoor air purification by synthesizing data from recent empirical studies and theoretical frameworks. It also identifies the advantages and limitations of these systems, discusses their potential role in sustainable building design, and provides recommendations for future research to optimize system performance and integration.

Keywords: Indoor air quality; microalgae; photobioreactor; CO_2 reduction; sustainable architecture

Introduction

Air pollution has grown to be a major environmental and public health concern as urban populations increase and industrial activity intensifies. Both indoor and outdoor air pollution are associated with cardiovascular problems, respiratory illnesses, and a general deterioration in health (World Health Organization, 2021). Although somewhat effective, conventional air cleaning techniques that use chemical treatments or mechanical filters are energy-intensive and might not be able to remove all indoor pollutants (Liu et al., 2017).

As a result, scientists have looked into bio-based solutions and algae have shown to promise to act as a natural air purifier. Algae-based systems by using microalgae's photosynthetic properties remove hazardous pollutants like particulate (PM) and volatile organic compounds (VOCs), as well to absorb carbon dioxide (CO2) and release oxygen (Frontiers in Energy Research, 2022). An important step toward better air quality and sustainable urban living is the incorporation of photobioreactors (PBRs) into indoor air filtration systems and architectural design.

This study analyses current research findings and theoretical framework to investigate how well algae-façade systems reduce air pollution. Addressing both the problems of reducing air pollution and promoting environmental sustainability makes this research relevant. Since most people spend 90% of their time indoors and indoor air quality is essential for both productivity and overall health (U.S. Environmental Protection Agency, 2023).

Although algae-based air purification systems have many potential uses, issues with scalability, effectiveness in different environmental conditions, and economic viability remain (Bender et al., 2018). For example, the regulation of airflow and the availability of light have a major impact on the metabolic activity of microalgae, which directly affects their ability to purify the air. Furthermore, additional cost-benefit evaluations are needed to assess the feasibility of photobioreactors in various urban environments and for maintenance. By reviewing recent studies on algae's function in air filtration, analysing successful implementation case studies, and talking about potential future large-scale adoption, this paper aims to close these gaps.

This study's key question is: What are the obstacles and prospects of the broad adoption of algae-based systems, and how successful are they in enhancing indoor air quality? This paper is structured as follows: The thorough literature analysis of prior research on algae-based air filtration and its reported advantages is given in the following section. A review of the techniques used to evaluate the effectiveness of algae systems, including both practical and experimental applications, with an emphasis on their advantages and disadvantages. Lastly, suggestions for further study and useful factors for incorporating algae-based air purification into urban settings are included in the paper's conclusion.

Given the growing concern about air pollution and the need for sustainable solutions, this research is important. This study adds to the increasing amount of information on biofiltration strategies and their function in environmental health, evaluating the potential of algae-based systems. Its purpose is to offer ways to environmental scientists, urban planners, and architects, creative ways to enhance indoor air quality. If the implementation issues with algae-based systems can be resolved, they could provide a sustainable and feasible solution to the urgent need for eco-friendly air purification methods.

Literature Review

The Scope Of Indoor Air Pollution

In recent years, algae-based purification systems have drawn more interest because of their potential to improve air quality and promote sustainability. The research on algae-based systems and their incorporation into the built environment, and their efficiency in lowering indoor air pollutants is summarized in this overview of the literature. Despite notable progress, questions regarding long-term efficiency, economic viability, and scalability remain unanswered.

Evolution Of Nature-Based Air Purification Strategies

Early studies focused on plants' capacity to filter air pollutants, but nature-based solutions have gone through significant evolution (Irga et al., 2013). Algae, which have demonstrated excellent $CO2$ absorption and pollution filtration capacity, have been included in the recent research (Han et al., 2023). Microalgae are more suited for urban settings since they may be integrated into small systems and require less area than terrestrial plants (Ainsworth, 2021). The potential of photobioreactors, a crucial algae-based air filtration technology to improve air quality while generating oxygen, has been investigated (George, 2023).

Integration Into Building Systems

To improve indoor air quality and sustainability, algae-based technologies have been effectively incorporated into architectural designs. In their discussion of algae facades in green buildings, Hariyanto et al. (2022) demonstrate how these systems not only clean the air but also increase energy efficiency by acting as insulation. Their analysis also shows that photobioreactors (PBR) facades work well for controlling indoor humidity levels and filtering volatile organic compounds (VOCs). Although a particular study by Mata et al. (2022) discovered limitations of these systems in large-scale urban settings due to their high installation costs and maintenance needs.

Integration Into Building Systems

There are still study gaps on the long-term effects of algae-based air purification on indoor spaces, despite notable developments (Talaei & Prieto, 2024). To evaluate the resilience, effectiveness in many environmental settings, and economic viability of algae systems, more empirical research is required (Matos et al., 2021). Furthermore, by offering real-time data on improvements in air quality, the integration of smart monitoring technologies may increase the efficacy of these systems (Zhang et al., 2023). To optimize their potential benefits, future research should concentrate on improving photobioreactor (PBR) designs, optimizing algae strains, and creating economical implementation strategies (Talaei & Prieto, 2024).

Methodology

Research Design

This study is a thorough analysis that summarizes recent research and findings related to indoor air purification using algae. A comprehensive review of the literature analysis of studies released in the previous five years comprises the methodology used. Reviews, conference papers and research publications that addressed the functionality, integration and design of algae-based systems in indoor settings were give special attention to.

Systematic Literature Review

Several databases, including Google Scholar and Scopus, were searched systematically. Keywords like “algae-based air purification,” “indoor air quality,” “photobioreactor,” “Spirulina maxima,” and “nature-based solutions” were used to find relevant studies. The inclusion criteria were as follows:

- Peer-reviewed articles, conference proceedings, and high-quality reviews.
- Studies focusing specifically on indoor applications, experimental evaluations of system performance, or architectural design proposals integrating algae-based technologies.

Comparative Data Analysis

Extracted data from the selected studies were compared with regard to:

- Pollutant removal efficiency (e.g., percentage reduction in CO_2, VOCs)
- Energy consumption and operational costs
- Design parameters (e.g., reactor geometry, light intensity, and nutrient flow)

A comparison analysis made it easier to identify the crucial design elements and optimal operating conditions. Results from different studies were analysed and compared.

Theoretical Modeling and Framework Development

A number of theoretical models were reviewed in addition to empirical data. According to Mata et al. (2021), these models replicate the rates of CO_2 absorption, the kinetics of algal growth, and the impact of external factors on system performance. An enhanced comprehension of the design specifications and operational thresholds required to attain peak performance in practical contexts was made possible by the examination of these models. Light penetration, nutrient availability, and airflow dynamics were among the variables that were thoroughly analysed to ascertain their effects on the short- and long-term performance of algae-based air purification systems.

Synthesis and Validation

The inclusion criteria, data extraction and literature search have been clearly defined. However, there are limitations in this methodology. Variability may be caused in measuring methods, indoor ambient conditions, and experimental design across studies.

Results

Performance Of Algae-Based Systems

The majority of studies reviewed indicate that algae-based systems are effective at reducing key indoor pollutants. Algae-based systems can efficiently reduce indoor air pollutants, according to the study. Under ideal circumstances, removal efficiencies for fine particulate matter (PM2.5) and volatile organic compounds (VOCs) reached significant levels; in controlled settings, particulate removal efficiencies approached 80%, while some studies reported VOC removal up to 96% using species like Chlorella vulgaris. This high efficiency highlights the devices' potential as competitive substitutes for traditional indoor air purifiers. Interestingly, performance is strongly influenced by the kind of microalgae used, with Chlorella vulgaris showing very good VOC-capture capacities (Vitaliano et al., 2024).

According to Dalay and Aytaç (2024), including algae-based photobioreactors into building designs has the potential to significantly enhance indoor air quality. Their architectural suggestions, which prioritize regulated airflow and light levels, show that well-designed systems may enhance thermal regulation and energy efficiency in buildings in addition to lowering pollution levels.

This study shows that algae systems may significantly reduce pollutants when given the right conditions and upkeep, in contrast to previous research that suggested algae had limited efficacy in practical applications.

All things considered, this study adds to the increasing amount of data demonstrating the efficacy of algae-based indoor air filtration systems and exploring their usefulness for urban sustainability. (Vitaliano, et al., 2024).

The incorporation of algae-based systems into pre-existing building designs was also investigated in the study. Significant increases in interior air quality were noted when algae-based photobioreactors (PBRs) were integrated into indoor air handling systems and building facades. Lower levels of indoor CO_2, VOC, and PM_2 were observed, indicating that integrating these systems into buildings may lessen respiratory health problems for residents (Mata et al., 2021).

Data and Analytical Findings

The performance of algae-based indoor air filtration systems has been determined by combining data from several controlled trials. According to the meta-analysis, these systems can remove volatile organic compounds (VOCs) and fine particulate matter (PM 2.5) with a removal efficiency of up to 80% when operating under ideal conditions. Average removal efficiency for both pollutant categories in controlled trials was found to be between 50% and 80% across various systems. When environmental conditions are carefully regulated, algae-based systems are not only successful at lowering CO_2 levels but also excel at removing other indoor contaminants, according to this meta-analytical finding (Han et al., 2023).

These results suggest that when environmental conditions are optimized—particularly in terms of light exposure, nutrient supply, and airflow—algae-based systems are capable of achieving significant improvements in indoor air quality.

Factors Affecting System Performance

Light Exposure

One important factor influencing the effectiveness of microalgal photosynthetic activity is light intensity. According to experimental research, keeping light levels normally between 1,000 and 10,000 lux maximizes biomass production and improves the absorption of pollutants such as particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs) (Maltsev et al., 2021; Metsoviti et al., 2019). Algal development is hindered by inadequate sunlight, which lowers the overall efficacy of algae-based air or wastewater treatment systems. Therefore, to guarantee that these systems operate at their best, precise control over light intensity is essential.

Airflow Dynamics

To maintain the constant interaction of indoor air pollutants with microalgae cells, airflow is essential. By improving air exchange, increased airflow lengthens the period that contaminants and microalgal cells are in contact. According to studies, better airflow dynamics increase removal efficiencies because ongoing dirty air renewal keeps local saturation at bay and promotes prolonged photosynthetic activity. Designing an efficient air circulation system is essential to maximizing algal performance (Wang et al., 2023).

Airflow Boosts Algae Cleanup

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Nutrient Availability

The rate at which microalgae develop, as well as their ability to fix CO_2 and absorb pollutants, are closely connected to the content and concentration of nutrients in the algae culture medium. Tests show that a well-balanced nutrition medium, which includes the right amount of bicarbonate ($NaHCO_3$), encourages fast algae growth, which improves pollution removal. Low or unbalanced nutrient levels, on the other hand, may cause the algal culture to grow more slowly, which would lower removal efficiency. Consequently, a crucial component of system function is accurate nutrient control (Mata et al., 2021).

Chamber Volume and Pollutant Concentration

The measured pollutant reduction percentages are influenced by the physical characteristics of the indoor space where the algae-based system is installed. Comparing smaller test chambers with greater beginning pollutant concentrations to bigger ones, the percentage reductions are typically more pronounced. This association suggests that the initial pollution load and the system's magnitude are both crucial factors to take into account when assessing system performance. Real-world applications may yield more consistent and repeatable outcomes if these parameters are optimized (Han et al., 2023).

Economic and Practical Considerations

Even though algae-based systems exhibit encouraging technical performance, economic viability is still a major obstacle. The need for regulated environmental conditions like artificial lighting in low sunlight locations, capital costs, and maintenance requirements (e.g., periodic cleaning and replacement of culture medium) may prevent widespread use. According to preliminary techno-economic evaluations, even if operating costs might be less than those of some traditional air purifiers, more optimization is needed to address the upfront investment and integration issues in existing building structures (Dalay & Aytaç, 2024).

Efficacy of Microalgae Photobioreactor Systems

A thorough assessment was conducted on the effectiveness of microalgae photobioreactor (PBR) systems for indoor air treatment. These devices efficiently lower CO_2 concentrations as well as VOCs and PM_2, according to experimental results.

For instance, systems employing Spirulina maxima showed removal efficiency of over 80% for both VOCs and PM_2, whereas controlled trials using Chlorella vulgaris reached VOC removal efficiencies as high as 96%. These findings suggest that, provided optimal operating parameters are maintained, algae-based PBR systems can operate on par with or better than traditional mechanical filtering technologies (Han et al., 2023).

Integration Into Building Systems

From a performance and aesthetic standpoint, the incorporation of algae-based photobioreactors (PBRs) into architectural systems had been studied. According to Semang and Razali (2022), adding PBRs to a building's facade or green wall can have two advantages: better indoor air quality and better building thermal performance. Because of the cooling effects of the water evaporating from the reactors, buildings with integrated PBR systems showed lower ambient temperatures as well as lower interior CO_2 levels in one pilot study.

According to Al Horr et al. (2016), these integrated systems lessen the need for air conditioning and mechanical ventilation, which results in energy savings. According to their findings, even if PBR installation has a comparatively high initial cost, the investment may be justified in the long run by the energy savings and increases in occupant productivity.

Economic and Energy Considerations

Algal-based systems provide a number of potential benefits from an energy and financial perspective. The systems make use of natural photosynthetic processes, which use less energy than traditional HVAC and air purification systems that use filters that are powered by electricity. Over time, this energy efficiency can result in significant operational cost savings and a decrease in the building's carbon impact. However, the initial installation costs and the requirement for recurring maintenance to guarantee sustained operation have an impact on these systems' economic sustainability.

In addition, even while the environmental advantages and energy savings seem promising, a positive return on investment requires careful management of the high initial capital costs and integration difficulties. Therefore, to improve the financial and energy-efficient aspects of algae-based indoor air purification systems, future research should concentrate on optimizing design parameters and maintenance procedures (Dalay & Aytaç, 2024; Mata et al., 2021).

Variability in System Performance

Indoor environmental elements, including humidity, temperature, and light intensity, have a big impact on system performance. According to Mata et al. (2021), insufficient indoor light levels can restrict microalgae's ability to photosynthesize, which lowers the effectiveness of pollution removal (Mata et al., 2021). As shown by Han et al. (2023), laboratory experiments carried out in controlled settings with optimal light exposure frequently yield better removal efficiencies than those seen in practical applications.

Additionally, changes in indoor humidity and temperature have an impact on the physical characteristics of reactor systems as well as the rate at which microalgae grow; recent reviews by the European Environment Agency (2023) have highlighted the substantial influence that these environmental fluctuations can have on system performance (European Environment Agency, 2023).

According to Gonzalez-Martin et al. (2021) and Dalay and Aytaç (2024), theoretical models and design evaluations demonstrate that consistent performance depends on steady operating circumstances. To maximize pollutant removal and overall system efficacy in settings where these factors change, adaptive system designs incorporating sensors and automated controls are required (Mata et al., 2021).

Discussion

Interpretation of Key Findings

According to the study, algal-based systems can efficiently remove up to 80% of fine particulate matter (PM 2.5) and volatile organic compounds (VOCs) from indoor air. Under ideal circumstances, some algal species, like Chlorella vulgaris, can remove up to 96% of VOCs. Algal-based photobioreactor (PBR) systems show a lot of promise as environmentally friendly substitutes for traditional air purifiers, according to these findings. In addition, the study found that crucial operational factors that maximize pollution removal include airflow dynamics, nutrient availability, and light intensity. To make sure the systems run reliably and efficiently, it is essential to maintain these ideal circumstances (Han et al., 2023; Mata et al., 2021).

Advantages Over Conventional Technologies

Comparing algae-based systems to traditional air cleaning technology reveals a number of benefits. In contrast to conventional techniques that use chemical absorbents or energy-intensive mechanical filters, which frequently need to be replaced and produce secondary waste, algae-based systems purify the air using natural photosynthetic processes. In addition to producing renewable biomass that can be used to make biofuel or other value-added products, this technique lowers pollutants like CO2, VOCs, and PM (2.5). Furthermore, including these systems in building facades can improve thermal management and add to urban environments' aesthetic appeal, both of which support sustainability in general (Mata et al., 2021; Han et al., 2023).

Operational Challenges and Limitations

Algal-based systems have a number of operational issues that could prevent them from being widely used, despite their potential. Strict control over environmental parameters like humidity, temperature, and light intensity is necessary to maintain constant system operation. Changes in these variables may lead to varying rates of algae development and, as a result, uneven efficacy in removing pollutants. Furthermore, to avoid problems like nutrient depletion and culture contamination, routine maintenance is required. These difficulties highlight the necessity of adaptive system designs that use automated controls and sensors to continuously monitor and modify the environment for long-term performance (Dalay & Aytaç, 2024; Mata et al., 2021).

Environmental Control

It is essential to maintain the ideal parameters for microalgae growth, including temperature, light intensity, and nutrient availability. Performance may suffer from changes in certain parameters (Novoveska et al., 2023).

Maintenance and Contamination

To avoid contamination by undesirable bacteria, which might impair system performance and need for extra cleaning procedures, routine maintenance is crucial (Novoveska et al., 2023).

Scalability

One of the problems in scaling microalgae systems from laboratory settings to large-scale applications is making sure that light is distributed uniformly and that CO_2 is delivered efficiently throughout the system (Novoveska et al., 2023).

Economic Viability

Despite the fact that algae-based systems are less expensive to operate than some traditional technologies, integration complexity and high initial capital costs continue to be obstacles. It is necessary to conduct further study on cost-cutting measures including modular designs and streamlined maintenance protocols.

Comparison With Conventional Air Purification Systems

Algae-based PBRs offer a strong substitute for traditional air purification systems because of their many uses and reduced energy consumption. Conventional systems, like activated carbon units and HEPA filters, are good at absorbing pollutants, but they usually use a lot of energy and produce waste that needs to be changed often. Algal-based systems, on the other hand, provide continual purification with little energy input because they replenish continuously through biological processes. Furthermore, including these systems in building designs can result in secondary advantages that conventional systems do not offer, like better temperature regulation (Han et al., 2023; Gonzalez-Martin et al., 2021).

Future Research Directions

Even if the current research appears encouraging, there are still a number of unanswered problems that need to be addressed in subsequent studies:

The majority of experiments have been carried out in controlled laboratory settings thus far. In order to evaluate the durability and maintenance needs of algae-based systems and to comprehend how they function in a variety of situations, long-term field investigations in actual building environments are crucial.

Multi-Pollutant Removal

The elimination of other indoor pollutants, such as VOCs, NOx, and particulate matter, requires more research, even if the decrease of CO_2 is well established. The design of systems that handle every facet of IAQ will be aided by thorough studies that quantify the entire range of pollutant removal.

Design Optimization

Innovative reactor designs that optimize light collection, enhance mixing efficiency, and consume the least amount of energy should be the focus of future research. Performance optimization under changing indoor conditions may be greatly aided by advanced materials and adaptive control systems.

Economic Viability

In order to assess the economic viability of algae-based systems in comparison to traditional air purifiers, comprehensive cost studies are required, encompassing capital, operational, and maintenance expenses. Research on possible sources of income from algal biomass will also be beneficial.

Integration Strategies

Taking into account variables like limited space, current ventilation systems, and architectural design, research should concentrate on the most effective ways to incorporate algae-based systems into various building types. For the most practical options, hybrid systems that mix mechanical and natural air purifying techniques may be available.

Future research can help turn algae-based systems from interesting prototypes into reliable, affordable solutions for improving indoor air quality by filling in these research gaps.

Conclusion

In the modern built environment, the increasing amount of indoor air pollution presents a serious health and financial problem. By using microalgae's natural photosynthetic processes, algae-based systems provide a sustainable way to purge indoor air contaminants. Microalgae photobioreactors have the ability to drastically lower indoor CO2 levels and other dangerous pollutants, according to recent studies. For example, a study using a tubular photobioreactor system with Chorela vulgaris demonstrated the effectiveness of microalgae in air purification efforts by achieving a 26.59% reduction in CO2 emissions over 11 days (Minh et al., 2021).

Spirulina maxima was used in a different study to examine the performance of a microalgae photobioreactor system in a $NaHCO_3$-reduced medium. The results showed stable microalgae growth and efficient CO_3 absorption, which provided information for improving indoor air remediation techniques (Kim et al., 2023). Furthermore, studies on photobioreactor systems for reducing carbon dioxide and ammonia from broiler houses have demonstrated that microalgae can successfully lower these pollutants; Ankistrodesmus sp. have been found to achieve high biomass concentrations, and Synechococcaceae species have demonstrated a 70.8% mitigation efficiency for CO_2 (Uguz et al., 2024). All of these studies highlight the promise of photobioreactors based on microalgae as workable ways to improve indoor air quality and support sustainable building practices.

Algae-based systems, whether integrated into budling facades or used independently, have a number of advantages, including better indoor air quality (IAQ), lower energy use, greater budling aesthetics, and the potential to produce useful byproducts like biomass for fertilizer or energy. However, before these systems can be used on a large scale, issues with high costs, restricted light supply and system maintenance must be resolved.

Based on findings from recent research publications, this synthesis emphasized the necessity of more long-term field research, design optimization, and thorough cost-benefit evaluations. The development of algae-based air filtration technologies and the verification of their efficacy in practical settings will depend heavily on such initiatives. A major advancement in the search for environmentally friendly, sustainable ways to enhance indoor air quality, algae-based devices may not yet completely replace traditional air purifiers.

It is expected that advancements in material science, control systems, and reactor design will help in the overcoming present limitations. Also, combining algae-based systems with other renewable theologies may open door to structures that support the environmental sustainability white simultaneously creating healthy indoor spaces.

In conclusion, indoor air purification systems based on algae offer a viable, environmentally friendly way to reduce the levels of indoor air pollutants. Empirical research has shown that these systems can significantly help remove particulate matter and volatile organic compounds (VOCs), while also providing other advantages like better thermal insulation and the production of renewable biomass (Han et al., 2023; Dalay & Aytaç, 2024). Building designs that use algae-based photobioreactors present a strong alternative to traditional air purification systems, despite ongoing issues with environmental control, maintenance, scalability, and economic viability. Realizing the full potential of these systems will require research focused on cost-effective integration methodologies, long-term performance evaluation, and operational parameter optimization. When incorporated into building facades or used independently, algae-based systems provide several advantages, including better indoor air quality, lower energy usage, better building aesthetics, and the potential to produce byproducts like fertilizer or biomass for electricity. But before these systems can be used widely, issues including high costs, scarce light, and system maintenance need to be resolved.

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