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Microalgae Based Air Purifiers: A Sustainable Approach To Urban Air Pollution Mitigation In Environmental Context

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Abstract
Air pollution poses a serious threat to human health, ecosystems, and climate stability. While conventional air purification technologies provide partial relief, they often lack scalability, cost-effectiveness, and environmental sustainability. In recent years, microalgae-based air purifiers have emerged as promising bio-inspired solutions. Through photosynthesis, microalgae absorb carbon dioxide (CO_2) and various airborne pollutants while releasing oxygen, making them ideal agents for bioremediation in urban settings. This review explores the biological mechanisms underlying microalgal air purification, evaluates major photobioreactor designs, and assesses real-world applications in urban environments. It also contextualizes the role of this innovation in broader sustainability debates, particularly within policy conflicts surrounding land use, biodiversity loss, and Indigenous rights in regions like Indonesia. Ultimately, the paper underscores the need for responsible integration of green technologies within ethically sound and ecologically sensitive policy frameworks.

Keywords: *Microalgae, Air Purifier, Sustainability, Photobioreactor, Environmental Policy.*

1. INTRODUCTION

Urban air pollution has reached critical levels, with the World Health Organization (2021) reporting that 99% of the global population is exposed to air exceeding safe quality guidelines. The resulting impacts include respiratory and cardiovascular diseases, increased mortality, and economic strain. In response, biological alternatives such as microalgae have gained attention for their dual ability to sequester CO_2 and produce oxygen—essential for air remediation in densely populated, polluted areas.
Microalgae are unicellular photosynthetic organisms known for their rapid biomass growth and remarkable pollutant absorption capabilities. These traits render them particularly suitable for compact, sustainable air purification systems in urban environments, where traditional solutions often prove insufficient.

2. BIOLOGICAL MECHANISMS IN MICROALGAL AIR PURIFICATION

2.1 CO_2 Absorption via Photosynthesis

Microalgae perform photosynthesis using sunlight, water, and atmospheric CO_2, producing glucose and oxygen: $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$ Certain strains can absorb up to 2 kg of CO_2 per kilogram of dry biomass (Rawat et al., 2011), making them highly efficient natural carbon sinks (Delrue et al., 2013).

2.2 Removal of Pollutants

2.2.1 Indoor air pollution and the need for sustainable solutions

Indoor air pollution is a major contributor to respiratory and cardiovascular diseases, requiring effective mitigation strategies. Conventional methods (HEPA filters, activated carbon, photocatalysis) can remove

pollutants, but they are energy-intensive and lack sustainability. Nature-based solutions (NBS) such as plants and microalgae offer co-benefits like CO_2 sequestration and O_2 generation, while also contributing to urban sustainability goals (Mata et al., 2021).
Beyond CO_2, microalgae are capable of capturing nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs) through processes like biosorption and bioaccumulation (Yadav et al., 2021). Their adaptability allows consistent performance under controlled photobioreactor (PBR) conditions.

2.2.2 Nature-based solutions in buildings

Mata et al. (2021) highlight the role of green walls, green roofs, and algae-based systems as architectural interventions to enhance indoor air quality (IAQ). Their review emphasizes that algae photobioreactors (PBRs) can function as **bio-filters**, simultaneously improving IAQ, generating biomass, and contributing to thermal regulation in buildings.

2.2.3 Microalgae versus conventional purification technologies

Kumar et al. (2023) conducted a comparative analysis of conventional air purification and microalgae-based systems. They conclude that microalgal air purification technology (MAPT) is a sustainable alternative capable of removing **CO_2, VOCs, and particulates** while producing O_2 and valuable biomass. However, they note practical challenges, including **light management, mass transfer, and maintenance requirements**.
Wang et al. (2023) experimentally validated that microalgae can reduce indoor pollutants and CO_2 under controlled conditions, performing comparably to some common methods. Their study used multiple air-quality parameters, reinforcing the need for standardized protocols in future research.

2.2.4 Architecture and device-level implementations

At the architectural scale, Dalay & Aytaç (2024) proposed algae-integrated architecture where PBR modules are incorporated into façades to reduce CO_2 indoors. Such systems not only clean air but also align with **biophilic design principles** for healthier living environments.
On the product side, Bharathy & Murali (2025) introduced a **smart biotechnological algal plate air purification system** with real-time air-quality monitoring, showing how IoT integration enhances reliability and performance. Similarly, Ferdynand et al. (2025) designed a **self-sustaining microalgae purifier** as an alternative to indoor plants, demonstrating innovation in household-scale IAQ improvement.

3 PHOTOBIOREACTOR DESIGNS FOR AIR PURIFICATION

Various PBR configurations have been engineered to optimize microalgal growth and pollutant uptake: Microalgae are typically cultivated in photobioreactors (PBRs) that allow controlled growth while maximizing light exposure.

3.1 Flat-Plate Photobioreactors

Flat-plate PBRs are compact and offer high surface area- to -volume ratios, suitable for integration into urban infrastructure (Chisti, 2007).

3.2 Tubular Photobioreactors

Tubular systems allow continuous culture in vertical or horizontal configurations, optimizing gas exchange and light penetration (Grobbelaar, 2009).

3.3 Living Walls and Architectural Integration

Projects such as the BIQ House in Hamburg, Germany, have demonstrated how microalgal panels can serve both environmental and aesthetic purposes in buildings (Sani, 2022).

4. CASE STUDIES OF URBAN APPLICATIONS

Pilot projects in cities such as Mexico City and Paris have deployed microalgae systems like GreenFluidics' BIO

Urban 2.0, using strains such as *Spirulina* to improve localized air quality (GreenFluidics, 2023). Results from such systems indicate significant CO_2 sequestration and public engagement with green technologies.
In their 2019 study published in the *Journal of Chemical Technology & Biotechnology*, Lu et al. introduce an innovative microalgae film based air purifier that simultaneously enhances indoor air quality by producing oxygen and removing fine particulate matter ($PM_{2.5}$) The system features a dense microalgae film supported by hydrogel, which notably reduces moisture loss (to 24.76% over 8 hours), thereby sustaining photosynthetic oxygen output and particulate capture Mechanistic investigations reveal that microalgae remove particulates primarily through electrostatic attraction owing to their negatively charged surfaces while the hydrogel enhances this performance by maintaining film hydration The authors emphasize that controlling moisture content and pH is essential for reliable real-world operation. Overall, this study demonstrates the feasibility of a lightweight, low-energy, bio-inspired purifier that could complement or replace conventional air filtration systems in enclosed environments.(Lu et al., 2019).
In their 2023 study published in *Applied Sciences*, Han et al. experimentally explored a lab-scale microalgae photobioreactor (PBR) employing *Spirulina maxima* cultivated in media with reduced sodium bicarbonate ($NaHCO_3$) concentrations to remediate indoor air by absorbing CO_2. They evaluated three cultivation conditions full, 50%, and zero $NaHCO_3$—monitoring biomass growth over 30 days and measuring CO_2 uptake in air chambers of 2, 4, and 7 L at ambient levels (~1100 ppm) and elevated (~10,000 ppm) CO_2 concentrations Results showed a ~55% reduction in CO_2 within a 0.064 m^3 chamber, peaking at ~20% reduction by Day 4, with up to ~90% removal under high CO_2 before reaching saturation These findings demonstrate that *S. maxima* can efficiently capture CO_2 in indoor settings, even when bicarbonate supply is limited, offering a promising, resource-efficient biological option for improving air quality in sealed environments. (Han et al. (2023) *Comparative study on conventional and microalgae-based air purifiers: Paving the way for sustainable green spaces"* by **Pradeep Kumar et al.** offers an insightful comparative analysis of traditional air purification technologies and innovative microalgae-based systems. It effectively highlights the advantages of microalgae, including carbon dioxide sequestration, oxygen release, and low energy consumption, positioning them as sustainable alternatives to conventional mechanical filters. The paper is well-structured and interdisciplinary, drawing from environmental science and biotechnology to argue for greener urban solutions. However, the review could be strengthened by incorporating more recent empirical data, addressing practical limitations of algae-based systems in real-world applications, and updating references to include the latest research. Overall, it is a valuable contribution to the growing body of literature on sustainable air purification technologies.

5. BROADER ENVIRONMENTAL CONTEXT: THE INDONESIAN CASE

Innovations in green technology, however, must be evaluated against wider environmental and policy backdrops. Indonesia exemplifies a paradox: while investing in sustainability, it simultaneously faces criticism for accelerating deforestation under the Food Estate Program.

5.1 Biodiversity Loss and Carbon Emissions

Indonesia's primary forests, home to endangered species and essential carbon sinks, are increasingly being converted to monocultures. Studies estimate deforestation could release up to 315 million tons of CO_2 (Mighty Earth, 2023), and replanted areas often lack ecological complexity (Margono et al., 2014).

5.2 Ethical and Social Concerns

Government land-use policies have drawn criticism for displacing Indigenous communities and violating customary land rights (HRW, 2024). Environmental technologies, while beneficial, cannot substitute for preserving intact ecosystems and must not be used to justify ecological harm.

6. EMERGING AND PRELIMINARY STUDIES

Kalisi (2025) also evaluated algae-based systems for pollutant reduction, reinforcing their potential but noting that most studies remain **pilot or laboratory-based** rather than long- term in situ implementations.

7. CONVERGING THEMES AND RESEARCH GAPS

Across these studies, three key themes emerge:
Co-benefits: Algae systems uniquely provide CO_2 capture, O_2 production, and biomass valorization (Mata et al., 2021; Kumar et al., 2023).
IoT integration: Smart controls help maintain algal growth conditions and link purification to air-quality monitoring (Bharathy & Murali, 2025; Ferdynand et al., 2025)
Evidence gaps: While short-term experiments are promising, there is a need for **standardized benchmarking, techno-economic analysis, and long-term field validation** (Wang et al., 2023; Dalay & Aytaç, 2024).

8. SUSTAINABLE INNOVATION AND POLICY RECOMMENDATIONS

1. To maximize the ecological and social benefits of microalgae-based air purifiers
2. .Integrate algae systems into urban sustainability plans and green building standards.
3. Enforce rigorous environmental impact assessments before large-scale land conversion.
4. Safeguard Indigenous land rights in national environmental strategies.

5. Promote international collaborations for scalable, low-cost microalgae technology.

9. CONCLUSION

Microalgae-based air purifiers offer a novel, ecologically sound solution to urban air pollution. Their scalability, low energy demands, and CO_2 sequestration capabilities position them as future assets in sustainable city planning. However, their implementation must occur within ethical and environmentally responsible frameworks. Lessons from regions like Indonesia underscore the importance of aligning innovation with conservation and justice. Only through integrative and inclusive policymaking can technological progress genuinely support long-term ecological resilience.

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