Beyond Filters: Evaluating Biotechnological Indoor Air Purification with Microalgae Systems

Yonca Yaman [1], Ayça Tokuç [1, 2], Seda Nur Apdik [1], İrem Deniz [3], Azize Ayol [2,4], Gizem Tuna Tuygun [4], Tunahan Akış [2,5], and Mehmet Akif Ezan [2,6]

[1] Department of Architecture, Dokuz Eylül University, 35390, İzmir, Türkiye, yaman.yonca@ogr.deu.edu.tr; ayca.tokuc@deu.edu.tr; sedanurapdik@hotmail.com
[2] Energy Research and Application Center (EUAM), Dokuz Eylül University, 35390, İzmir, Türkiye
[3] Department of Bioengineering, Manisa Celal Bayar University, 45140, Manisa, Türkiye, iremdenz@gmail.com
[4] Department of Environmental Engineering, Dokuz Eylül University, 35390, İzmir, Türkiye, azize.ayol@deu.edu.tr; gizem.tuna@deu.edu.tr
[5] Electric and Energy Department, İzmir Vocational School, Dokuz Eylül University, 35360, İzmir, Türkiye, tunahan.akis@deu.edu.tr
[6] Department of Mechanical Engineering, Dokuz Eylül University, 35390, İzmir, Türkiye, mehmet.ezan@deu.edu.tr

Abstract. Managing indoor air quality is crucial to prevent harmful health impacts on building occupants. Prominent strategies are controlling the source of emissions and pollutants, effective design of ventilation systems, and active reduction technologies. The various air purification methods range from conventional physicochemical techniques to sustainable biological treatments. Among these, biofiltration technologies stand out due to their environmental, economic, and social benefits. Additionally, emerging systems such as microalgae technologies offer carbon capture potential, while also retaining other pollutants, and contribute to improved quality of life, human health, and productivity of occupants. In recent years, while the potential benefits of microalgae on indoor air quality have attracted significant attention. However, the limited scope of existing literature and the need for deeper research into the potential effects of microalgae systems are the motivations of this study. This study evaluates biological air purification systems, particularly microalgae-based technologies, comparing them with conventional mechanical and plant-based approaches. The method is an Excel-based mass balance simulation to model pollutant removal performance for CO_2, VOCs and $PM_{2.5}$. The representative environment is an office with 96 m³ air and 15 occupants working over an 8-hour period. The simulation compares four system configurations; 1. Microalgal air purification with *Chlorella vulgaris*, a green wall, a HEPA filter, and a hybrid system with microalgal air purification and green wall. Results show that microalgal systems achieve superior performance in VOC removal and CO_2 mitigation, reaching steady-state concentrations of ~745 ppm compared to ~834 ppm without treatment. HEPA filters excelled at particulate matter removal (>99.97%) but provided no CO_2 reduction. Results indicate that biological air purification systems offer superior environmental sustainability compared to conventional mechanical approaches, with lower operating costs and multiple co-benefits including oxygen production and biomass generation. Although microalgal air purifiers are not widely used on the market, they stand out as a promising alternative for future air purification technologies due to their lower environmental impact, higher efficiency, and effectiveness across a broader range of pollutants, particularly in sustainable building design. However, pilot-scale studies and standardized evaluations are essential to advance and validate these technologies for widespread adoption.

Keywords. Air purification, biofiltration, carbon capture, indoor air quality, sustainable buildings

1 Introduction

Air pollution is one of the greatest environmental threats to human health worldwide, contributing to over 3.1 million premature deaths annually and accounting for 3.2% of the global diseases [1]. The COVID-19 pandemic has fundamentally shifted public awareness regarding indoor air quality (IAQ), highlighting the critical role of adequate ventilation and air purification in preventing airborne disease transmission. This heightened awareness has accelerated research and development of innovative air treatment technologies. Despite advances in air purification technologies, many buildings continue to experience inadequate IAQ due to insufficient ventilation, emissions from building materials and furnishings, and the accumulation of pollutants such as carbon dioxide

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

(CO_2), volatile organic compounds (VOCs), and particulate matter ($PM_{2.5}$). International standards recommend the maintenance of IAQ by decreasing CO_2 levels below 1000 parts per million (ppm) and $PM_{2.5}$ concentrations below 12 μg/m³ [1].

Traditional approaches to maintaining IAQ depend on mechanical filtration systems and increased ventilation rates. High-Efficiency Particulate Air (HEPA) captures PM with high removal efficiencies but demonstrates minimal effectiveness for gaseous pollutants such as CO_2 and VOCs. Activated carbon systems provide moderate VOC removal through adsorption mechanisms. Beyond their limited pollutant targets, conventional mechanical systems present several challenges including high energy consumption, production of secondary pollutants, ongoing maintenance costs, and environmental impact from filter manufacturing and disposal. Furthermore, these systems offer no additional environmental benefits beyond pollutant removal.

In response to these limitations, biological air purification systems have emerged as promising alternatives. They utilize the natural processes of living organisms to remove indoor air pollutants while providing secondary benefits such as improved thermal comfort, aesthetic value, and positive psychological effects. Plant-based systems have commercial and residential applications. Research demonstrates their capacity to remove multiple pollutant types simultaneously. However, the relatively low Clean Air Delivery Rate (CADR) of plant-based systems limits their practical applicability in many building contexts.

Microalgae offer promising biological air purification technologies. These photosynthetic organisms capture carbon and account for approximately 40% of global carbon capture [2]. Microalgae can be cultivated in compact photobioreactor systems. Studies show that microalgae also have remarkable pollutant removal capabilities. These performance metrics significantly exceed those of conventional plant-based systems and offer capabilities that mechanical filters cannot provide—particularly for CO_2 removal and oxygen generation. Some real-world applications such as LIQUID3 show that even small-scale installations (occupying as little as 1.11 m²) can deliver the carbon capture equivalent of mature trees while removing multiple air pollutants simultaneously [3].

Despite the promising performance in controlled laboratory studies and pilot installations, significant knowledge gaps remain regarding the effectiveness of different air purification approaches for IAQ applications. Most existing research focuses on single-system performance evaluations rather than systematic comparisons across different technologies. Furthermore, accessible computational tools that enable building designers and facility managers to evaluate alternative air purification strategies for specific building contexts are lacking. This study addresses these gaps by developing an Excel-based practical simulation framework based on mass balance principles that enable rapid evaluation of different air purifications and systematically comparing the performance of air purification systems across multiple pollutants (CO_2, VOCs, $PM_{2.5}$).

This research aims to show the potential of air purification technologies in building design and operation. The simulation uses performance data from peer-reviewed literature to model four systems: (1) microalgae photobioreactors, (2) green wall systems, (3) HEPA filtration, and (4) hybrid configurations. The findings contribute to the evidence supporting biological air treatment as a promising alternative to conventional mechanical systems.

2 Background and literature review

IAQ is primarily determined by the control of various pollutants. The main pollutant causes affecting IAQ can be categorized into three groups: (i) outdoor environmental conditions, (ii) factors related to occupant behaviour in buildings, and (iii) building related factors such as materials, equipment and furnishings. Three prominent strategies exist for managing indoor air quality: controlling the source of emissions and pollutants, effective design of ventilation systems, and active reduction technologies. Various air purification methods range from conventional physicochemical techniques to sustainable biological treatments. Among these, biofiltration technologies stand out due to their environmental, economic, and social benefits.

2.1 Mechanical filtration strategies

Mechanical filtration is one of the most widely used methods for capturing particulate matter. High-Efficiency Particulate Air (HEPA) filters can achieve PM removal rates of 99.97%, though they require regular replacement to maintain performance. Studies have shown that HEPA-equipped air purifiers can reduce PM levels by 12-68% depending on the device capacity [4]. However, these filters demonstrate minimal effectiveness for VOC removal (0-10%) and no capacity for CO_2 reduction.

Activated carbon systems provide 70-90% VOC removal efficiency through adsorption mechanisms but show limited effectiveness for particulate matter (10-30% removal) [5]. The main limitations of conventional systems include high energy consumption, production of secondary pollutants, and the need for regular filter replacement, which contributes to environmental waste.

2.2 Biological air purification systems

Green walls and botanical air filtration systems have gained attention for their ability to improve IAQ while providing additional benefits such as thermal insulation, acoustic performance, and biophilic design elements. Active green wall systems, equipped with fans to enhance airflow through plant root zones, demonstrate superior

performance compared to passive systems. Research indicates that active green walls can achieve 60-90% $PM_{2.5}$ removal, 50-80% VOC reduction, and 5-15% CO_2 mitigation. A comparative study in a building corridor showed that $PM_{2.5}$, PM_{10}, and total suspended particulates were 48.5%, 82.6%, and 5.5% lower respectively in corridors with green walls compared to those without [6]. However, the Clean Air Delivery Rate (CADR) for plant-based systems remains relatively low, with individual potted plants providing CADRs of only 0.002-0.084 m^3/hour, necessitating 10-1000 plants per square meter of floor area to achieve VOC removal equivalent to outdoor air exchange [7].

Microalgae have emerged as a promising biotechnological solution for indoor air purification, offering carbon capture potential while retaining other pollutants and contributing to improved quality of life, human health, and occupant productivity. Microalgae are known as carbon reducers due to their high CO_2 capture capacity, absorbing approximately 1.8 kg of CO_2 per 1 kg of biomass produced [2]. Experimental studies demonstrate that microalgae-based systems achieve remarkable pollutant removal efficiencies.

Different microalgae species exhibit varying tolerances to pollutants, with Chlorella vulgaris, Spirulina, and Scenedesmus obliquus standing out as particularly effective species. Applications such as photobioreactors (PBRs), biochar, and hybrid systems achieve 80-99% removal of CO_2 and nearly 100% of volatile organic compounds. *Chlorella vulgaris*, one of the most studied species for indoor air applications, has been shown to remove 55.42% of $PM_{2.5}$ and 45.76% of PM_{10}, while achieving nearly 100% removal of formaldehyde and VOCs—demonstrating higher performance than ornamental plant species [8].

Microalgae can be integrated into building facades or designed as urban elements, offering more efficient and applicable solutions compared to forestation due to their higher CO_2 fixation capacity per unit area. The BIQ Building in Hamburg, recognized as the first building-facade integrated application, removes approximately 6 tons of CO_2 annually through biomass production [9]. The system also generates 150 kWh/m^2 of thermal energy and 30 kWh/m^2 of bioenergy. Real-world applications demonstrate the practical viability of these systems.

The LIQUID3 system in Belgrade occupies only 1.11 m^2 of footprint while performing the function of one mature tree or 200 m^2 of grass area, capturing approximately 50 kg of CO_2 annually along with 22.94 kg of biomass [3]. The AIRoffice system, containing 10 liters of growth medium, reduces pollutants such as CO, NO_x, PM_{10}, and $PM_{2.5}$, with measurements showing 20 μg/m^3 CO_2, 0.69 μg/m^3 NO_2, 0.29 μg/m^3 PM_{10}, and 0.14 μg/m^3 $PM_{2.5}$ removal capacity [10].

Microalgae-based systems offer multiple advantages over conventional filtration methods such as lower environmental impact, higher efficiency, effectiveness across a broader range of pollutants, and the ability to convert biomass into value-added products including fertilizer, biofuel, and bioplastics. The systems also create positive impacts on building occupants [11]. However, these systems require optimization of growth medium conditions and regular maintenance. Factors affecting efficiency include light intensity, temperature, nutrient balance, and CO_2 concentration. Technology also faces challenges in terms of higher initial costs compared to conventional systems and the need for standardized evaluation protocols and pilot-scale demonstrations to support widespread applicability.

3 Methodology

This study provides an Excel-based mass balance simulation to evaluate the time-dependent performance of four different indoor air purification systems in a representative office environment. The simulation tracks CO_2 accumulation, VOC decay, and $PM_{2.5}$ removal over typical 8-hour working time.

3.1 Simulation model

The simulation approach is based on fundamental mass balance principles, tracking pollutant concentrations over time in a representative indoor space. The model accounts for three primary processes.

- Generation is from the continuous pollutant CO_2 generation from occupants' respiration.
- Removal by air purification systems is based on efficiency values from literature.
- Ventilation shows pollutant dilution through air changes.

The general mass balance equation for any pollutant is expressed as:

$$dP/dt = [G - \eta_{sys} \cdot P - Q\,(P - P_{out})] / V \quad (1)$$

where, P is indoor pollutant concentration (ppm or μg/m^3), V is the room volume (m^3), G is the generation rate (ppm/h), η_{sys} is system removal efficiency depending on system type, Q is ventilation rate (m^3/h), P_{out} is outdoor pollutant concentration (ppm or μg/m^3), t = time (hours).

For CO_2, the discrete form of the mass balance equation with a 5-minute time step (Δ_t is 0.0833 hours) is:

$$P(t+\Delta t) = P(t) + \{[G_{CO2} - \eta_{sys} \cdot P(t) - Q\,(P(t) - P_{out})] / V\} \cdot \Delta t \quad (2)$$

where, G_{CO2} is the generation of rate of 0.3 L/min per person representing typical light office work activity [12], η_{sys} is system removal efficiency between 0 to 0.55 depending on system type, Q is $V \times ACH$ (m^3/h), P_{out} is 410 ppm which is measured outdoor CO_2 data for model validation (see 3.4 for details). CO_2 removal rate for microalgae systems was modeled as a term based on photosynthetic uptake capacity. It does not explicitly model the effects of light limitation, nutrient depletion, pH changes, or culture density, which may influence actual

performance. The constant efficiency assumption represents steady-state operation under optimal maintenance conditions.

VOC removal follows an exponential decay model, appropriate for pollutants that are removed at rates proportional to their concentration:

$$P(t) = P_0 \cdot e^{-\eta_{VOC} \cdot t} + (E/\eta_{VOC}) \cdot (1 - e^{-\eta_{VOC} \cdot t}) \quad (3)$$

where P_0 is the initial VOC concentration (μg/m³), η_{VOC} is the system VOC removal efficiency (fraction per hour), E is the continuous emission rate from materials (μg/m³/h) and t is time in hours. For this study, an initial concentration of 500 μg/m³ was assumed, representing a moderately polluted indoor environment, with negligible continuous emissions to isolate system removal performance.

$PM_{2.5}$ removal similarly follows an exponential decay model with negligible generation during occupancy:

$$P(t) = P_0 \cdot e^{-\eta_{PM} \cdot t} \quad (4)$$

where, P_0 is the initial $PM_{2.5}$ concentration (35 μg/m³, representing moderate air quality) and η_{PM} is system PM removal efficiency as a fraction per hour.

Key assumptions for the simulation are:

• The model assumes constant removal efficiencies, whereas actual performance may vary with pollutant concentration and system maturation.

• The model assumes perfect air mixing throughout the room volume.

• Potential interactions between pollutants are not explicitly modeled.

• Performance degradation over time due to insufficient maintenance is not included.

The simulation was implemented in Microsoft Excel using discrete steps; 5 minutes for CO_2 and 1 hour for VOC and PM. Different temporal resolutions were selected based on the dynamic characteristics of each pollutant and computational efficiency considerations. CO_2 requires finer temporal resolution (5-minute timestep) due to: (i) continuous generation from occupant respiration creating rapid concentration changes, (ii) the need to capture transient behavior during occupancy transitions, and (iii) relatively fast equilibration timescale. In contrast, VOC and $PM_{2.5}$ follow exponential decay from initial concentrations with no continuous generation during occupancy, slower equilibration timescales and removal processes that are well-approximated by first-order kinetics. The Excel platform was selected due to its widespread availability, user-friendly interface, and sufficient computational capability for the required mass balance calculations.

3.2 Reference scenario definition

To enable systematic comparison, a reference office scenario was defined for a space of 4 m × 5 m × 2.5 m (L × W × H), with a total volume of 50 m³ and floor area of 20 m². Two people work inside for a typical workday of 8 hours. The indoor temperature is controlled by HVAC and changes between 20-25°C with a relative humidity of 40-60%. The ventilation (according to validation data) is 0.9 air changes per hour (ACH) with a ventilation rate of 85 m³/h. The baseline model does not provide any additional pollutant removal beyond dilution.

3.3 Evaluation of air purification systems

Four primary system configurations were evaluated, with performance parameters derived from the literature review. The microalgal purification system uses *Chlorella vulgaris*, for a cultivation volume of 60 liters with a 5000 lux LED light source and an air pump for circulation. The 6 m² green wall system is active with a mixture of species. The hybrid system combines both microalgae and green wall systems. The pollutant removal effectiveness calculates the final concentration after 8 hours (CO_2) or 4 hours (VOC, $PM_{2.5}$). In addition, the metrics evaluated include percentage reduction from baseline and time to reach acceptable concentration thresholds except for microalgae.

The removal efficiency parameters used in this simulation were synthesized from multiple peer-reviewed sources representing diverse experimental conditions. This is because there is no specific study that reliably provides all the required values in literature to the best of the authors' knowledge. The microalgae CO_2 removal rate is based on pooled estimates from our systematic review and meta-analysis of 13 studies [13]. Green wall parameters were derived from active green wall systems with fan-assisted airflow. HEPA filter performance represents manufacturer specifications under standard test conditions [14]. These values are indicative performance benchmarks rather than exact predictions for all contexts.

Table 1. System specifications and performance parameters

	Microalgae	*Green Wall*	*HEPA Filter*	Hybrid
CO_2 removal rate (%/h)	21	12	0	31
VOC removal (%/h)	98	65	5	85
$PM_{2.5}$ removal (%/h)	68	75	99.97	87

3.4 Model Validation

To validate the simulation framework, we compared model predictions against experimental CO_2 measurements collected in a controlled chamber study. Measurements were conducted on October 14, 2025 in an office with the same dimensions and people number as the reference scenario (Figure 1). CO_2 concentrations were recorded by three independent sensors at 5-minute

intervals for 24 hours. The MQTT cards have Winsen Sensors Multi-in-One ZPHS01B Sensor Modules. Two sensors are inside the office, while one is outdoors. The data is shown and recorded by both wireless central interface and local Raspberry Pi + MSI station.



Fig. 1. The reference office (Red X's show sensor placement).

The two people working inside gave breaks (between 12:00-13:00 and 14:30-15:00). Therefore, the results in Figure 2 are for a workday of five hours interrupted by breaks. The number of people inside the office is changed to "0 (zero)" during breaks. Figure 2 shows good agreement between simulated and measured CO_2 concentrations. The model sufficiently captured the rate of CO_2 accumulation during occupancy, steady-state concentration levels, and decay patterns during unoccupied periods. Quantitative analysis shows RMSE = 17.4 ppm (3.1% of mean concentration), MAPE: 2.1%, and R^2 = 0.9857. The predictive changes suggest limitations in the assumptions because of disregarded parameters. Overall, the validation demonstrates that the mass balance framework provides reliable predictions of indoor CO_2 concentrations under controlled conditions.

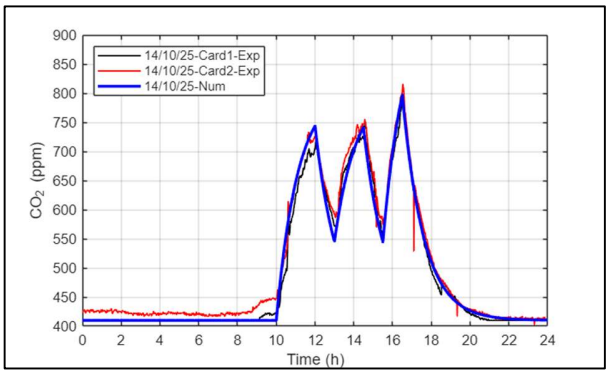


Fig. 2. Indoor CO_2 concentrations on 14.10.2025. Card1-Exp and Card2-Exp show measured data while -Num shows simulation results.

4 Results and discussion

The results show performance profiles along the four evaluated air purification systems for CO_2, VOCs, and $PM_{2.5}$ removal and a comparison of systems.

4.1 CO_2 Concentration

Figure 3 shows the change of indoor CO_2 concentrations over the eight-hour workday for each system. The CO_2 concentrations in the baseline with only ventilation of 0.9 ACH shows a rapid increase during the first four hours and reaching approximately steady state at 834 ppm. This represents 424 ppm increase from outdoor levels of 410 ppm by only two workers. Since the HEPA filtration has no CO_2 removal capability, its concentration profile is identical to the baseline. The microalgal system achieves 21% reduction in CO_2 generation rates and steady-state concentrations stabilized at approximately 745 ppm, with around 22% reduction compared to baseline conditions. Green wall system reaches 783 ppm after 8 hours. The hybrid system of microalgae and green wall achieves the highest CO_2 removal with 31% of generation rates and resulted in approximately 702 ppm in steady-state concentrations. This performance suggests a complementary mechanism between photosynthetic elements that enhanced air purification.

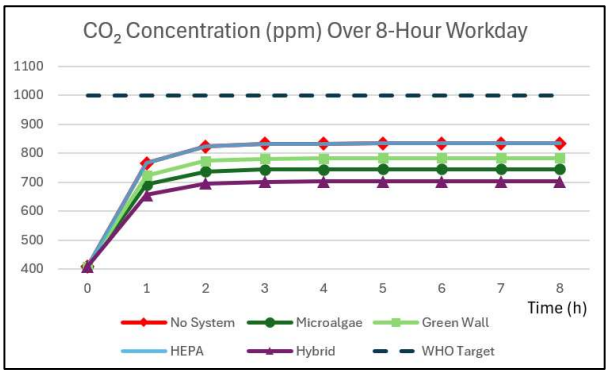


Fig. 3. Indoor CO_2 concentrations over an eight-hour workday.

4.2 VOC Concentration

VOC removal performance is in Figure 4. The initial level of 500 µg/m³ concentration shows decay over 4-hours. The microalgae system demonstrates good VOC removal efficiency, achieving 98% reduction within four hours down to 10 µg/m³, which is below WHO guidelines of 300 µg/m³ for TVOC [1]. These results confirm prior

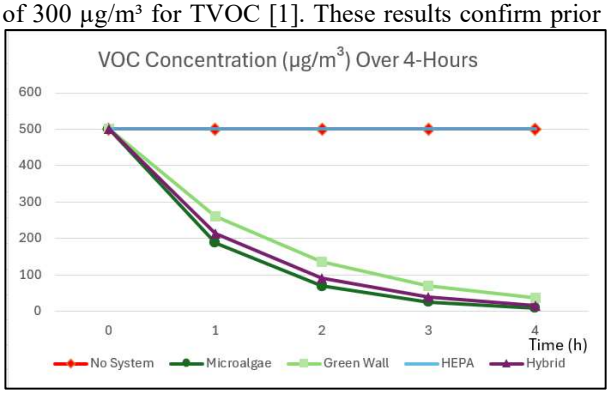


Fig. 4. Indoor VOC concentration changes over four hours.

experimental findings showing near-complete formaldehyde and VOC removal by *Chlorella vulgaris* [8]. The green wall achieves 65% VOC removal over the same period, reducing concentrations to 37 µg/m³. HEPA filtration, as anticipated, provided minimal VOC removal (~5%), confirming literature reports of 0-10% effectiveness for gaseous pollutants [4]. The hybrid system achieved a VOC removal down to 17 µg/m³.

4.3 PM Concentration

Figure 5 illustrates $PM_{2.5}$ removal performance, modeled from an initial concentration of 35 µg/m³ representing moderately polluted indoor conditions. Here, conventional HEPA filtration seems to have superiority with more than 99.97% particle removal efficiency in Table 1. All systems reached nearly excellent decline in $PM_{2.5}$ concentrations to less than 1 µg/m³. HEPA filters and the hybrid system reached these values within four hours, green wall system took five hours and microalgal system reached it in six hours.

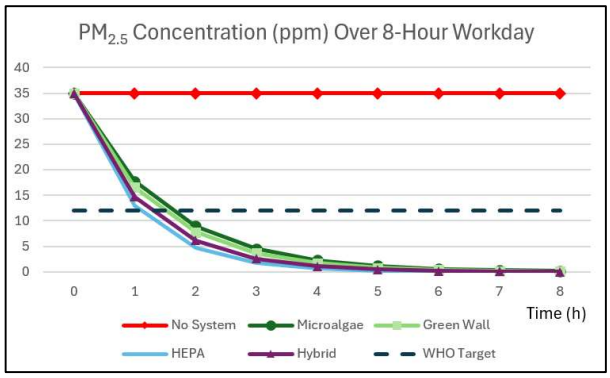


Fig. 5. Indoor $PM_{2.5}$ concentrations over eight hours of work.

4.4 Comparative performance analysis

Simulation results show that microalgal air purification systems are efficient biological mechanisms for CO_2 and VOC removal from indoors. Comparative analysis reveals distinct performance profiles, with each system demonstrating specific strengths for different pollutant categories and application contexts. Microalgae photobioreactor systems are the most effective biological solution for CO_2 and VOC removal. These systems provide important co-benefits including oxygen production at approximately 1.8 kg O_2 per kg of biomass produced [2], potential for biomass valorization into biofuels, bioplastics, and fertilizers, and visual appeal with educational value in building applications.

Green wall systems offer multi-pollutant removal with moderate effectiveness. They demonstrate good $PM_{2.5}$ removal performance at 75% per hour. Green walls provide established long-term operational reliability and significant biophilic design benefits that improve occupant well-being [11]. Additional co-benefits include thermal and acoustic insulation properties. The primary considerations for green wall implementations are the necessity for large installation areas.

Conventional HEPA filtration systems are the best for PM removal. They offer reliable performance through standardized technology, low complexity and space requirements. However, they provide no CO_2 or VOC removal capability. These filters offer no co-benefits beyond pollutant removal.

The hybrid configuration combining microalgal air purification with green walls demonstrates synergistic performance that exceeds independent system operation. This approach has the highest overall multi-pollutant removal potential. The combined system delivers the co-benefits of both biological technologies while providing the most comprehensive pollutant removal.

Based on simulation results and system characteristics, some places to consider utilizing bio-based systems for indoor air purification can be reaching sustainable building certifications for credit categories including IEQ, innovation, and materials/resources. Another value is the demonstration potential for biophilic design and building-integrated carbon capture, especially for research and educational buildings, supporting education and public engagement.

4.5 Limitations of the study

Several limitations should be considered when interpreting these results. The assumptions for the simulation model are the most prominent. The simulation assumes constant removal efficiencies, though actual performance may vary. In addition, perfect mixing may not reflect real buildings. VOC and $PM_{2.5}$ modelling assumed negligible continuous emissions to isolate system removal performance. Real-world applications can have active emission sources and would establish higher steady-state concentrations or conditions where removal rate equals emission rate. These computational predictions require experimental validation through long-term monitoring in real building conditions. Therefore, this model is a comparative screening tool for preliminary system selection rather than a precise prediction instrument for specific installations. The primary value lies in relative performance comparison across systems under standardized conditions. Actual implementation requires site-specific assessment, pilot testing, and ongoing performance monitoring.

5 Conclusions

This study systematically evaluated four air purification system configurations through Excel-based mass balance simulations, comparing conventional mechanical filtration with emerging biological alternatives for indoor air quality management. Key findings show that biological air purification systems offer advantages for specific pollutant categories in buildings.

No single system provides optimal performance across all scenarios. HEPA filtration is superior for PM applications; microalgae systems excel in CO_2. Green walls offer moderate pollution removal. However, hybrid systems offer more comprehensive solutions.

Microalgal systems are the most effective biological solution for CO_2 and VOC removal, achieving 22% reduction in CO_2 generation and 98% VOC removal efficiency. These capabilities address critical limitations of conventional mechanical systems, which provide no CO_2 mitigation and minimal gaseous pollutant control. However, green walls provide balanced multi-pollutant treatment with moderate effectiveness. Hybrid system which combines microalgae and green wall demonstrates synergistic effects that deliver superior overall performance. This integrated approach can be a solution for high-occupancy environments requiring multi-pollutant management. In addition, biological systems can provide other benefits including oxygen production, biophilic design elements, thermal/visual regulation, and potential biomass production.

The developed Excel-based framework enables rapid evaluation of alternative air purification strategies for specific building contexts, providing accessible decision-support tools for architects, engineers, and facility managers. The transparent mass balance approach facilitates parameter customization and sensitivity exploration without specialized software requirements. While this study provides comparative performance benchmarks based on literature, several critical research needs remain including long-term monitoring in real building conditions to validate model predictions, characterize seasonal performance variations, and assess maintenance requirements across diverse climate zones and occupancy patterns.

This research was supported by the Research Fund of Dokuz Eylül University. Project Number: FBA-2025-3655. This paper has been produced as part of the first author's PhD thesis funded by TÜBİTAK 2211-A National PhD Scholarship Program.

References

1. World Health Organization (WHO). Global air quality database. WHO, Geneva (2021).
2. Q. Wang, L. Li, Y. Hong, Q. Zhai, Y. He, Novel insights into indoor air purification capability of microalgae: characterization using multiple air quality parameters and comparison with common methods, Environ. Sci. Pollut. Res. 30(17) (2023) 49829-49839. https://doi.org/10.1007/s11356-023-25799-8
3. M.R. Villalba, M.J.M. Sancho, J.M. López, M.I.G. Sánchez, Green solutions for urban sustainability: photobioreactors for algae cultivation on façades and artificial trees. Buildings 13(6), 1541 (2023). https://doi.org/10.3390/buildings13061541
4. S. Dubey, H. Rohra, A. Taneja, Assessing effectiveness of air purifiers (HEPA) for controlling indoor particulate pollution. Heliyon 7, e07976 (2021). https://doi.org/10.1016/j.heliyon.2021.e07976
5. M.A. Sidheswaran, H. Destaillats, D.P. Sullivan, S. Cohn, W.J. Fisk, Energy efficient indoor VOC air cleaning with activated carbon fiber (ACF) filters. Build. Environ. 47, 357-367 (2012). https://doi.org/10.1016/j.buildenv.2011.07.002
6. A.J. Ghazalli, C. Brack, X. Bai, I. Said, Alterations in use of space, air quality, temperature and humidity by the presence of vertical greenery system in a building corridor. Urban For. Urban Green 32, 177-184 (2018). https://doi.org/10.1016/j.ufug.2018.03.010
7. B.E. Cummings, M.S. Waring, Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies. J. Expo. Sci. Environ. Epidemiol. 30(2), 253-261 (2020). https://doi.org/10.1038/s41370-019-0175-9
8. Q. Wang, L. Li, Y. Hong, Q. Zhai, Y. He, Novel insights into indoor air purification capability of microalgae: characterization using multiple air quality parameters and comparison with common methods. Environ. Sci. Pollut. Res. 30(17), 49829-49839 (2023). https://doi.org/10.1007/s11356-023-25799-8
9. IBA Hamburg, BIQ House SolarLeaf: The use of microalgae for bio-reactive façade system. (2013). https://www.pocacito.eu/sites/default/files/BIQhouse_Hamburg.pdf
10. EcoLogicStudio, AIRoffice: Urban Photobioreactor for Air Purification. Design Collective, Belgrade (2021). https://www.ecologicstudio.com/projects/airoffice
11. F. Torpy, M. Zavattaro, P. Irga, Green wall technology for the phytoremediation of indoor air: a system for the reduction of high CO_2 concentrations. Air Qual. Atmos. Health 10, 575-585 (2017). https://doi.org/10.1007/s11869-016-0452-x
12. ASHRAE, ANSI/ASHRAE Standard 62.1-2022: Ventilation and acceptable indoor air quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA (2022).
13. A. Tokuç, Y. Yaman, T. Akış, G. Tuna Tuygun, İ. Deniz, M.A. Ezan, A. Ayol, Microalgae for cleaner indoor air: A systematic review and meta-analysis of CO_2 fixation and pollutant removal performance, Open Science Framework, 2025. https://osf.io/68rcu
14. EN 16798-1:2019, Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings, European Committee for Standardization, Brussels, 2019.