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INTEGRATING PHOTOBIOREACTORS IN ARCHITECTURE FOR SUSTAINABLE DESIGN AND PERFORMANCE

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Abstract
Growing threats to the world environment due to climate changes, energy crises, and pollution of the urban areas pose a high degree of urgency to come up with new sustainable architectural solutions. Building-Integrated Photobioreactors (BIPBRs), In which microalgae produce biomass powered by CO 2 and sunlight, have cropped up as an effective solution to increase the sustainability and multifunctional architecture of buildings. There is no research, apart from photobioreactor systems as isolated industrial solutions, and little to say about the practical integration of photobioreactor systems in building facade in diverse climatic environments, mainly its long-term performance, cleaning and environmental modelling. In a critical analysis of the design, classification, performance measures and architectural integrability of BIPBR systems, the analysis in this review evaluates the field of BIPBR systems in an endeavor to embrace all these parameters with the context of productivity, cost-intensiveness and aesthetic feasibility. Results have shown that sophisticated PBR schemes especially helical and hybrid facades are more productive and beneficial in terms of energy production but also at a higher cost and intricacy of construction. A viable trade off is evident in flat panel systems. The paper outlined a full assessment between biological engineering and architecture design with support by comparison data and modeling schemes to direct further development of BIPBR. These findings confirm the use of BIPBRs as an efficient means in green architecture, which helps to build carbon-neutral buildings and have adaptive building systems. Additional interdisciplinary studies will also be required to standardize species choice, control systems in the environment and large scale prototyping to enable long-term deployment of such systems in cities.

Keywords: Building-Integrated Photobioreactors, Microalgae, Sustainable Architecture, Biomass Productivity, Green Facades, Environmental Modeling, Urban Sustainability.

Introduction
In the context of escalating global energy demands, climate change, and urban population growth, sustainable architectural practices have become an urgent necessity. Traditional buildings are major contributors to greenhouse gas emissions and urban heat islands, prompting researchers and engineers to explore energy-efficient alternatives. One innovative solution gaining traction is the integration of photobioreactors (PBRs) into building structures. These systems, which cultivate microalgae using sunlight, CO_2, and water, offer a unique opportunity to merge renewable energy generation, carbon sequestration, and building design, fostering bio-responsive architecture that can adapt to environmental challenges [1].

Building-Integrated Photobioreactors (BIPBRs) represent a novel intersection of biotechnology and architecture. The concept leverages the photosynthetic capabilities of microalgae to produce biomass, purify air, and regulate building temperatures. Numerous configurations have been explored, including flat panel systems, helical tube designs, and hybrid façades, each offering varying degrees of productivity, thermal performance, and aesthetic integration. Theoretically grounded in environmental design, bioenergy systems, and green infrastructure models, BIPBRs provide both ecological and functional value to built environments. Prior research has demonstrated the potential of PBRs for biomass production and energy savings; however, their architectural deployment remains limited by technical, economic, and aesthetic challenges [2].

Despite these advancements, several critical knowledge gaps persist. Most existing studies have focused either on microalgae cultivation in controlled environments or on PBR technology in isolation from architectural integration. There is limited empirical data on how PBR systems perform when embedded in full-scale building façades across different climatic zones [3]. Furthermore, research on real-time modeling of light intensity, nutrient dynamics, and temperature regulation remains fragmented. This calls for comprehensive, interdisciplinary studies that link engineering simulation, biological optimization, and architectural design to assess the full spectrum of BIPBR impacts and feasibility.

In this review-based study, a systematic analysis was conducted to evaluate various BIPBR designs, focusing on biomass productivity, construction cost, light utilization, and sustainability performance. Mathematical modeling, theoretical frameworks, and previous simulation studies were analyzed to identify critical design parameters and operational constraints [4]. Particular emphasis was placed on evaluating the environmental and architectural implications of integrating PBR systems into vertical building surfaces. The analysis also incorporated a comparative review of different PBR configurations and their potential for scalability and adaptability within urban contexts.

The findings indicate that advanced PBR systems, especially helical and hybrid designs, outperform traditional models in terms of biomass yield and thermal efficiency, though they present higher costs and design complexity [5]. These results imply that with continued optimization and technological innovation, BIPBRs can serve as multi-functional building elements that enhance energy efficiency, support carbon neutrality, and offer aesthetic benefits. Future research should prioritize dynamic simulation models, species-specific cultivation strategies, and prototyping across diverse environments to bridge current knowledge gaps and facilitate the mainstream adoption of photobioreactor-based architecture in sustainable urban development [6].

Materials and Methods

It is a qualitative and review-based study that uses an inductive research methodology to incorporate a broad range of academic and industrial literature to explore architectural coupling and technological fabrication of building-integrated photobioreactors (BIPBRs). The research is framed upon crucial content analysis: the latest innovation in photobioreactor construction is questioned, especially in terms of its applicability to urban building facades. This paper currently observes existing structural typologies, functional operational frameworks, and material characteristics of the frequent BIPBR typologies, that is, flat-panel, tubular, helical, and hybrid, with the use of comparative criteria, such as light distribution, thermal efficiency, CO_2 sequestration, and biomass productivity. Special attention is given to the use of simulation-based models used in previous studies, which allowed predicting algal growth dynamics in conditions of the changing light, temperature, and nutrient availability. Solar incidence, photoperiodicity, orientation of the facade; the climatic zone are the variables that have been introduced to the performance models; quantify the photon flux density, oxygen evolution, energy consumption. The simulations state a basis on an adaptive design strategy whereby the data can be used to optimize reactor location, geometry, and operating procedures before the physical prototype. The SWOT analysis is also conducted to evaluate the strengths, weaknesses, opportunities, and threats as applied to the large-scale implementation of BIPBR. Collectively, this holistic nature works to cultivate a wholesome understanding of how engineering, ecological, and economic viability of photobioreactor systems would be considered into green buildings solutions in the approach to carbon neutrality and energy freedom [7].

Results and Discussion

This study highlights significant differences in biomass productivity and construction cost across various types of Building-Integrated Photobioreactor (BIPBR) systems. As shown in Table 1, the highest biomass productivity was recorded in Helical Tube PBRs (30 g/m²/day), followed by Hybrid Façade systems (28 g/m²/day) and Tube Panel PBRs (27 g/m²/day). In contrast, the Green Façade PBR, while more cost-effective with a relative construction index of 0.8, produced the lowest biomass (18 g/m²/day). This data suggests a trade-off between economic feasibility and energy-biological efficiency, where advanced systems yield better performance but at higher construction complexity and costs [8].

Table 1

Biomass Productivity and Construction Cost of Different BIPBR Types

№	PBR Type	Biomass Productivity (g/m²/day)	Construction Cost Index (relative)
1	Panel	22	1.0
2	Green Façade	18	0.8
3	Hybrid Façade	28	1.5
4	Helical Tubes	30	1.7
5	Flat Vertical Panel	25	1.3
6	Tube Panel	27	1.4

From an architectural and functional perspective, Flat Vertical Panels offer a balanced outcome moderate productivity (25 g/m²/day) with manageable construction challenges. This makes them attractive for urban buildings requiring both aesthetics and environmental performance. The data indicates that more complex geometries (such as helical designs) enhance light capture and fluid dynamics, thereby increasing algae growth, but demand sophisticated materials and engineering [9].

However, the current research landscape still reveals a notable knowledge gap. Most existing simulation models for BIPBR performance focus on light exposure and temperature regulation in static conditions, overlooking dynamic interactions such as seasonal solar variations, shading patterns, and varying photoperiods. Furthermore, real-world testing is limited for façade systems in extreme climates or polluted urban environments [10].

Another critical area underexplored is biofouling and maintenance. Flat vertical panels and tube panels, although efficient, are vulnerable to biofilm formation on internal surfaces, leading to reduced light penetration and contamination risks. Cleaning techniques remain insufficiently studied, especially in systems with narrow chambers or irregular geometries [11].

Future research must emphasize hybrid modeling, integrating Computational Fluid Dynamics (CFD) with Artificial Neural Networks (ANNs) to simulate light temperature nutrient interactions in complex urban environments. Additionally, building prototypes under real environmental conditions will allow for validation of theoretical predictions and the refinement of design parameters [12].

Table 2

Future strategic research directions based on existing gaps:

№	*Research Area*	*Focus*
1	Dynamic simulation models	Incorporate seasonal, hourly solar angles and temperature profiles
2	Cleaning and maintenance	Develop automated or passive anti-fouling methods
3	Species selection	Optimize strains for region-specific light and thermal conditions
4	Hybrid systems integration	Couple PBR with HVAC and wastewater systems for circular efficiency
5	Real-world prototyping	Test structural resilience and long-term performance on buildings

In conclusion, BIPBR systems hold strong potential for sustainable architecture, but scaling their use demands rigorous theoretical development and practical experimentation [13]. Bridging the engineering-environmental divide through cross-disciplinary innovation is key to making photobioreactors a viable and visible feature of future green cities [14][15].

Conclusion

The paper gives focus on Building-Integrated Photobioreactors (BIPBRs) as a potential sustainable development in architecture that could integrate microalgae technology and infrastructure within the urban framework. In its key findings, it is demonstrated that the higher productivity of biomasses, better thermal performance, and the significant carbon sequestration capacities with most significant potentials are achieved in advanced photobioreactor structures particularly helmet-tube and hybrid façade systems, but with the disadvantages of higher complexity of design and construction cost. The findings support the two-fold environmental and building benefit of BIPBRs, such as enhanced indoor air quality, saved energy requirements, and building aesthetics. However, a number of the key shortcomings are noted, including the inability to clean up and insufficient long-term operational robustness along with knowledge deficit involving interactions with the dynamic environment. This limitation reveals a need to conduct interdisciplinary researches to combine computer simulation, bio technological development, and testing prototypes in various climatic conditions. The next idea of research must focus on the optimization of design parameters, species-specific cultivation dynamics, and scalable cost-effective systems, which will help popularize the usage of BIPBRs in smart and sustainable urban development.

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