NAVIGATING TRANSITIONS IN GREEN ARCHITECTURE: A MULTI-LEVEL PERSPECTIVE ON PHOTOBIOREACTOR-INTEGRATED FAÇADES IN INDONESIA

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Abstract

In tropical countries like Indonesia, architectural design faces the pressing challenge of mitigating excessive heat, humidity, and solar exposure, yet many buildings continue to adopt imported, non-contextual design models. This study explores the implementation and transitional trajectory of a novel microalgae-based photobioreactor (PBR) window façade—an innovation that integrates biological systems into building envelopes for thermal shading, light modulation, and ecological performance. Using the Multi-Level Perspective (MLP) framework, this research examines the interplay between niche experimentation, regime-level constraints, and landscape drivers shaping the adoption of green building technologies in Indonesia. The PBR façade, developed through a university–industry collaboration and installed in Semarang, demonstrates how architectural innovation can evolve through iterative learning, cross-sector collaboration, and real-environment testing. However, its broader uptake is constrained by entrenched design norms, lack of regulatory standards, and limited institutional mechanisms for certification. Landscape pressures such as ESG imperatives and climate adaptation goals offer promising opportunities, but systemic change requires alignment across policy, professional practice, and cultural narratives. The study contributes a process-oriented roadmap for embedding biologically integrated façades into the sustainability transition of tropical urban architecture.

***Keywords**: photobioreactor façade; green architecture; sustainable design; multi-level perspective; innovation; transition*

INTRODUCTION

Architectural design in tropical regions must contend with persistent heat, high humidity, and year-round solar exposure. These climatic realities call for context-sensitive solutions that prioritize thermal comfort, natural ventilation, and solar control. However, building practices in Indonesia often replicate imported models from temperate regions without adequate adaptation (Wijaya et al., 2020). The widespread use of fully glazed façades and sealed building envelopes has resulted in excessive reliance on mechanical cooling systems, contributing to elevated energy demand and increased carbon emissions (Ferla et al., 2020; Rizkiyah et al., 2023).

Although the global discourse on green architecture has gained momentum—driven by carbon reduction targets, ESG commitments, and international certification systems such as LEED, BREEAM, and Greenship—its implementation in tropical developing countries remains partial and fragmented. In Indonesia, green building practices are often limited to pilot projects or high-profile developments. They have yet to become standard across the broader construction industry (Babalola et al., 2024; Adegbie, 2024). Moreover, the dominant strategies employed tend to be passive, focusing on material efficiency and cross-ventilation, while overlooking the potential for biologically integrated, functionally active systems within the building envelope.

This gap presents an opportunity to reconceptualize the boundaries of sustainable design. Moving beyond conventional green building approaches, the integration of microalgae-based photobioreactor façades (PBR façades) introduces a novel layer of ecological functionality to buildings. These systems—capable of producing biomass, filtering air, and shading interiors—signal a shift towards "living architecture," where biological processes become integral to building performance and environmental impact mitigation. This trend aligns with a wider exploration of biomimetic and adaptive façades that integrate biological or bio-inspired systems (Nwoba et al., 2020; Díaz et al., 2019; Goyes-Balladares et al., 2025).

This study is grounded in an ongoing real-world initiative involving the design and testing of a window-integrated PBR façade system. Developed through collaboration between academic researchers and a microalgae cultivation industry partner, the prototype has been installed at a working algae production facility in the Uptown district of Semarang. While Semarang is a coastal city on the northern shore of Java—characterized by high humidity and urban heat—uptown lies at a higher elevation, offering a microclimate more similar to upland zones. This dual condition provides a valuable context for exploring the system's environmental performance and scalability across diverse tropical urban settings.

However, the development of bio-facade systems like PBR is not solely a technical matter. Their adoption intersects with institutional inertia, regulatory uncertainty, limited technical expertise, and prevailing aesthetic norms in the architectural profession (Riihiaho et al., 2025). These factors raise a broader question that goes beyond performance metrics: can such innovations transcend their experimental origins and be embedded into mainstream building practices? (Kim et al., 2025). Addressing this question requires a theoretical framework that accounts for the layered socio-technical dynamics influencing architectural change.

Several frameworks have attempted to explain how innovations emerge and stabilize within design and construction systems. Technology Acceptance Models emphasize user uptake but are often inadequate in capturing institutional and cultural dimensions. Design Thinking for Sustainability promotes iterative innovation but tends to focus on project-level interventions without addressing regime-level structures. In contrast, the Multi-Level Perspective (MLP) offers a systemic view by situating innovation within three interdependent levels: niche (where novel ideas are incubated), regime (the dominant practices and rules), and landscape (wider societal, economic, and environmental pressures) (Geels in Asquith, 2019; Babalola et al., 2024). MLP is particularly useful in understanding how architectural transitions unfold under overlapping technical, institutional, and cultural influences.

Applying the MLP framework, this study does not aim to assess the technical efficiency of the PBR façade per se, but rather to map its transition trajectory within Indonesia's urban and architectural landscape. Through a visualized roadmap, we identify four key dynamics: (i) the phase of early prototyping and university–industry collaboration (Early Niche Innovation Cluster) (Yaman & Tokuç, 2024); (ii) systemic inertia reflected in dominant design norms and construction practices (Legacy System Cluster); (iii) the emergence of supportive frameworks and the potential for regulatory mainstreaming (Emerging Practice Cluster); and (iv) external drivers including energy crises, environmental regulation, and the circular economy (Landscape Pressures) (Asquith, 2019; Goyes-Balladares et al., 2025). In doing so, the study contributes a contextual and process-oriented understanding of green architectural innovation in the tropics.

METHOD

This study employs the Multi-Level Perspective (MLP) framework as a conceptual and analytical tool to examine how niche architectural innovations—specifically, a photobioreactor (PBR) window system—may initiate, interact with, or challenge existing building regimes in Indonesia's tropical urban context (Figure 1).

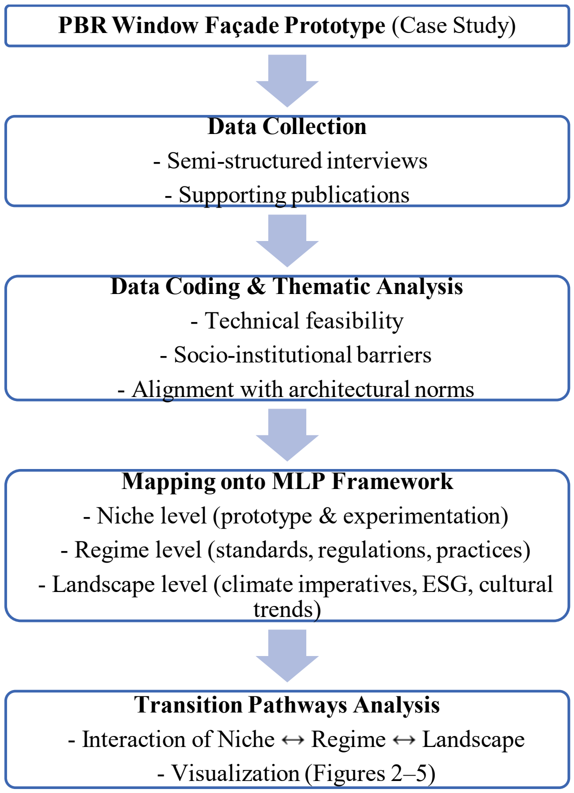

Fig. 1. The Multi-Level Perspective (MLP) methodological framework

Theoretical Framework: Multi-Level Perspective (MLP)

The Multi-Level Perspective (MLP) is a well-established framework in sustainability transition studies, offering a structured way to understand how socio-technical systems evolve through interactions across three analytical levels: niche, regime, and landscape (Geels, 2002; Geels & Schot, 2007).

At the niche level, radical innovations emerge in protected spaces, allowing actors to experiment and iterate with limited exposure to market, institutional, or cultural resistance. These niches are essential for developing alternative socio-technical configurations. In architecture, niches can include research-led pilot projects, demonstration façades, or university–industry collaborations where experimental technologies are field-tested.

The regime level consists of dominant practices, infrastructures, standards, and institutional logics that stabilize the existing system. Architectural regimes often include conventional building codes, supply chain relationships, client expectations, and aesthetic preferences—many of which resist integration of unconventional systems such as living or bio-integrated façades.

At the landscape level, exogenous forces—such as global climate imperatives, policy shifts, ESG regulations, and public environmental concern—apply pressure on the regime. These macro developments can destabilize entrenched structures, thereby opening up "windows of opportunity" for niche innovations to scale up and reshape the regime (Asquith, 2019)

This theoretical positioning is illustrated in Figure 2, adapted from Geels and modified by Asquith (2019), which captures the dynamic interplay between levels over time and the potential for niche innovations to contribute to systemic transitions.

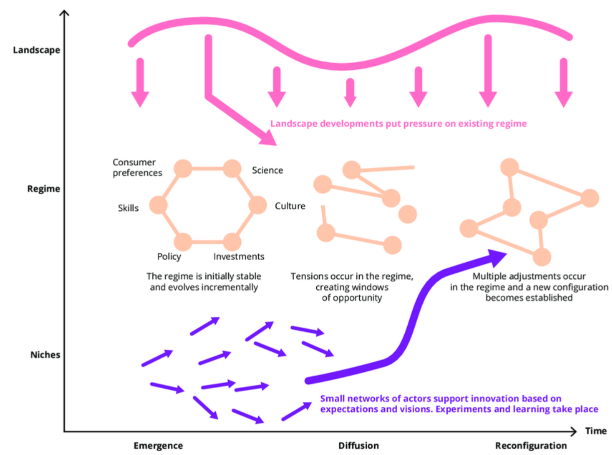

Fig. 2. The Multi-Level Perspective (MLP) framework on sustainability transitions from Geels, modified by Asquith (2019).

Analytical Procedure

The analytical procedure in this study followed a qualitative, interpretive approach guided by the Multi-Level Perspective (MLP) framework. The aim was to understand how the PBR window prototype operates not merely as a technological device, but as a niche innovation navigating the complex socio-technical dynamics of the built environment.

Primary empirical material was collected through semi-structured interviews with two key informants:

- Informant 1, a senior researcher in microalgae systems from the authors' host institution, with an academic background in environmental science and energy systems. This expert provided insight into the biological performance of the photobioreactor, the environmental implications of microalgae integration, and the potential alignment with sustainable energy and climate strategies.
- Informant 2, a technical operator from the algae cultivation company where the prototype was installed. This respondent shared perspectives on practical integration, material compatibility, maintenance challenges, and user engagement during and after the pilot deployment.

The interview transcripts were coded and analyzed thematically, with attention to:

- Perceived technical feasibility and operational concerns;
- Socio-institutional barriers such as unfamiliarity, risk aversion, and lack of regulation;
- Narratives of alignment or misalignment with prevailing architectural norms, client expectations, and green building discourses.

These insights were then mapped onto the MLP framework, categorizing the empirical findings into three levels:

- Niche level: reflections on prototyping, learning processes, and protective experimentation;
- Regime level: responses from institutional actors and infrastructure constraints;
- Landscape level: interpretations of broader climate imperatives, ESG trends, and Indonesia's urban vulnerability.

To strengthen the robustness of the analysis, the interview data were further contextualized by scientific publications on photobioreactor applications, green architecture or green building, and energy systems. This combination of field-based insight and theoretical anchoring enabled a situated reading of the PBR window as a sustainability innovation in the early stages of socio-technical transition. It also provided the basis for constructing the transition diagram in the Results section, which visualizes the shifting interactions among niche practices, regime logics, and landscape pressures.

RESULTS

This section presents the results of applying the Multi-Level Perspective (MLP) framework to analyze the development and implementation of the PBR-integrated façade.

PBR Window Façade as Niche Innovation in MLP Framework

The foundation of this study lies in the development and implementation of a photobioreactor (PBR) window façade prototype, which serves as the niche innovation baseline explored throughout this transition analysis. The system was designed to integrate microalgae cultivation into a building's envelope, combining thermal shading, daylight modulation, and ecological performance into a single architectural component.

Installed in 2024 at the front façade of an algae cultivation office in uptown area of Semarang, Central Java, Indonesia, the PBR panel occupies one of the vertical glass sections of a double-glazed window (Figure 3). The green hue is a result of microalgae biomass suspended in a sealed fluid medium. Light entering through the façade is filtered, and heat gain is mitigated while allowing partial visibility. In addition to demonstrating functional capacity, the façade serves as a visual and symbolic statement of integration between biological systems and built form.

Fig 3. Installation view of the photobioreactor façade system, representing the baseline niche innovation in this study.

Based on findings from field interviews and supporting documentation, the development of the PBR façade system illustrates how architectural innovation can take root through niche experimentation—particularly in contexts where environmental performance and material agency are increasingly central to design thinking. This early-stage initiative demonstrates a departure from conventional façade logic, where building skins are typically conceived as passive barriers. In contrast, the PBR system embraces an ecological function, transforming the façade into a biologically active, responsive membrane (Sedighi et al., 2023; Yaman et al., 2021). This shift reflects a growing architectural interest in performative envelopes—those that not only modulate light and temperature but also engage in environmental processes such as carbon sequestration, biomass generation, and microclimate mediation (Vardapetyan et al., 2023).

The niche innovation process was also shaped by a transdisciplinary collaboration between academic designers and practitioners in the local algae cultivation industry. This partnership bridged distinct knowledge domains: architectural design and environmental engineering. Through this collaboration, the prototype was not developed in abstraction, but embedded in a functioning building context—situated within a working algae facility in Uptown Semarang. The site's elevated microclimate and real-use conditions offered an authentic platform for experimentation, enabling the system to be evaluated as a working façade, not merely a lab model. Such integration of prototyping into built environments is critical for advancing architectural transitions towards sustainability, as it allows for dialogue between design intent, technical constraints, and operational feedback.

Moreover, the innovation journey was characterized by iterative learning—both material and conceptual. Issues such as algae stability, heat transmission, fluid clarity, and visual permeability prompted a series of adjustments during and after installation (Talaei, 2021) (Vardapetyan et al., 2023). These iterations were not limited to technical fixes but extended to questions of aesthetics, integration with glazing systems, and perceptions of maintenance among users. In this way, the process not only yielded a functioning component but also produced architectural knowledge about how living systems might inhabit, transform, and re-signify conventional building elements (Geels, 2024).

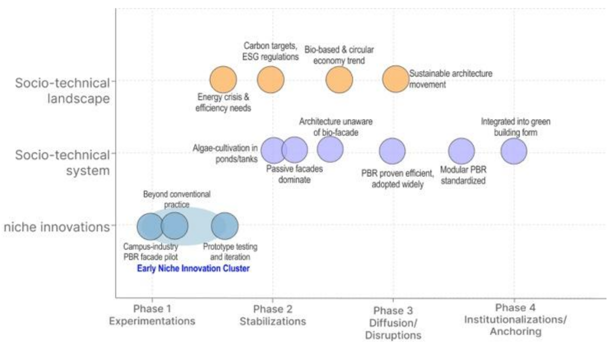

Fig 4. Early Niche Innovation Cluster of the PBR façade within the MLP framework.

The diagram illustrates the sequential logic of experimentation: starting from conceptual departure from passive façades, moving through academic-industry prototyping, and culminating in site-based learning iterations. The relationships among these early-stage processes—experimentation beyond conventional building logic, pilot collaboration, and iterative design learning—are visually mapped in Figure 4, which situates the project within the niche level of a broader sustainability transition trajectory.

Regime-Level Constraints to the Integration of the PBR Facade

The integration of photobioreactor (PBR) façades into building envelopes remains constrained by the dominant structures of Indonesia's current architectural and construction systems. Within the Multi-Level Perspective (MLP) framework, the regime level consists of existing design standards, institutional routines, construction supply chains, professional cultures, and building regulations. These elements collectively form a stable system that is resistant to unconventional architectural approaches.

In the Indonesian context, the architectural regime continues to prioritize sealed glass façades, which are often perceived as symbols of modernity and commercial value. However, in tropical climates such as Indonesia, this approach leads to increased thermal loads and reliance on mechanical cooling systems. As documented by (Nurdiani & Zahran, 2025) and (Rahim et al., 2023), such design preferences contribute significantly to high operational energy demand and reduced environmental performance in urban buildings.

The current regime has not yet accommodated bio-integrated façade technologies like PBR systems. Existing building codes do not provide specific provisions for the installation (Ayuni, 2022), performance assessment (Harahap, 2023), or maintenance of façade-integrated microalgae systems. Additionally, green building certification systems such as Greenship do not explicitly recognize or award points for innovations of this kind. As a result, architects and developers lack normative and regulatory support to adopt these systems into formal projects.

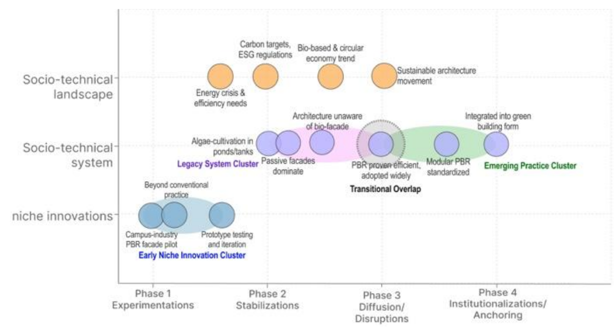

Fig. 5. Positioning of the PBR façade system in relation to the legacy regime cluster.

Figure 5 shows the position of the PBR innovation within the socio-technical regime. The legacy system cluster includes conventional passive façade models, limited cross-disciplinary knowledge in architecture regarding biological systems, and the absence of technical standards for hybrid façade types. These regime-level conditions were confirmed during interviews with two key stakeholders: a microalgae researcher from the environmental energy sciences field and a representative from the algae industry partner where the prototype was installed. Both emphasized that the current building system lacks mechanisms for integrating façade systems that involve biological maintenance, fluid dynamics, and light–growth interaction.

In conclusion, the analysis indicates that the PBR façade system faces several structural barriers at the regime level. First, there is currently no established design standard or safety guideline that accommodates biologically integrated façades. This regulatory absence creates uncertainty for architects and developers who may otherwise be willing to adopt such systems. Second, institutional mechanisms for performance validation—

such as durability testing, energy efficiency rating, or environmental impact assessment—remain unavailable for façade-integrated bioreactors. Without these mechanisms, innovations such as the PBR façade cannot be formally assessed or certified within existing building frameworks. Third, the integration of environmental technologies into mainstream design practice remains limited. Architectural workflows and procurement systems continue to prioritize conventional materials and mechanical systems, leaving little room for novel components that require cross-disciplinary coordination.

These regime-level conditions suggest that, despite its demonstrated functional potential at the prototype scale, the PBR façade still operates outside the formalized structures of the Indonesian building sector. As such, its diffusion remains constrained, and its development is limited to isolated or research-driven applications rather than being positioned for broader institutional uptake.

Landscape Pressures and Opportunities for the PBR Window

Beyond the regime-level barriers, the development and future uptake of the PBR window system are influenced by broader structural changes occurring at the landscape level. Within the Multi-Level Perspective (MLP), the landscape level refers to long-term, macro-scale developments that are generally beyond the control of individual actors but shape the context in which regimes and niches evolve. These include global environmental shifts, policy frameworks, energy crises, and shifting market expectations—all of which exert pressure on established systems and can create openings for innovation.

In the case of Indonesia and other tropical developing countries, at least three key landscape developments are relevant to the trajectory of bio-integrated architectural systems like the PBR façade. First, increasing concerns about energy efficiency and climate resilience in the building sector are prompting both government and private developers to reconsider carbon-intensive designs (Berawi et al., 2020). The national net-zero target and rising urban temperatures—exacerbated by urban heat island effects—are aligning public discourse more closely with green building narratives (Liu et al., 2024).

Second, the global rise of ESG (Environmental, Social, and Governance) criteria and climate-related financial disclosures is starting to influence investment decisions in the construction and real estate sectors. Although still limited in scale, there is growing interest among developers and policymakers in infrastructure that meets not only energy benchmarks but also ecological and social indicators (Ye et al, 2024).

Third, emerging movements in sustainable design culture—including regenerative architecture, circular construction, and nature-based solutions—are gradually influencing architectural education and discourse in Southeast Asia. These shifts, although more pronounced in global north contexts, are slowly being adapted into local frameworks and present cultural momentum for more integrative design strategies.

These pressures are mapped in Figure 4, which shows how external forces act upon the existing regime, shaping the conditions under which niche innovations such as the PBR façade may either flourish or stagnate.

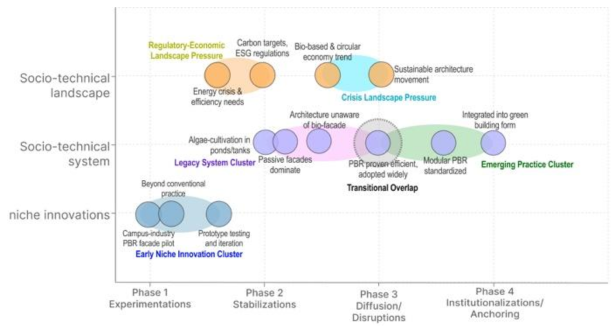

Fig. 6. Positioning of the PBR façade system in relation to the landscape drivers.

Figure 6. Landscape-level drivers that influence the potential integration of PBR window systems within the MLP framework. The figure highlights the convergence between climate imperatives, economic transformation, and design culture shifts. However, it is important to note that landscape pressures do not automatically lead to transformation. Without strong institutional alignment and policy translation, these pressures may remain abstract or fail to influence built environment practices directly. In interviews conducted for this study, respondents from both academia and industry acknowledged the symbolic weight of green agendas, but also highlighted the gap between discourse and operational frameworks.

In summary, while landscape-level change provides important enabling conditions, the translation of these drivers into concrete support for innovations like the PBR window system still requires coordinated action across regulatory, professional, and educational domains. These external pressures may accelerate regime adaptation or open protected spaces for niche expansion, but only if aligned with internal mechanisms for change.

Transitional Pathways of the PBR Window System

Following the detailed examination of niche, regime, and landscape levels, this section synthesizes how interactions across these levels contribute to the transitional trajectory of the photobioreactor (PBR) window system. Within the Multi-Level Perspective

(MLP), transitions are not driven by a single level but result from dynamic interactions between levels over time—especially when landscape pressures destabilize the regime, and niche innovations are sufficiently mature to be considered viable alternatives.

The current study observes three main inter-level dynamics relevant to the PBR façade development:

First, there is evidence of bottom-up pressure from the niche level. The experimental deployment of the PBR window—conducted through university–industry collaboration—has created a precedent for how biological systems can be embedded into building envelopes. Though still operating at a limited scale, the prototype introduces new design vocabulary and ecological performance considerations into architectural discussions.

Second, the regime has shown limited but identifiable responsive shifts. While mainstream design remains bound to conventional material systems, there are isolated interests—especially among environmentally aware developers and progressive architects—that indicate potential for future alignment. The regime, however, continues to lack codified tools, standards, or incentives for scaling bio-integrated technologies.

Third, landscape-level pressures—including ESG policies, climate adaptation targets, and the global rise of regenerative design principles—are exerting increasing influence on both public discourse and institutional agendas. These pressures are capable of indirectly altering regime structures by redefining funding priorities, reshaping investor expectations, and reframing what counts as innovation in architecture and urban infrastructure.

These relationships are visualized in Figure 5, which presents the full MLP diagram with inter-level and intra-level arrows connecting niche, regime, and landscape elements. Arrows indicate not only directional influence but also potential pathways of diffusion, conflict, or institutional translation.

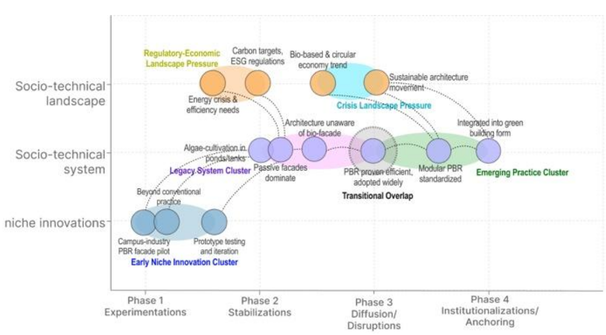

Fig. 7. MLP diagram of the PBR window system with full inter-level and intra-level arrows.

The visualization in figure 7 highlights how niche experiments, regime constraints, and landscape pressures interact and overlap across the phases of sustainability transition.

From this integrated view, the PBR window system can be seen as situated at a transitional intersection: it emerges from niche experimentation, interacts with a stable but partially receptive regime, and is increasingly supported by converging landscape drivers. However, the actual realization of system-wide change depends on whether connections among these levels can be stabilized—through institutional innovation, policy incentives, and standard-setting mechanisms.

In summary, the visual model reinforces the interpretation that while the PBR façade system has not yet reached widespread adoption, it is no longer operating in isolation. Its success in contributing to the green building transition will depend on the consolidation of cross-level support structures and the formal recognition of bio-integrated design as part of sustainable architectural practice in tropical urban environments.

CONCLUSION

This study demonstrates that the photobioreactor (PBR) window façade system represents a promising yet early-stage sustainability innovation within Indonesia's architectural landscape. Positioned at the intersection of environmental engineering and architectural design, the PBR façade challenges conventional building envelopes by introducing a living, performative component capable of ecological contribution. The MLP framework reveals that while niche-level experimentation has yielded functional and symbolic breakthroughs, systemic regime constraints—such as regulatory gaps, entrenched aesthetics, and institutional inertia—continue to inhibit broader adoption.

Nonetheless, the growing influence of landscape-level drivers, including ESG frameworks, climate policy, and shifts in sustainable design culture, suggests a slowly emerging window of opportunity. The potential for regime transformation hinges on the stabilization of cross-level connections: the translation of niche insights into policy instruments, the development of technical standards for bio-façades, and the mainstreaming of ecological performance within architectural practice.

This study did not fully assess the long-term energy performance, lifecycle impacts, or potential for scaling PBR façades across different building types. These aspects represent important avenues for future research. Moreover, policy-oriented studies are needed to explore how certification systems and regulatory standards could accommodate biologically integrated façades. Addressing these gaps would strengthen the institutional and cultural foundation for embedding living architecture into mainstream sustainable urban development.

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