Journal of Information Systems Engineering and Management
2025, 10(17s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

A Review of TRNSYS Model in Building-Integrated Microalgae Photobioreactor Facades for Thermal Performance Simulation

Bernadetha Grace Wisdayanti [1], Nappasawan Wongmongkol [2*], Chatchawan Chaichana [3], M. Allam Daffa Alhaqi [4], Sumiwon Wicharuck [5], Wahyu Nurkholis Hadi Syahputra [6]

[1] *Graduate Master's Degree Program in Agricultural Engineering, Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

[2] *Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

[3] *Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

[4] *Graduate Master's Degree Program in Agricultural Engineering, Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

[5] *Office of Research Administration, Chiang Mai University, Chiang Mai 50200, Thailand*

[6] *Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

**Corresponding Author: napassawan_k@cmu.ac.th*

ARTICLE INFO

Received: 08 Dec 2024

Revised: 30 Jan 2025

Accepted: 07 Feb 2025

ABSTRACT

Microalgae photobioreactor (PBR) facades offer innovative solutions for addressing climate change by integrating CO2 sequestration, thermal regulation, and bioresource production into building systems, addressing climate change and advancing sustainable practices. The thermal performance of these facades plays a critical role in reducing building energy demands while optimizing CO2 capture. TRNSYS, a dynamic simulation tool, offers significant potential in modeling the thermal behavior of building-integrated PBR systems, allowing for detailed analysis and optimization. The review consolidates findings from recent studies on TRNSYS applications in building energy simulations, focusing on its role in enhancing the thermal performance of microalgae PBR facades. The paper highlights TRNSYS's advantages in simulating complex interactions between building systems and environmental factors by identifying research gaps, limitations, and advancements. Key challenges, including process integration and data accuracy, are also addressed. The study underscores TRNSYS's potential to support the development of zero-emission architecture and sustainable building practices. By bridging existing research gaps and optimizing methodologies, TRNSYS-based simulations can contribute to more efficient, scalable, and cost-effective PBR systems, fostering innovation in climate-responsive architectural design.

Keywords: Microalgae, photobioreactor facades, thermal performance, TRNSYS.

INTRODUCTION

Buildings account for a significant portion of global energy consumption and carbon emissions, driving the urgent need for innovative technologies that enhance energy efficiency and sustainability. Among these technologies, the integration of microalgae photobioreactor (PBR) facades into building systems has gained significant attention. These facades leverage the unique properties of microalgae to sequester CO_2, regulate thermal performance, and produce valuable bioresources, presenting a multifunctional approach to sustainable building design. The thermal performance of such systems is critical, as it directly impacts their ability to reduce energy demands, enhance occupant comfort, and contributes to climate change mitigation [1], [2]. However, optimizing the thermal performance of microalgae PBR facades requires advanced modeling tools capable of simulating the dynamic interactions between the building envelope, environmental conditions, and operational strategies.

TRNSYS (Transient System Simulation Tool) is a widely recognized dynamic simulation tool for analyzing and optimizing building-integrated energy systems. Its modular architecture supports detailed simulations of thermal processes, enabling researchers to evaluate the performance of microalgae PBR facades under varying environmental and operational conditions [1]. By modeling critical factors such as biomass density, light transmittance, and heat exchange processes, TRNSYS provides valuable insights into the thermal performance and energy-saving potential of these innovative facades. Furthermore, TRNSYS's adaptability and accuracy in modeling complex systems make it an essential tool for integrating microalgae PBRs into sustainable building designs. Despite its demonstrated effectiveness in other building applications, the application of TRNSYS, specifically for microalgae PBR facades, remains underexplored, with significant gaps in system integration and performance optimization.

Existing research highlights the benefits of microalgae PBR facades, including enhanced thermal insulation, reduced heating and cooling demands, and stabilized indoor temperatures. For instance, the shading effect provided by the microalgae culture can lower interior temperatures, reducing reliance on mechanical cooling systems, while the thermal mass of the water-rich culture further stabilizes indoor conditions [2]. In addition, design parameters such as light intensity, nutrient availability, and hydraulic retention time significantly influence both microalgal growth and the thermal performance of the system [3], [4]. The use of TRNSYS to simulate these variables allows researchers to identify optimal configurations, maximizing both biomass productivity and energy efficiency.

This review consolidates existing research on TRNSYS-based simulations for building-integrated systems, focusing on its potential to advance the thermal performance of microalgae PBR facades. By addressing research gaps, limitations, and emerging opportunities, this study underscores the critical role of TRNSYS in promoting sustainable architecture and zero-emission buildings. The objective is to provide a comprehensive understanding of the capabilities and limitations of TRNSYS in modeling PBR facades, paving the way for more effective designs and applications in the built environment. Through this review, we highlight the transformative potential of TRNSYS in optimizing building-integrated microalgae systems, aligning with global sustainability goals and the transition toward zero-emission architecture.

TRNSYS APPLICATION IN BUILDING SIMULATION

TRNSYS (Transient System Simulation) is a versatile and modular software widely employed for building energy simulation, particularly in assessing thermal performance, energy efficiency, and system interactions across various building types. TRNSYS's flexibility and extensibility enable the integration of diverse components, including renewable energy systems, HVAC (Heating, Ventilation, and Air Conditioning) technologies, and thermal storage systems, making it a powerful tool for modeling complex energy systems in both commercial and residential contexts.

One of the significant advancements in TRNSYS is its ability to model advanced façade systems and renewable energy technologies. For instance, Maurer and Kuhn developed TYPE 871 to simulate transparent solar thermal collectors, facilitating coupled analyses with building envelopes and HVAC systems. This innovation enhances the precision of thermal performance simulations, providing critical insights into heat exchange processes and energy efficiency [5]. Similarly, TRNSYS has been utilized to simulate diverse building technologies under varying climatic conditions, as highlighted by Li M., Shi J., Cao J., Niu J., and Xiong M., demonstrating its adaptability to environmental variations [6]. The software's application extends beyond traditional building simulations to specialized scenarios, including greenhouses and other non-residential structures. Akpenpuun demonstrated the use of TRNSYS to model microclimates in greenhouses, emphasizing its role in optimizing thermal performance in agricultural settings [7]. Additionally, Yau employed TRNSYS to simulate HVAC systems for an extensive library in Malaysia, incorporating local weather data to enhance simulation accuracy [8]. Such applications underscore the software's versatility in addressing specific performance challenges across diverse building types.

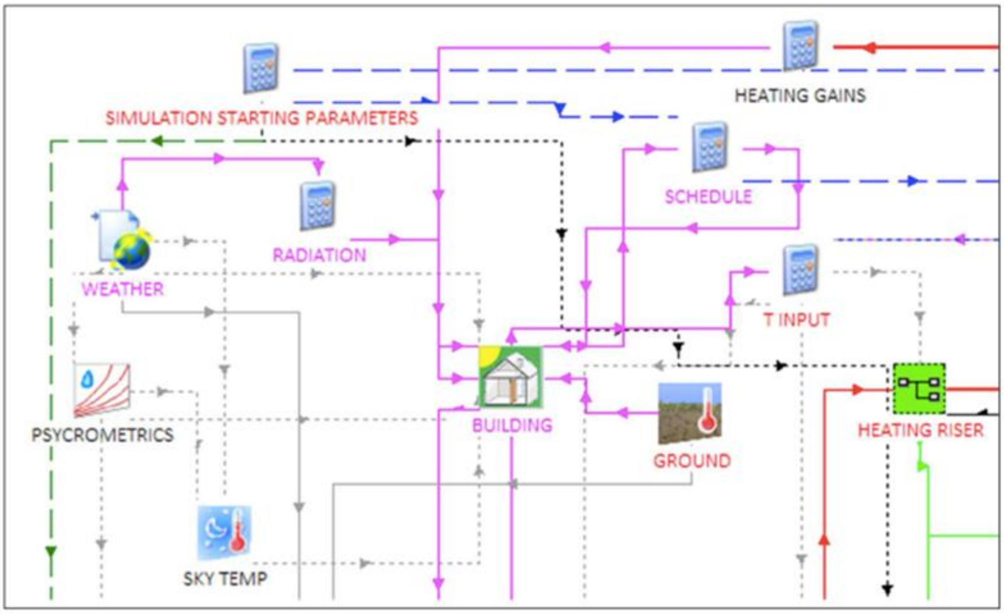

Figure 1. Extracted view of the TRNSYS detailed HVAC model connected according to an input – output logic [9].

Fig.1 provides a detailed view of the model, illustrating how the dynamic operation of the heating building- plant is simulated using TRNSYS components, known as "Types." Each type represents a specific system component and is configured with user-defined parameters and inputs to simulate its behavior accurately. These components are interconnected based on input-output logic. This interconnected structure enables the dynamic simulation of a complex system composed of multiple types, facilitating a comprehensive analysis of the system's performance [9].

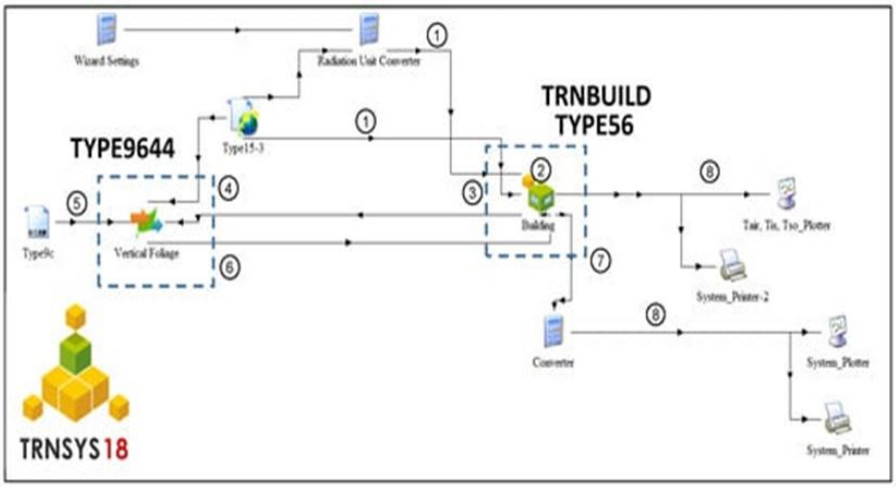

Figure 2. The multizone building model (Type 56) coupled with the green façade component (Type 9644) using TRNSYS [10].

The TRNSYS simulation workflow for integrating a multi-zone building model with a vertical foliage component encompasses several key phases illustrated in Fig. 2. Initially, local meteorological data—such as outdoor air temperature, relative humidity, wind speed and direction, and solar radiation (global, direct, and diffuse)—are input into the system. Subsequently, the building is modeled using Type 56, which involves defining opaque and transparent components, setting infiltration rates, and establishing boundary conditions. An energy balance is then performed on the building model with bare walls. The output data from this energy balance serves as feedback for the Vertical Foliage Component (VFC), which also incorporates the initial weather data. The VFC processes these inputs to calculate its energy balance outputs. These outputs are then integrated back into the Type 56 building model, now coupled with the VFC, to perform a comprehensive energy balance. Finally, the simulation yields critical outputs, including indoor air temperature, surface temperatures, and exchanged heat fluxes [10].

Another critical application of TRNSYS lies in its capacity to model systems incorporating phase change materials (PCMs). Plytaria explored TRNSYS's ability to simulate PCM-enhanced building designs, revealing significant improvements in thermal regulation and energy efficiency [11]. Similarly, Nayak and Hagishima emphasized TRNSYS's utility in evaluating heating and cooling loads, indoor thermal environments, and solar gains, which are pivotal for designing efficient HVAC systems and sustainable buildings [12]. Its integration with tools like MATLAB further enhances its modeling capabilities, enabling sophisticated analyses of nonlinear heat and moisture transfer phenomena.

Table 1 summarizes the literature reviewed in several studies related to multi-objective optimization for improving building performance using TRNSYS combined with various external numerical simulation tools.

Table 1. Review on multi-objective optimization using TRNSYS simulation in building performance

Building Type	Performance metrics	Design Parameter	Method	Result	Findings	Ref.
The roof surface of building	Thermal performance, nonlinear heat and moisture transfer	Conductive heat flux, net Radiation, external roof surface temperature, air temperature, relative humidity (RH), wind velocity, short wave radiation, precipitation (P).	TRNSYS + MATLAB	The modified TRNSYS model, integrated with MATLAB to simulate evaporative cooling from a wet roof, achieved high accuracy, with mean absolute temperature deviations of 0.3°C for room air, 0.7°C for the rooftop, and 0.5°C for the roof bottom surface compared to the original model. Applied to a building in New Delhi, India, the model effectively evaluated the impact of evaporative cooling on thermal performance by accounting for simultaneous heat and moisture transfer, which the standard TRNSYS Type 56 module cannot simulate.	A MATLAB/TRNSYS integration was developed to model evaporative heat and moisture transfer from wet roof surfaces, overcoming limitations of the TRNSYS Type 56 module in handling nonlinear phenomena such as latent heat and moisture transfer. This enhancement enables an accurate assessment of evaporative cooling effects in passive building designs while emphasizing the importance of accounting for dynamic moisture variations in roof materials. The model's accuracy relies on appropriate time base and step size selection, with smaller time bases improving precision but requiring advanced algorithms for CTF generation in Type 56.	[12]

Office	Heating and cooling loads	Building orientation, aspect ratio, window-to-wall, wall and window insulation solar heat gain coefficient.	TRNSYS + NSGA-II	The study identifies window performance and air leakage as key factors in energy-efficient building design, while the area aspect ratio is negligible. Using experimental design and a non-sorting genetic algorithm, it optimized heating and cooling loads and produced reliable results verified by TRNSYS simulations. The findings emphasize integrating active and passive components for achieving net-zero energy buildings.	The study reveals that window performance and air leakage significantly impact energy loads, while the building area aspect ratio does not. Using experimental design and a genetic algorithm, it optimized heating and cooling loads, verified by TRNSYS simulations. The findings highlight the importance of integrating active and passive design elements to achieve net zero energy buildings.	[13]
Residential	Thermal performance and life cycle cost	Envelope insulation thickness of external wall, window type, building tightness, and a heat-recovery unit	TRNSYS + NSGA-II + MATLAB	The study optimizes over 3 billion design combinations with minimal evaluations, identifying cost-optimal PEC levels of 93–103 kWh/m²a and nZEB feasibility at 70 kWh/m²a with incentives. Key design factors include envelope parameters, solar systems, and heat-recovery units, with ground source heat pumps essential for balancing cost and environmental impacts.	The study's three-stage optimization evaluates over 3 billion designs, identifying cost-optimal PEC levels of 93–103 kWh/m²a and nZEB feasibility at 70 kWh/m²a with incentives. Key factors like building-envelope parameters, solar systems, and efficient heating systems, such as ground source heat pumps, are crucial for energy-saving and renewable energy use, supporting EPBD-recast 2010 goals.	[14]
Office	Energy efficiency and thermal comfort	Window-to-wall ratio, outer and inner glass metrical, the filling gas.	TRNSYS + NSGA-II + Artificial Neural Network	The study introduces a multi-objective optimization method using NSGA-II and EnergyPlus to optimize window parameters, balancing energy consumption, indoor thermal	The research emphasizes the importance of multi-factor, multi-objective optimization in early-stage building design, addressing the limitations of single-objective approaches that primarily focus on	[15]

				environment, and visual performance. By addressing the limitations of single-objective optimization, this approach considers multiple parameters and objectives, enhancing overall performance and practicality for real-world applications.	energy performance. The proposed method effectively balances energy consumption, indoor thermal comfort, and visual performance, revealing inverse relationships between energy use and visual performance and between thermal comfort and visual performance.	
Residential	Thermal comfort and energy consumption	HVAC system setting, thermostat programming, and passive solar design.	TRNSYS + Geetic algorithm + Artificial Neural Network model	The study combines ANN and NSGA-II to optimize building design, achieving high accuracy with minimal errors. It finds that small reductions in thermal comfort can cut energy use by up to 13%. NSGA-II solutions outperform manual designs, offering diverse trade-offs between energy efficiency and comfort, highlighting its potential for effective building optimization.	An efficient optimization method using TRNSYS, genetic algorithms, and ANN enhances energy efficiency and thermal comfort in buildings. The ANN achieved high accuracy while reducing simulation time from years to minutes. Key findings include a 13% energy reduction by adjusting PMV and offering diverse design solutions for balancing energy savings and comfort.	[16]

IMPACTS OF THE MICROALGAE PHOTOBIOREACTOR FAÇADE

The integration of microalgae photobioreactor (PBR) façades into building systems represents a convergence of architectural innovation and environmental stewardship. These façades offer multifunctional benefits, including energy efficiency, carbon sequestration, thermal regulation, and resource production, making them a compelling addition to sustainable urban design.

One of the primary benefits of microalgae PBR façades is their ability to enhance thermal performance of buildings. A thermodynamic model tailored to PBR systems on building façades demonstrates the capacity to predict dynamic temperature changes in the culture medium in response to climatic conditions. This enables the development of control strategies for efficient thermal regulation, ensuring optimal energy consumption (as illustrated in Fig. 3) [17]. In line with the research by Talaei, a microalgae window can significantly reduce building energy consumption compared to single-glazed, double-glazed, and water windows [18].

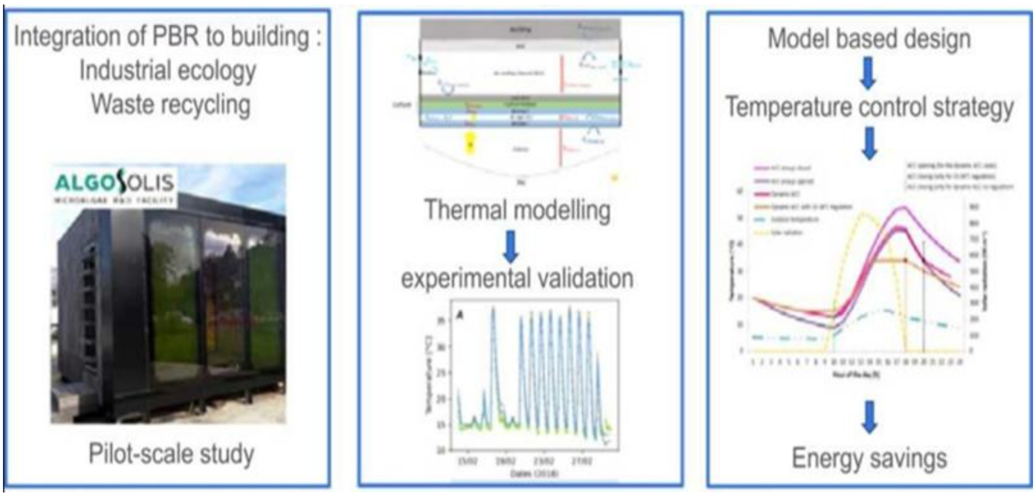

Figure 3. Integration of PBR building facades based on thermal modelling and experimental validation to reduce energy consumption through temperature control strategy [17].

Green microalgae can selectively absorb sunlight radiation, enabling photobioreactors (PBRs) to function as bio-shading devices or bio-curtains, effectively controlling light penetration and temperature in buildings [19], [20]. Additionally, photobioreactor façades (PBRFs) can improve indoor thermal comfort by enhancing relative humidity, a critical factor in hot-arid climates, although their potential for providing thermal comfort across various climate zones remains underexplored [21]. A comprehensive review of PBRF performance has highlighted key issues and benefits, including structural considerations, energy savings, thermal comfort, and daylight performance, while identifying challenges in their façade applications [22]. Furthermore, indoor air quality, which significantly impacts human health and thermal comfort, is an essential factor in enhancing energy efficiency and ensuring indoor comfort in building-integrated microalgae photobioreactor facades [23], [24].

In hot-arid climates, PBR façades also improve indoor thermal comfort by enhancing relative humidity, an essential factor in occupant comfort. Although their potential to provide similar benefits across diverse climate zones remains underexplored, initial studies suggest promising applications in both temperate and tropical regions [1]. Furthermore, these façades contribute to improved indoor air quality, which is critical for occupant health and thermal comfort. By incorporating green microalgae into building envelopes, PBR systems also mitigate urban heat island effects while enhancing overall building performance.

From an environmental perspective, PBR façades play a significant role in carbon sequestration and pollution reduction. Microalgae cultures in PBRs capture CO_2 through photosynthesis, reducing greenhouse gas emissions and aligning with global carbon neutrality goals [25]. In addition to CO_2 capture, these systems facilitate wastewater treatment by utilizing nutrients in the water, effectively minimizing environmental impacts associated with nutrient runoff [26], [27]. The integration of these systems into urban architecture thus contributes to sustainable water management practices and environmental remediation efforts.

Beyond their thermal and environmental impacts, microalgae PBR façades also offer economic advantages. The enhanced surface-to-volume ratio in these systems optimizes light utilization, improving biomass production rates and enabling the cultivation of microalgae for various high-value applications, including biofuel production and pharmaceuticals [28], [29]. This dual functionality of energy efficiency and resource production adds significant economic value to the implementation of PBR façades in buildings.

INTEGRATION OF PHOTOBIOREACTOR FAÇADE IN BUILDING SIMULATION

The integration of PBR facades into building simulations offers a novel approach to improving energy efficiency and environmental sustainability in architectural design. While the TRNSYS model is traditionally used for simulating thermal and energy performance in buildings, recent advancements have extended its application to biological systems, enabling the simulation of PBRs as building-integrated components.

Kenai demonstrated the adaptability of TRNSYS in simulating green facades, showcasing its ability to assess their impact on indoor temperature regulation [30]. Similarly, Nocera employed the TRNSYS tool to model the heat balance of a multi-zone building, enabling a comprehensive analysis of thermal performance across different building spaces [10]. This research explored various wall materials and structural adjustments, offering valuable insights into sustainable architectural practices.

Fig. 4 illustrates the heat exchange mechanisms integrated into the system's thermal model, which combines the building envelope's thermal dynamics with those of the PBR. This integration enables a detailed analysis of the interactions between the building structure and the PBR system, as described by Girard [31]. Such approaches allow researchers to evaluate the thermal implications of PBR integration comprehensively.

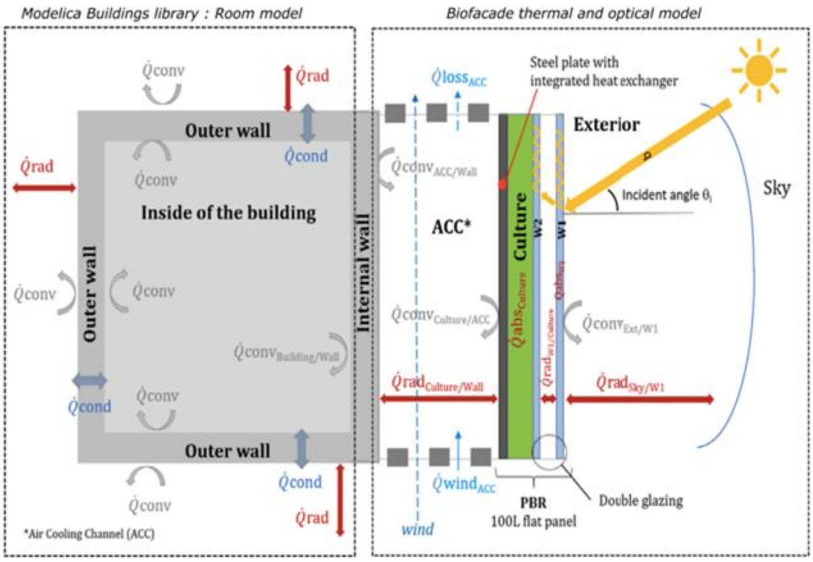

Figure 4. The bio-facade thermal and optical model mechanisms within the system's thermal model, which integrates the thermal dynamics of the building envelope and the photobioreactor (PBR) [31].

Case studies on existing algae windows have provided further evidence of PBR facades' potential to enhance building performance. Talaei focused on two critical parameters, window-to-wall ratio, algae concentration, and their impact on thermal performance. The study simulated four building orientations (north, south, east, and west) and six window-to-wall ratios, demonstrating how these variables influence the efficiency of building-integrated bioreactors [18].

Beyond structural considerations, PBRs offer functional benefits such as CO2 sequestration, biomass production, and thermal regulation. Ribeiro showcased the integration of a flexible microalgae growth model into TRNSYS for large-scale PBR systems. Their model enabled adjustments to key parameters such as biomass density, growth rate, and light absorption, allowing for accurate predictions of PBR facades' thermal and energy performance [32]. Similarly, Pruvost emphasized the advantages of vertical flat-panel PBRs, highlighting their potential for optimizing CO2 fixation and reducing energy consumption for thermal regulation.

Despite these advancements, integrating biological growth dynamics into TRNSYS remains a challenge. Yaman (2024) identified significant limitations in incorporating biological models into the software, revealing a gap in its capability to represent the growth processes of microalgae [33]. To address this, Sedighi (2023) integrated TRNSYS with MATLAB, enabling the inclusion of growth kinetics and environmental parameters. While this approach enhances simulation accuracy, it also introduces computational complexity, emphasizing the need for streamlined modeling techniques [34].

Empirical studies further validate the potential of PBR facades. Sarda and Vicente (2016) reviewed case studies demonstrating the successful integration of PBR systems into building facades, underscoring their role in reducing carbon emissions and enhancing energy efficiency [35]. Sedighi explored the multifaceted benefits of bioactive facades, such as thermal insulation, shading, and CO2 capture, all of which can be effectively modeled within TRNSYS [34].

Optimizing environmental conditions for microalgae growth is critical to maximizing PBR efficiency. Hindersin emphasized the importance of irradiance optimization for biomass production, while Goetz (2011) highlighted precise temperature modelling as a key factor for solar PBR efficiency [36], [37]. Additionally, Verso (2019) explored the multifunctional applications of PBRs as dynamic shading systems, demonstrating their ability to regulate natural light exposure and enhance visual comfort in architectural designs [38].

As the field evolves, advancing simulation tools and methodologies remain essential for overcoming current challenges and realizing the full potential of PBR façades. Yilmaz (2022) stressed the importance of building envelopes in regulating stressed the importance of building envelopes in regulating thermal and visual comfort, particularly when integrating biological systems such as PBRs into façade designs. Developing more sophisticated and user-friendly simulation frameworks will facilitate broader adoption of this technology, promoting sustainable architectural practices [39].

FUTURE DIRECTIONS FOR TRNSYS IN MICROALGAE PHOTOBIOREACTOR SIMULATION

The future evolution of TRNSYS in the domain of microalgae photobioreactor (PBR) simulation presents substantial prospects for advancement in sustainable building technologies, particularly in the context of zero-emission building design. To this end, it is imperative to address the prevailing limitations of TRNSYS's capabilities to model PBR systems and to explore innovative methodologies.

Development of Dedicated TRNSYS Components for PBR Modeling

A primary area for improvement lies in the development of open-source TRNSYS components specifically tailored to simulate PBRs. Previous research has identified gaps in the tool's ability to incorporate biological growth dynamics. Dedicated components would enhance TRNSYS's capability to model microalgal growth processes, improving the accuracy and reliability of simulations. These advancements would also enable researchers and designers to predict bio-thermal interactions better and apply findings to real-world building systems.

Integration with Advanced Computational Techniques

Incorporating machine learning (ML) techniques into TRNSYS models is another promising avenue. Alami emphasized the potential of ML algorithms to analyze large datasets, uncover complex relationships, and improve prediction accuracy for bio-thermal interactions [40]. By leveraging these algorithms, TRNSYS models could identify optimal operational parameters for PBRs, streamlining the design and optimization process. Similarly, integrating TRNSYS with MATLAB or Python has shown promise in improving modeling precision. For example, Nayak and Hagishima explored the incorporation of nonlinear heat and moisture that transfer phenomena into building simulations, a feature that could be extended to represent PBR dynamics better [12].

Hybrid modeling approaches, such as coupling TRNSYS with MATLAB or computational fluid dynamics (CFD), could provide robust frameworks for capturing the intricate interactions between biological and thermal systems. This approach would allow for incorporating sophisticated growth kinetics and environmental parameters, as demonstrated in studies by Sedighi [34]. However, these integrations also introduce computational complexities that future research must address by developing more streamlined methodologies.

Optimization Frameworks for Building-Integrated PBRs

Optimizing the integration of PBRs into building façades requires multi-objective design frameworks. Several studies have demonstrated the utility of combining TRNSYS with optimization techniques, such as Non-dominated Sorting Genetic Algorithm II (NSGA-II), artificial neural networks (ANNs), and graphical optimization methods, to enhance energy efficiency and thermal performance [13]–[16] For instance, Talaei [18] proposed a framework using metrics like useful daylight illuminance and energy use intensity to optimize algae windows integrated into office building façades. Similarly, Elmalky and Araji employed hourly thermal simulations and shading analysis to optimize the thermal and biological energy generation of integrated PBR systems [41].

Addressing Modeling Challenges and Data Limitations

While TRNSYS has proven effective in thermal simulations, modeling the complex dynamics of PBR systems presents unique challenges. Environmental factors such as light intensity, nutrient availability, and temperature fluctuations significantly impact microalgal growth, and accurately representing these variables within TRNSYS remains difficult. Enhancing the precision of simulations requires integrating TRNSYS with big-data approaches and secondary data sources to reduce reliance on assumptions and mitigate uncertainties. Comprehensive experimental data is also essential for validating and calibrating models to ensure their reliability.

Future advancements could involve incorporating advanced algorithms beyond ANNs into TRNSYS, potentially improving simulation accuracy and efficiency. Machine learning and deep learning models could further enhance the tool's predictive capabilities. Additionally, exploring hybrid approaches that combine TRNSYS with other advanced tools will be crucial for accurately representing the multifaceted interactions within PBR systems.

Towards Comprehensive and Integrated Simulation Tools

The long-term vision for TRNSYS in microalgae PBR simulation is to evolve into a holistic tool capable of seamlessly integrating biological and thermal systems. By addressing current gaps and leveraging computational advancements, TRNSYS could facilitate the development of energy-efficient and environmentally sustainable buildings. PBRs' potential to sequester CO_2, regulate thermal conditions, and enhance energy performance underscores their value in achieving zero-emission building designs.

Advancing TRNSYS-based simulations will require interdisciplinary collaboration, integrating expertise in architecture, engineering, biology, and computer science. By doing so, researchers and practitioners can harness the full potential of microalgae PBRs, driving innovation in sustainable architecture and contributing to a healthier planet.

CONCLUSION

This review underscores the transformative potential of TRNSYS in simulating building-integrated microalgae photobioreactor (PBR) facades for thermal performance. The integration of microalgae PBR facades into building systems demonstrates significant environmental, thermal, and economic benefits, including enhanced energy efficiency, carbon sequestration, improved indoor thermal comfort, and the potential for biomass production. TRNSYS, with its modular and dynamic simulation capabilities, serves as a robust platform for analyzing these systems, enabling the optimization of thermal regulation and energy consumption.

Key advancements in TRNSYS applications include modeling heat exchange mechanisms, coupling with biological systems, and integrating PBR dynamics into multi-zone building simulations. The software's flexibility, facilitated by its modular structure, allows for the integration of various components through a standard interface and supports interactions with external numerical simulation tools such as MATLAB and Python. This capability has been leveraged in several studies, including those utilizing artificial neural networks to enhance computational simulations. However, significant challenges remain, including the need for improved modeling accuracy, the integration of biological growth dynamics, and the exploration of alternative algorithms beyond neural networks to further optimize TRNSYS simulations. Addressing these challenges will require innovative algorithms, big data integration, and comprehensive experimental data for model validation.

Future research should focus on refining TRNSYS as a comprehensive tool for zero-emission architecture by enhancing its ability to represent complex interactions between biological and thermal systems. This includes developing dedicated TRNSYS components tailored for PBR modeling, incorporating machine learning techniques, and exploring hybrid modeling approaches that combine TRNSYS with advanced computational frameworks. These efforts would advance TRNSYS-based simulations and contribute to the efficient design and operation of microalgae cultivation systems.

The integration of PBR facades into TRNSYS simulations offers promising avenues for advancing sustainable building practices, fostering innovation in climate-responsive design, and aligning with global sustainability goals. As TRNSYS evolves, interdisciplinary collaboration across architecture, engineering, and biological sciences will be critical to fully realize its potential in optimizing building-integrated PBR systems for a sustainable future.

Acknowledgements

This research was supported by the CMU Junior Research Fellowship Program and partially funded by the Faculty of Engineering, Chiang Mai University. The authors sincerely appreciate for their financial support. The provided funding and resources were essential to the successful completion of this study.

REFERENCES

[1] Y. Yaman, N. Altunacar, A. Tokuç, G. Köktürk, İ. Deniz, and M. A. Ezan, “Effects of Photobioreactor Façades on Thermal and Visual Performance of an Office in Izmir,” Eskişehir Tech. Univ. J. Sci. Technol. A - Appl. Sci. Eng., vol. 23, pp. 68–75, Dec. 2022, doi: 10.18038/estubtda.1169876..

[2] J. Pruvost, B. Le Gouic, O. Lepine, J. Legrand, and F. Le Borgne, “Microalgae culture in building-integrated photobioreactors: Biomass production modelling and energetic analysis,” Chem. Eng. J., vol. 284, pp. 850–861, Jan. 2016, doi: 10.1016/j.cej.2015.08.118..

[3] Y. Gao et al., “Mariculture wastewater treatment with Bacterial-Algal Coupling System (BACS): Effect of light intensity on microalgal biomass production and nutrient removal,” Environ. Res., vol. 201, p. 111578, Oct. 2021, doi: 10.1016/j.envres.2021.111578.

[4] R. Tang, Y. Yang, and W. Gao, “Comparative studies on thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt-angles,” Sol. Energy, vol. 85, no. 7, pp. 1381–1389, Jul. 2011, doi: 10.1016/j.solener.2011.03.019.

[5] C. Maurer and T. E. Kuhn, “Variable g value of transparent façade collectors,” Energy Build., vol. 51, pp. 177–184, Aug. 2012, doi: 10.1016/j.enbuild.2012.05.011.

[6] M. Li, J. Shi, J. Guo, J. Cao, J. Niu, and M. Xiong, “Climate Impacts on Extreme Energy Consumption of Different Types of Buildings,” PLoS One, vol. 10, no. 4, p. e0124413, Apr. 2015, doi: 10.1371/journal.pone.0124413.

[7] T. D. Akpenpuun et al., “Building Energy Simulation Model Application to Greenhouse Microclimate, Covering Material and Thermal Blanket Modelling: A Review,” Niger. J. Technol. Dev., vol. 19, no. 3, pp. 276–286, Sep. 2022, doi: 10.4314/njtd.v19i3.10.

[8] Y. Yau, “Climate change implications for HVAC&R systems for a large library building in Malaysia,” Build. Serv. Eng. Res. Technol., vol. 33, no. 2, pp. 123–139, May 2012, doi: 10.1177/0143624410397991.

[9] A. Beltrami, M. Picco, and M. Marengo, “RAPID EXPLOITATION OF BUILDING ENERGY DESIGN THROUGH COMPACT TRNSYS MODELING,” AiCARR J., vol. 37, pp. 60–67, 2016.

[10] F. Nocera, V. Costanzo, M. Detommaso, and G. Evola, “Assessing the Impact of Vertical Greenery Systems on the Thermal Performance of Walls in Mediterranean Climates,” Energies, vol. 17, no. 20, p. 5090, Oct. 2024, doi: 10.3390/en17205090.

[11] M. T. Plytaria, C. Tzivanidis, E. Bellos, I. Alexopoulos, and K. A. Antonopoulos, “Thermal Behavior of a Building with Incorporated Phase Change Materials in the South and the North Wall,” Computation, vol. 7, no. 1, p. 2, Dec. 2018, doi: 10.3390/computation7010002.

[12] A. K. Nayak and A. Hagishima, “Modification of building energy simulation tool TRNSYS for modelling nonlinear heat and moisture transfer phenomena by TRNSYS/MATLAB integration,” E3S Web Conf., vol. 172, p. 25009, Jun. 2020, doi: 10.1051/e3sconf/202017225009.

[13] J. Xu, J.-H. Kim, H. Hong, and J. Koo, “A systematic approach for energy efficient building design factors optimization,” Energy Build., vol. 89, pp. 87–96, Feb. 2015, doi: 10.1016/j.enbuild.2014.12.022.

[14] M. Hamdy, A. Hasan, and K. Siren, “A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010,” Energy Build., vol. 56, pp. 189–203, Jan. 2013, doi: 10.1016/j.enbuild.2012.08.023.

[15] Y. Zhai, Y. Wang, Y. Huang, and X. Meng, “A multi-objective optimization methodology for window design considering energy consumption, thermal environment and visual performance,” Renew. Energy, vol. 134, pp. 1190–1199, Apr. 2019, doi: 10.1016/j.renene.2018.09.024.

[16] L. Magnier and F. Haghighat, “Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network,” Build. Environ., vol. 45, no. 3, pp. 739–746, Mar. 2010, doi: 10.1016/j.buildenv.2009.08.016.

[17] E. Todisco et al., “A dynamic model for temperature prediction in a façade-integrated photobioreactor,” Chem. Eng. Res. Des., vol. 181, pp. 371–383, May 2022, doi: 10.1016/j.cherd.2022.03.017.

[18] M. Talaei, M. Mahdavinejad, R. Azari, A. Prieto, and H. Sangin, “Multi-objective optimization of building-integrated microalgae photobioreactors for energy and daylighting performance,” J. Build. Eng., vol. 42, p. 102832, Oct. 2021, doi: 10.1016/j.jobe.2021.102832.

[19] S. L. Pagliolico, V. R. M. Lo Verso, M. Zublena, and L. Giovannini, “Preliminary results on a novel photo-bio-screen as a shading system in a kindergarten: Visible transmittance, visual comfort and energy demand for lighting,” Sol. Energy, vol. 185, pp. 41–58, Jun. 2019, doi: 10.1016/j.solener.2019.03.095.

[20] S. S. Oncel and D. Şenyay Öncel, “Bioactive Façade System Symbiosis as a Key for Eco-Beneficial Building Element,” 2020, pp. 97–122. doi: 10.1007/978-3-030-20637-6_5.

[21] F. Ahmadi, S. Wilkinson, H. Rezazadeh, S. Keawsawasvong, Q. Najafi, and A. Masoumi, “Energy efficient glazing: A comparison of microalgae photobioreactor and Iranian Orosi window designs,” Build. Environ., vol. 233, p. 109942, Apr. 2023, doi: 10.1016/j.buildenv.2022.109942.

[22] M. Talaei and A. Prieto, “A review on performance of sustainable microalgae photobioreactor façades technology: exploring challenges and advantages,” Archit. Sci. Rev., vol. 67, no. 5, pp. 387–414, Sep. 2024, doi: 10.1080/00038628.2024.2305889.

[23] A. Asif, M. Zeeshan, and M. Jahanzaib, “Indoor temperature, relative humidity and CO2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems,” Build. Environ., vol. 133, pp. 83–90, Apr. 2018, doi: 10.1016/j.buildenv.2018.01.042.

[24] N. Ma, D. Aviv, H. Guo, and W. W. Braham, “Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality,” Renew. Sustain. Energy Rev., vol. 135, p. 110436, Jan. 2021, doi: 10.1016/j.rser.2020.110436.

[25] H. Choi, “Intensified Production of Microalgae and Removal of Nutrient Using a Microalgae Membrane Bioreactor (MMBR),” Appl. Biochem. Biotechnol., vol. 175, no. 4, pp. 2195–2205, Feb. 2015, doi: 10.1007/s12010-014-1365-5.

[26] A. P. Abreu, B. Fernandes, A. A. Vicente, J. Teixeira, and G. Dragone, “Mixotrophic cultivation of Chlorella vulgaris using industrial dairy waste as organic carbon source,” Bioresour. Technol., vol. 118, pp. 61–66, Aug. 2012, doi: 10.1016/j.biortech.2012.05.055.

[27] N. C. Bhatt, A. Panwar, T. S. Bisht, and S. Tamta, “Coupling of Algal Biofuel Production with Wastewater,” Sci. World J., vol. 2014, pp. 1–10, 2014, doi: 10.1155/2014/210504.

[28] Y. Gong, H. Hu, Y. Gao, X. Xu, and H. Gao, "Microalgae as platforms for production of recombinant proteins and valuable compounds: progress and prospects," J. Ind. Microbiol. Biotechnol., vol. 38, no. 12, pp. 1879–1890, Dec. 2011, doi: 10.1007/s10295-011-1032-6.

[29] N. Yan, C. Fan, Y. Chen, and Z. Hu, "The Potential for Microalgae as Bioreactors to Produce Pharmaceuticals," Int. J. Mol. Sci., vol. 17, no. 6, p. 962, Jun. 2016, doi: 10.3390/ijms17060962.

[30] M.-A. Kenai, L. Libessart, S. Lassue, and D. Defer, "Impact of green walls occultation on energy balance: Development of a TRNSYS model on a brick masonry house," J. Build. Eng., vol. 44, p. 102634, Dec. 2021, doi: 10.1016/j.jobe.2021.102634.

[31] F. Girard, C. Toublanc, Y. Andres, E. Dechandol, and J. Pruvost, "System modeling of the thermal behavior of a building equipped with facade-integrated photobioreactors: Validation and comparative analysis," Energy Build., vol. 292, p. 113147, Aug. 2023, doi: 10.1016/j.enbuild.2023.113147.

[32] R. L. L. Ribeiro, J. V. C. Vargas, A. B. Mariano, and J. C. Ordonez, "The experimental validation of a large-scale compact tubular microalgae photobioreactor model," Int. J. Energy Res., vol. 41, no. 14, pp. 2221–2235, Nov. 2017, doi: 10.1002/er.3784.

[33] Y. Yaman and A. Tokuç, "An optimization of thermal, visual and energy indicators for retrofit with photobioreactors in the mediterranean climate," E3S Web Conf., vol. 546, p. 03006, Jul. 2024, doi: 10.1051/e3sconf/202454603006.

[34] M. Sedighi, P. Pourmoghaddam Qhazvini, and M. Amidpour, "Algae-Powered Buildings: A Review of an Innovative, Sustainable Approach in the Built Environment," Sustainability, vol. 15, no. 4, p. 3729, Feb. 2023, doi: 10.3390/su15043729.

[35] R. Cervera Sardá and C. A. Vicente, "Case Studies on the Architectural Integration of Photobioreactors in Building Façades," in Nano and Biotech Based Materials for Energy Building Efficiency, Cham: Springer International Publishing, 2016, pp. 457–484. doi: 10.1007/978-3-319-27505-5_17.

[36] S. Hindersin, M. Leupold, M. Kerner, and D. Hanelt, "Irradiance optimization of outdoor microalgal cultures using solar tracked photobioreactors," Bioprocess Biosyst. Eng., vol. 36, no. 3, pp. 345–355, Mar. 2013, doi: 10.1007/s00449-012-0790-5.

[37] V. Goetz, F. Le Borgne, J. Pruvost, G. Plantard, and J. Legrand, "A generic temperature model for solar photobioreactors," Chem. Eng. J., vol. 175, pp. 443–449, Nov. 2011, doi: 10.1016/j.cej.2011.09.052.

[38] V. R. M. Lo Verso, M. H. S. Javadi, S. Pagliolico, C. Carbonaro, and G. Sassi, "Photobioreactors as a Dynamic Shading System Conceived for an Outdoor Workspace of the State Library of Queensland in Brisbane: Study of Daylighting Performances," J. Daylighting, vol. 6, no. 2, pp. 148–168, Dec. 2019, doi: 10.15627/jd.2019.14.

[39] Y. Yılmaz, K. E. Şansal, M. Aşcıgil-Dincer, S. Kültür, and S. H. Tanrıöver, "A methodology to determine appropriate façade aperture sizes considering comfort and performance criteria: A primary school classroom case," Indoor Built Environ., vol. 31, no. 7, pp. 1874–1891, Aug. 2022, doi: 10.1177/1420326X221080566.

[40] A. Alami et al., "Artificial Intelligence Approach for Bio-Based Materials' Characterization and Explanation," Buildings, vol. 14, no. 6, p. 1602, Jun. 2024, doi: 10.3390/buildings14061602.

[41] A. M. Elmalky and M. T. Araji, "Multi-objective problem of optimizing heat transfer and energy production in algal bioreactive façades," Energy, vol. 268, p. 126650, Apr. 2023, doi: 10.1016/j.energy.2023.126650.