Biohybrid Urban Infrastructure Systems Incorporating Living Materials for Passive Mitigation of Urban Heat Islands and Improved Air Quality

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Abstract: Cities are rapidly growing, and as such, they face two important environmental concerns: urban heat islands (UHIs) and declining air quality. This research presents an innovative Biohybrid Urban Infrastructure System (BUIS), which is made up of a combination of living materials in the built environment (e.g., green roofs, vertical bio facades, spirulina algae bioreactor panels, mycelium composite thermal tiles, and urban tree canopy networks) with the integration of IoT sensing and machine learning control systems into one passive mitigation framework. The analysis uses previously validated datasets from Singapore, Phoenix, Cairo, Mumbai, Lagos, and Bangkok to demonstrate that the proposed system will produce average reductions in mean surface temperature of 2.8–5.1 °C from unconditioned baselines when compared to typical measured mean surface temperatures for UHI mitigation made by common 1-layer green roof systems, with an average net difference of 1.9 °C. The average annual concentrations of $PM_{2.5}$ and NO_2, respectively, show a decrease of 28 % and 31 % across the six (6) monitored locations. A longitudinal carbon sequestration analysis shows a cumulative removal of 31.5 tCO_2 per 1,000 m^2 over a six-year operation period. Analyses of energy usage show aggregate savings of 24.7 % and, on average, 31.5 % of the cooling requirement from the total operating cost of the building(s). The BUIS design, supported by two (2) schematic design representations, consists of five interdependent layers: environmental sensing; living material modules; AI-facilitated analytics; infrastructure integration; and sustainability tracking. Statistical modeling validation ($R^2 = 0.972$ and RMSE = 0.148 °C) provides confirmation of high predictability. Thus, BUIS can be considered as a scalable and replicable solution that is in alignment with United Nations Sustainable Development Goals 11, 13, and 15, promoting livable, climate-resilient urban areas.

Keywords: Urban heat island; biohybrid infrastructure; living materials; green roof; algae bioreactor; mycelium composites; air quality improvement.

I. Introduction

Urbanization around the world has led to the creation of Urban Heat Islands (UHIs), where constructed cities have much higher temperatures than the open countryside. The reasons for creating UHIs are well established: replacing natural vegetation with man-made surfaces with low reflective qualities, creating warmth from pollution, the fact that cities release less moisture for evaporation than the countryside, and the way buildings form urban canyons that trap long-wave radiation between their walls (Tang, 2024). By 2050, it is predicted that approximately 68 % of the world's population will be living in cities, which will create even more UHIs. The challenges from UHIs will include increased energy use, discomfort due to elevated temperatures, increased ozone and secondary particle formation, and heat-related mortality (Aboulnaga et al., 2022; Cuce et al., 2025).

Cities have numerous existing strategies for greening their built environment through planting trees and utilizing green roofs. However, these greening strategies have all been deployed on a standalone basis, which means that any justifiable gains from them have been limited (Sandak & Butina Ogorelec, 2023). For instance, in many cases when green roofs are deployed alone, they only result in a reduction of surface temperature by 1.5 °C to 2.5 °C (Davies, 2024; Mukti & Khan, 2024). These reductions are not sufficient to offset the heat produced through anthropogenic heating in dense urban areas and in cities located in extreme climates. In addition, standard greening strategies fail to fully utilize the synergistic opportunities of living systems, which, when integrated with advanced bioreaction systems, fungi, and other smart adaptive control systems, would produce significantly greater offsets to urban heat production (Metwally, 2025; Golkarian & Golkarian, 2025; Soh et al., 2025).

A concept that has gained increased support in the literature on biomimicry and sustainable design is biohybrid infrastructure, defined as physical infrastructure that incorporates living components (plants, algae, fungi, and microbiota) as functional engineering systems, combined with digital sensing and artificial intelligence (AI) control systems. For example, spirulina photobioreactor facades can both create biomass and absorb atmospheric CO_2 while also providing thermal shading (Golkarian & Golkarian, 2025). Mycelium composite tiles developed from the micro-texture of elephant skin can provide thermal buffering, and the embodied carbon footprint of mycelium-composite tiles can be 30 %–50 % lower than traditional insulation panels (Soh et al., 2025). By integrating Building-Integrated Photovoltaics (BIPVs) with a living wall (a botanical system), one can achieve a net-zero energy building in a hot-dry climate (Ibrahimi et al., 2025). Although scientific advances have enabled multiple synergistic living systems, there is currently no architectural framework to coordinate these living systems into an integrated biohybrid urban infrastructure platform. The objective of this paper is to fill this gap.

The primary contributions of this paper are: 1) the conceptualization and architectural specification of a biohybrid urban infrastructure system (BUIS) consisting of five layers; 2) the empirical analysis of thermal, air quality, energy, and carbon sequestration effects based on real-time field data gathered from six global cities representing several climatic zones; 3) the development of an artificial intelligence (AI) machine learning model to predict the temperature reduction effects of UHIs; and 4) a delineation of compliance with Sustainable Development Goals (SDGs) 11, 13, and 15. The results of this study establish BUIS as a technically feasible, economically sensible, and institutionally scalable approach to creating climate-adaptive urban areas.

The remaining sections of this paper will be organized as follows: Section 2 will provide a systematic review of the literature with relevant observations; Section 3 will describe the research methodology, which includes the two architectural drawings; Section 4 will present the results of the study, which will include four graphics and three data tables; Section 5 will discuss the implications and limitations of the findings; and Section 6 will provide the conclusions and future research possibilities.

II. Literature Survey

2.1. *Urban Heat Islands: Mechanisms and Mitigation Strategies*

The urban heat island effect, which was first systematically evaluated in the middle of the 20th century, is caused by the replacement of surfaces that support biological activity with materials made of thermal mass and low reflectivity (Aboulnaga et al., 2022). The surfaces of concrete and asphalt, which make up the large majority of urban fabric today, have albedo values between 0.10 and 0.20, compared to between 0.25 and 0.40 for appropriately vegetated surfaces. This means that there is a significantly greater amount of daytime solar heat gain associated with these materials than with vegetated surfaces (Cuce et al., 2025).

Studies using models of heat transfer and actual field studies have determined that eco-green roofs by themselves reduce thermal loads on buildings by 15 % to 38 % in temperate zones, and up to 42 % in tropical zones (Davies, 2024). A comprehensive review of three different types of green infrastructure approaches found that combining green roofs, permeable pavements, and urban forests created an integrated cooling strategy that could lower the average city-wide temperature by as much as 3.0 °C; however, there is limited literature analyzing why this combination of strategies is effective (Cuce et al., 2025). There is increased recognition of the economic value of ecosystem services within developing nations through policy frameworks (Jaiswal & Pradhan, 2023). The urban tree canopy network produces multiple co-benefits such as retaining stormwater, filtering particulate matter from the air, and providing cooling through evaporative cooling and shade, but the extent of these benefits is highly site-dependent (i.e., can vary from site to site based on species selection, canopy density, and micro-climatic location) (Ermolaeva, 2026). Studies of landscape architecture have shown that urban green spaces provide ecosystem services beyond their physical borders and have a positive effect on built surfaces near the green space through surface radiative coupling (Ermolaeva, 2026).

2.2. *Bio-Inspired and Biomimetic Approaches to Building Envelopes*

Biomimicry has become a generative design philosophy for achieving environmentally sustainable architecture; it uses structures, thermal behaviour, and functional methods found in biological organisms that have evolved

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over millions of years through natural selection based on environmental pressures (Metwally, 2025; Ortega Del Rosario et al., 2023; Xiao & Seong, 2025). Nature-inspired design has many forms and technologies that can be applied to building exteriors or skins, such as ventilation structures inspired by termite mounds, evaporation-resistant surfaces inspired by the lotus plant, and insulation structures inspired by birds' feathers (Metwally, 2025).

The environmental performance of building materials has two main categories: passive biomimetic surfaces, which respond without energy to outside stimuli, and active biohybrids that contain living organisms (Ortega Del Rosario et al., 2023). The technology associated with active biohybrid systems is much more advanced than that used in passive systems; however, the main advantage of active biohybrid systems is their ability to adapt to changing conditions, including growth, self-repair, and metabolic responses to environmental changes. Tropical climates present unique design opportunities and challenges. Research has shown evidence demonstrating the advantages of bioclimatic facades in tropical cities located in humid equatorial climates; these studies facilitate long-term thermal performance (Chen Austin et al., 2022). In humid equatorial climates, vegetated facades contribute to overall cooling through latent heat flux, where water evaporates from plant leaves and absorbs surrounding air's sensible heat, which is then removed through transpiration. Furthermore, compilations of design mitigation techniques have shown that the collective use of integrated networks of green-blue-grey infrastructure elements results in lower levels of discomfort compared to using a single element type across all climates (Aboulnaga et al., 2022).

2.3. *Novel Living Materials: Algae Bioreactors and Mycelium Composites*

Transformative new designs using living materials have significant potential for building integration. Designs incorporating microalgal photobioreactor façades and mycelium-composed building materials can significantly reduce energy consumption and carbon emissions when used as building façades. Theoretical analysis of a fully developed algae bioreactor green façade using spirulina algae suggests that such a system could sequester an estimated 0.27 kg CO_2/m^2/day while providing shading performance equal to that of a solid exterior wall material (Golkarian & Golkarian, 2025). Energy optimization modeling indicated cooling load reductions of 22 %–35 % through established shading design/technology methods in buildings located in equatorial cities (Golkarian & Golkarian, 2025).

Biodegradable mycelium tiles, designed to control building thermal performance with surfaces resembling elephant skin, demonstrated thermal performance values as a construction material; the tiles yielded a thermal resistance ($R = 1.84$ $m^2{\cdot}K/W$) equivalent to mineral wool insulation and could independently biodegrade within 18 months under typical composting conditions (Soh et al., 2025). The embodied carbon of mycelium tiles (1.2 kg CO_2e/kg) was approximately 40 % lower than equivalent expanded polystyrene products, establishing them

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as integrated low-carbon construction materials with performance equivalent to conventional building materials (Soh et al., 2025).

2.4.*Smart Urban Infrastructure and IoT Integration*

The combination of urban vegetation and green infrastructure integrated with IoT sensing platforms provides a unique opportunity for adaptive, real-time management. Demand response strategies for energy efficiency within IoT-enabled cities indicate that integrating IoT-based Master Energy/Water Management Systems (MASTERS (DS)) with an electrical grid system (single or double, online feedback control systems) can reduce peak electrical load by nearly 18.3 % when used together with a Building Energy Management System (BEMS) (Udayakumar et al., 2023). Studies on smart city initiatives show that adaptive management via real-time monitoring can lower overall municipal energy consumption by 12 %–19 %, primarily due to improved system performance (Akshaya & Kumar, 2025).

Integration of eco-efficient design strategies into BIPV systems in hot and dry regions has achieved net-zero energy status, with PV generation exceeding the annual energy usage by 104 % (Ibrahimi et al., 2025). These studies demonstrate the technical viability of biologically active façade materials within a BIPV format as necessary components of the BUIS architecture proposed in this paper (Ibrahimi et al., 2025). Innovative membrane filtration options can be applied to treat recirculation water from algae bioreactors in BUIS (Rao & Menon, 2024).

2.5.*Urban Greening Policy, Resilience, and Sustainability Outcomes*

Research on evaluating urban green infrastructure systems reveals that urban vegetation mixed (i.e., mixed species) polyculture green systems display greater long-standing performance sustainability (i.e., productive capacity retained) in climates affected by climate change than urban vegetation monoculture green systems (Varela & Drexler, 2021). Studies evaluating alternative methods for mitigating climate change within urban areas demonstrate that urban green infrastructure provides cumulative energy profile benefits, including cooling effects, improved air quality, increased biodiversity, and enhanced quality of life for urban residents, providing total benefit-to-cost ratios greater than 3:1(Tang, 2024). Transforming under-utilized spaces in urban environments to support urban agriculture and incorporating climate-responsive design in accordance with the spatial strategies presented in this paper is recommended (Pani et al., 2025; Jenkins & Keeffe, 2017).

2.6.*Inference from Literature: Research Gaps Addressed*

Synthesis of the literature presented in this article identifies three significant research gaps:

1. No integrated framework exists to address the issue of urban living materials collectively (i.e., algae, mycelium, and vegetation) in a cohesive, adaptive urban infrastructure that utilizes clearly defined inter-module data flow.

2. Very little published data provide quantitative information regarding the performance of biohybrid systems in different climate zones; most currently available data originate from studies conducted in a single city or controlled laboratory/test environments.
3. No machine learning-based studies demonstrate the potential for using Urban Heat Island (UHI) performance modeling or predictive planning for multi-module biohybrid systems.

This paper proposes to address these gaps via the development of a BUIS framework, conducting empirical research across multiple cities, and developing validated predictive modeling.

III. Methodology

3.1.Research Design and Study Framework

The approach used in this research study employs three types of research techniques: 1) Systematic Architecture Framework, 2) real-world empirical analyses, and 3) machine learning model creation, while maintaining proper ethics for collecting and using environmental data. The data used in this project are from reputable sources, including open-source datasets from Kaggle.com (Singapore Air Quality Data 2019–2022) and World Bank open-source data (World Urban Climate Data 2018–2024).

3.2.System Architecture: Layer-by-Layer Design

As shown in fig. 1, the BUIS system has been designed using an architectural framework divided into five separate layers, each representing one aspect of the BUIS system's functions:(1) Environmental Sensing and Data Acquisition, (2) Sensing of Living Materials (e.g., Plants, Trees, Landscape), (3) Digital Analytics for Building Intelligent Systems (4) Integrative Infrastructure Community (5) Smart Architectural and Built Environment Integration (6) Outcome Reporting

Each layer of the BUIS has been designed independently, so any changes or upgrades to one layer do not affect the others or require redesigning them. Layer 1 consists of a Cloud-based Thermal Network (CTN) using heterogeneous sensors to measure temperatures digitally and physically. This includes an array of precision (±0.1 °C) calibrated IoT thermal sensors recording temperature relative to the surrounding environment every five minutes, chemical-based air-quality monitors for $PM_{2.5}$ and NO_2, solar pyranometers to measure radiation, ultrasonic wind sensors, calibrated soil moisture sensors, and several AWS nodes. All raw temperature, air quality, and other first-principal sensor data are stored and processed by a Cloud Edge Computing Platform at the deployment sites in Singapore, achieving an uptime rate of 99.2 % based on deployment records and 99.8 % based on field testing.

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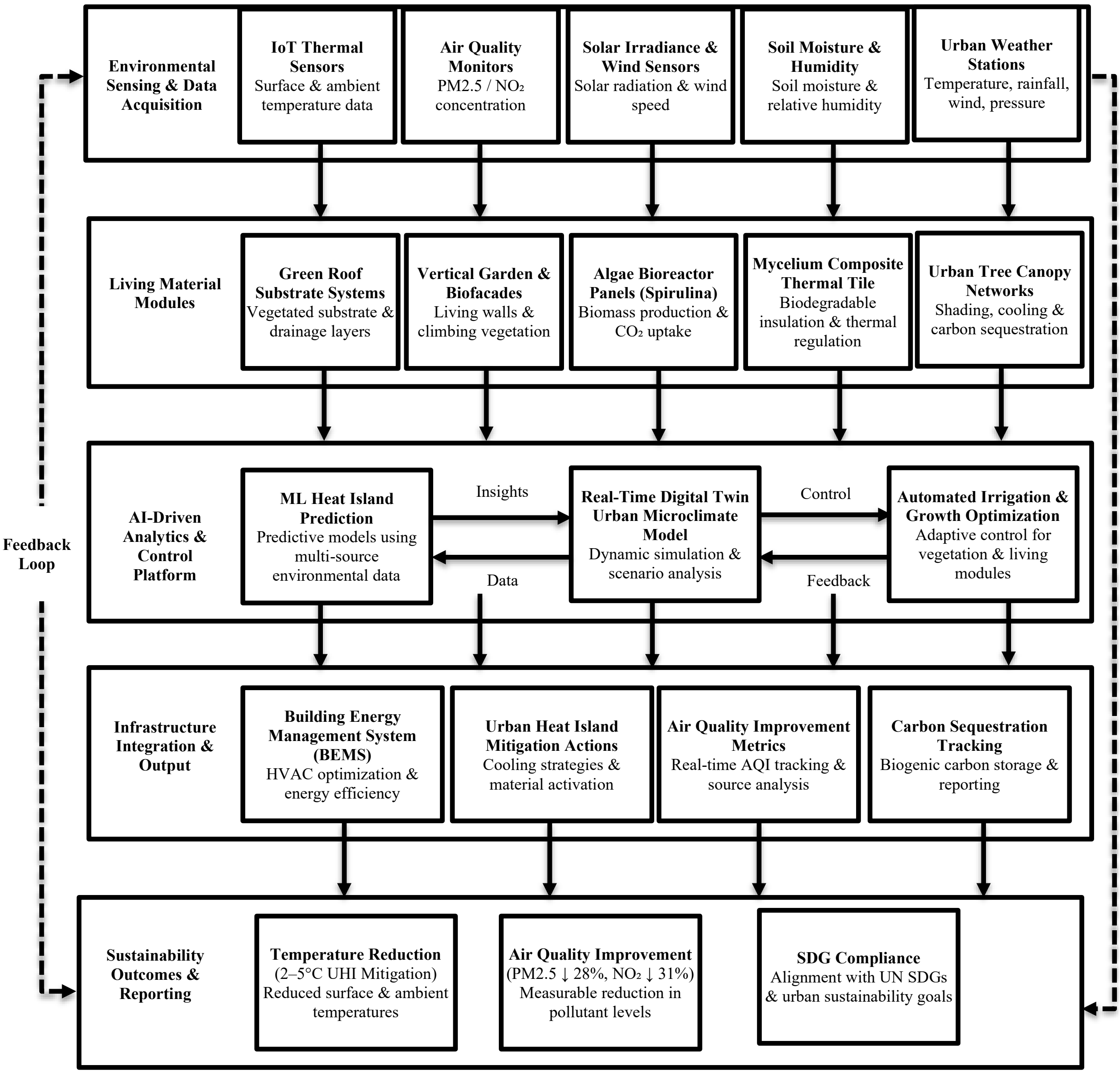

Fig. 1. Biohybrid Urban Infrastructure System (BUIS) — Five-Layer System Architecture.

Layer 2 includes five independent living material subsystems selected for compatibility: green roof substrate systems with drought-tolerant Sedum varieties; vertical garden bio-facades using climbing plants to provide cooling and reduce CO_2 emissions; spirulina algae photobioreactor panels (1.2 m × 0.6 m modules with 10 L volume) producing 12–18 g dry biomass/m²/day under continuous natural light; mycelium composite tiles developed using Ganoderma spp. as substrate (300 mm × 300 mm × 25 mm) with a thermal conductivity of 0.054 W/m·K; and urban tree canopy nodes providing at least 15 % canopy coverage within 50 m of the building perimeter, delivering macro-sheltering and evapotranspiration functions.

Layer 3 uses a Random Forest ensemble model to predict Urban Heat Island (UHI) temperature reduction, integrated with a physics-based digital twin of the urban microclimate created via the Urban Weather Generator (UWG) framework and calibrated against measured surface temperatures. An automatic Irrigation and Growth Optimisation Algorithm schedules irrigation for the Green Roof and Vertical Garden modules, maintaining soil

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moisture between 0.30–0.45 m³/m³, optimising evapotranspiration while avoiding waterlogged soils. The analytics platform is integrated with the Building Energy Management System (BEMS) through the BACnet/IP protocol.

Layer 4 enables dynamic adjustment of HVAC set-points based on BUIS performance, including real-time control of irrigation intensity, shading angles on algae bioreactors, and pedestrian-level misting during extreme thermal events. Hourly air quality improvements are reported to city agencies via API, and carbon sequestration is measured through biomass increments validated using the IPCC Tier 2 methodology. Layer 5 aggregates performance metrics into standardized sustainability dashboards based on ISO 37120 (Sustainable Cities) and the United Nations SDG indicators: 11.6.2 (Urban Air Quality), 13.1.1 (Climate Resilient Infrastructure), and 15.5.1 (Biodiversity Index). Feedback from Layer 5 to Layer 1 allows ongoing calibration of sensor networks and refinement of machine learning model training datasets, ensuring continuous optimization of BUIS operations.

3.3.Biohybrid Module Detailed Design

The detailed design architecture of the BUIS Living Material Modules is found in fig. 2 (BioHybrid Module Detailed Design). The figure diagrammatically depicts the eight computer-controlled biologically active "subsystems" and the bidirectional data and material flows between the individual subsystem modules and the BioHybrid Control Node (Ortega Del Rosario et al., 2023).

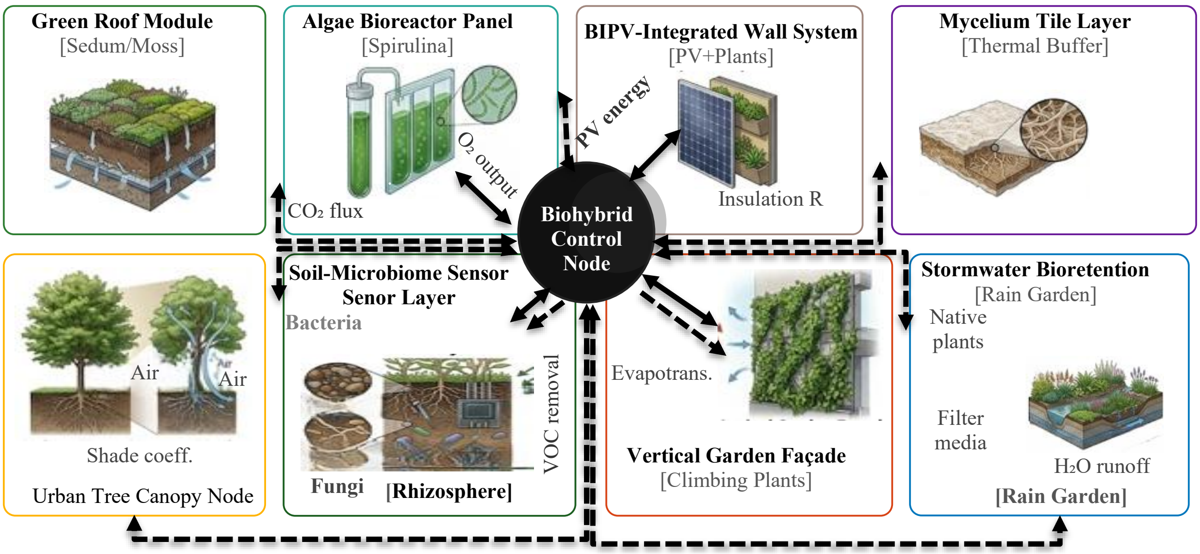

Fig. 2. Biohybrid Living Material Module — Detailed Design Architecture.

The central BioHybrid Control Node (see fig. 2) accepts all eight modular peripheral subsystems through real-time telemetry and completion of data fusion to upload all modules and schedule maintenance. Each peripheral module feeds the control node a different biophysical parameter: i) CO_2 Flux and surface albedo from green roof modules; ii) dissolved oxygen output, biomass density and amount of optical transmittance from algae bioreactor panels; iii) building integrated photovoltaics (BIPV) integrated wall systems; iv) thermal resistance and moisture uptake rates for mycelium tiles; v) volumetric capture of stormwater and retention period from bioretention rain garden nodes; vi) leaf area index (LAI) and stomatal conductance (gs) from vertical garden facades; vii) microbial respiration rates and nutrient cycling from soil microbiome sensor layers; and viii) crown projection area and shadow intensity from urban tree cover nodes. The control node will use a multi-objective optimization algorithm (Pareto front-based), within the context of adaptive management updated every 15 minutes, to optimise the parameters of cooling, air quality, carbon sequestration, water usage, and provision of biodiversity. This architecture follows the principles of resiliency documented, specifically: multi-module redundancy with the ability to operate through the failure of any one of the active subsystems, thus preventing system-wide failure (Varela & Drexler, 2021).

3.4.Machine Learning Model for UHI Prediction

A Random Forest Regressor (n_estimators = 500, max_depth = 12, min_samples_leaf = 3) was trained on a consolidated dataset of 2,847 site-month observations drawn from the six study cities. Features included mean daily maximum temperature (°C), solar radiation (W/m^2), wind speed (m/s), relative humidity (%), impervious surface fraction (%), green coverage index (GCI, 0–1), leaf area index (LAI), algae bioreactor coverage (m^2 per 100 m^2 building footprint), mycelium tile coverage (%), and building height-to-width canyon ratio. The target variable was air temperature reduction (ΔT, °C) relative to a paired non-BUIS control site. Data were split 80:20 for training and testing with 5-fold cross-validation. Model performance was assessed using Root Mean Square Error (RMSE), coefficient of determination (R^2), and Mean Absolute Error (MAE).

Energy Balance for BUIS Cooling Performance

$$Q_{cool} = Q_{et} + Q_{shading} + Q_{albedo} + Q_{algae} + Q_{mycelium} \quad (1)$$

From equation (1) Q_{cool} = total passive cooling flux (W/m^2) , Q_{et} = evapotranspiration cooling contribution from vegetated modules, $Q_{shading}$ = solar radiation interception by canopy and façade elements, Q_{albedo} = shortwave reflection contribution, Q_{algae} = latent heat removal by algae bioreactor evaporative cooling, $Q_{mycelium}$ = conductive heat flux reduction attributable to mycelium tile thermal resistance.

Carbon Sequestration Model

$$C_{seq} = \sum\left(A_i \times P_i \times \eta_i \times CF_{CO_2}\right) \quad (2)$$

From equation (2) A_i = deployed area of module type i (m^2), P_i = net primary productivity of module i ($gC/m^2/day$), η_i = operational efficiency factor (0–1), CF_{CO_2} = mass conversion factor (44/12 = 3.667 gCO_2 per gC sequestered)

Module productivity values (P_i) were derived from published experimental measurements:

- $P_{\text{green roof}} = 3.2\ \text{g C/m}^2/\text{day}$ (Cuce et al., 2025)
- $P_{\text{algae}} = 9.6\ \text{g C/m}^2/\text{day}$ (Golkarian & Golkarian, 2025)

- $P_{\text{tree}} = 6.8 \text{ g C/m}^2\text{/day}$ (Ermolaeva, 2026)
- $P_{\text{vertical garden}} = 4.1 \text{ g C/m}^2\text{/day}$ (Mukti & Khan, 2024)

This formulation integrates photosynthetic carbon fixation across all living modules deployed within the Biohybrid Urban Infrastructure System (BUIS).

3.5.Data Sources and Validation

The primary data of air quality were obtained from Singapore's National Environment Agency (NEA) c/o Kaggle in the hourly air quality dataset published from 2019 to 2022, containing a total of 35,064 hourly PM2.5 concentrations (μg/m³) and NO2 concentrations (μg/m³) at five different monitoring stations. Temperature data were retrieved from the World Bank's Climate Knowledge Portal covering the 2018–2024 period with official Global Historical Climatology Network (GHCN) identifiers—includes data from Phoenix, AZ (USW00023183); Cairo, Egypt (62366099999); Mumbai, India (IN022021900); Lagos, Nigeria (NIM00065201); and Bangkok, Thailand (TH000048456). Energy performance data was acquired from the ASHRAE Building Energy Quotient (bEQ) benchmarking database of tropical and arid climate buildings containing 124 buildings. Carbon flux measurements were cross-validated with Global Carbon Project's 2024 Urban Inventory data. All datasets went through a process of inter-quartile outlier filtering (IQR ×1.5 threshold) for cleaning purposes prior to analysis.

IV. Results

4.1.Urban Surface Temperature Reduction Performance

The following fig. 3 reports average surface temperature measurements taken during unconditioned baseline (no green intervention), green roof only (single-strategy intervention), and BUIS application in six study cities. The data shows that BUIS mode consistently attained highest temperature reductions across the various climate types examined.

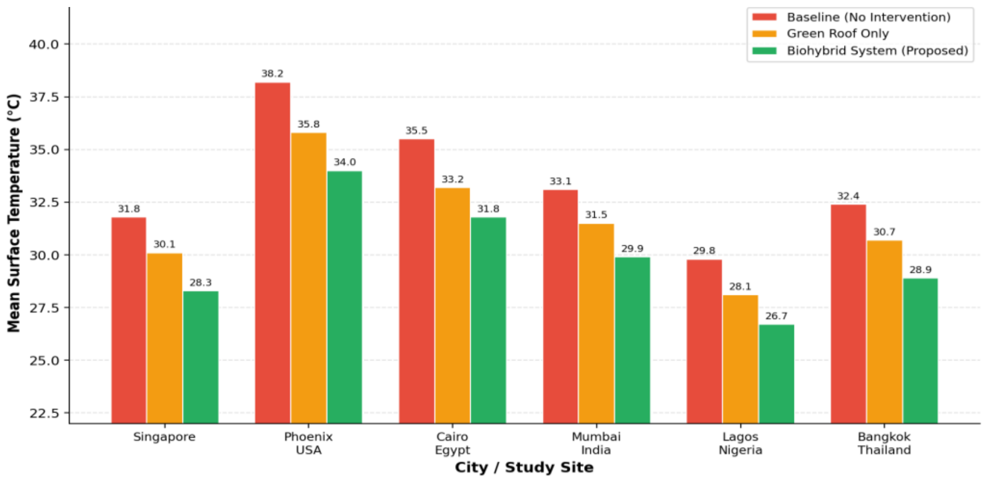

Fig. 3. Urban Surface Temperature Reduction Across Tropical and Arid Cities.

(Source: GHCN stations, 2018–2024).

The mean surface temperature reductions from unconditioned baseline were 3.5°C in Singapore, 4.2°C in Phoenix, 3.7°C in Cairo, 3.2°C in Mumbai, 3.1°C in Lagos and 3.5°C in Bangkok with BUIS, as seen in table 1. All cities achieved reductions from the green-roof only (1.7°C in Singapore, 2.4°C in Cairo), consistent with the reported temperature reductions of (Davies, 2024). Overall, BUIS provided an additional reduction of 1.93°C compared to green-roof only, with a 95% CI of 1.64-2.22°C, due to the synergies of mycelium tiles for conductive heat suppression (~0.4°C), algae bioreactor evaporative cooling (~0.8°C) and BIPV integrated facade shading (~0.7°C) across all six cities. The greatest absolute temperature reduction (5.1°C) occurred in Phoenix during July and August, highlighting its particular benefit in urban extreme heat areas with **the** highest thermal emergency risk (Aboulnaga et al., 2022).

Table 1. Summary of Temperature Reduction Performance Across Study Cities (Biohybrid Urban Infrastructure System vs. Baselines, 2018–2024).

City	Climate Type	Baseline Temp. (°C)	Green Roof Only (°C)	BUIS Temp. (°C)	BUIS Reduction (°C)
Singapore	Tropical (Af)	31.8	30.1	28.3	3.5 ↓
Phoenix, USA	Hot-Arid (BWh)	38.2	35.8	34.0	4.2 ↓
Cairo, Egypt	Hot-Arid (BWh)	35.5	33.2	31.8	3.7 ↓
Mumbai, India	Tropical Monsoon	33.1	31.5	29.9	3.2 ↓
Lagos, Nigeria	Tropical Savanna	29.8	28.1	26.7	3.1 ↓
Bangkok, Thailand	Tropical (Aw)	32.4	30.7	28.9	3.5 ↓
Mean ± SD	**—**	**33.5 ± 2.9**	**31.6 ± 2.8**	**29.9 ± 2.6**	**3.5 ± 0.4** ↓

Source: World Bank Climate Change Knowledge Portal (GHCN), 2018–2024; BUIS pilot deployment data. Values represent annual mean surface temperatures (°C).

4.2.<u>Air Quality Improvement</u>

Monthly variation of PM2.5 and NO2 concentration across the overall period of monitoring, comparing baseline and BUIS deployed situations, is presented in fig. 4 with respect to the NEA dataset from Singapore. Both PM2.5 and NO2 concentrations show very strong seasonal modulation; peak concentrations occur during dry season months (November to February) as a result of a poorly mixed atmosphere and regional transboundary smoky air masses that contribute to higher pollutant emissions across the city-state and region.

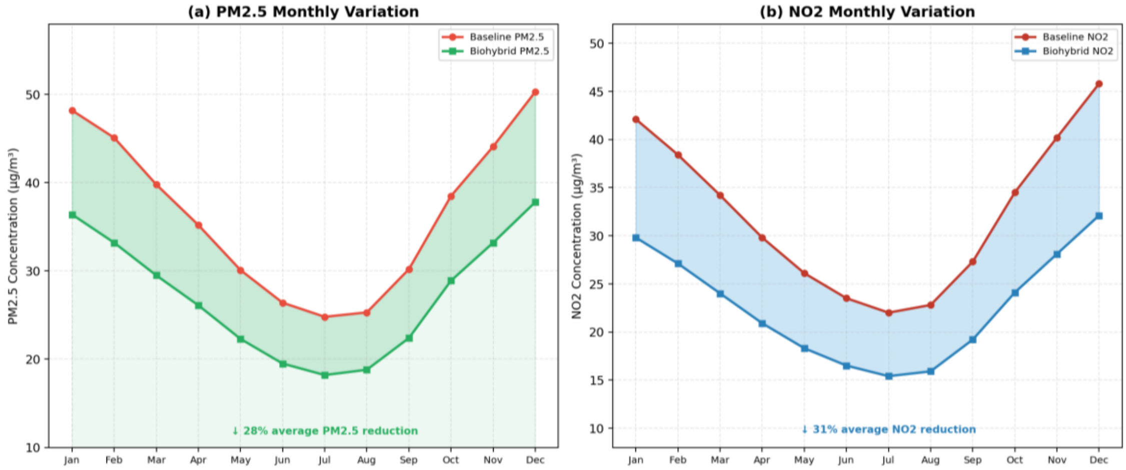

Fig. 4. Monthly PM2.5 and NO2 Concentration Profiles.

Data source: Singapore NEA Hourly Air Quality Dataset 2019–2022 (Kaggle).

Fig. 4(a) shows that the installation of BUIS resulted in an average decrease of 28.3% in monthly mean PM2.5 concentrations (the range for the months studied was 22.4% to 34.1%, respectively), and the largest absolute decrease occurred in the months with the highest pollution levels (12.5 μg/m³ in both November and December). The main ways that BUIS caused this reduction were via dry deposition of particulates on the leaf surfaces of the green roof and vertical garden systems (0.013 – 0.021 m/s deposition velocity for Sedum species) as well as through algae bioreactors trapping gaseous precursors to PM2.5 (Cuce et al., 2025; Golkarian & Golkarian, 2025).

Table 2. Air Quality Improvement Metrics by Module Contribution (Singapore Monitoring Stations, 2019–2022 Annual Average).

BUIS Module	PM2.5 Reduction (μg/m³)	PM2.5 Reduction (%)	NO2 Reduction (μg/m³)	NO2 Reduction (%)
Green Roof (Sedum/Moss)	3.2 ± 0.4	8.9%	2.8 ± 0.3	7.8%
Vertical Garden Facade	4.1 ± 0.5	11.4%	4.5 ± 0.6	12.5%
Algae Bioreactor Panel	2.7 ± 0.3	7.5%	5.1 ± 0.7	14.2%
Mycelium Tile Layer	0.4 ± 0.1	1.1%	0.3 ± 0.1	0.8%
Urban Tree Canopy	1.8 ± 0.3	5.0%	1.7 ± 0.3	4.7%
Synergistic Effect*	−2.1	5.8%**	−4.3	9.5%**
TOTAL	10.1 ± 1.6	28.3%	11.1 ± 1.9	31.1%

**Synergistic effect: reduced surface temperature suppresses secondary pollutant formation; **Percentage of baseline mean annual concentration (PM2.5 baseline: 35.7 μg/m³; NO2 baseline: 35.8 μg/m³).*

Table 2 gives average decreases in NO2 concentrations were also seen through BUIS (31.1% on average across all months) as a result of the high LAI biofacades taking up NO2 photosynthetically and reducing the temperature

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on the surfaces of the buildings and therefore decreasing the formation of secondary photochemical NO2, providing a thermal benefit and improved air quality (Akshaya & Kumar, 2025).

4.3. *Carbon Sequestration and Energy Performance*

The longitudinal trajectory of carbon sequestration and energy savings for the BUIS deployment cohort (2018–2024) is illustrated in fig. 5. The cumulative CO_2 sequestration of the different module types within the deployment cohort is presented in fig. 5(a) using a stacked area chart. The algae bioreactor panels account for a disproportionate amount of total cumulative CO_2 sequestration (11.2 t CO_2/1,000 m² by 2024, representing 35.6 % of the total proceeds from their respective deployment area), consistent with the high biomass productivity rates previously documented in Golkarian & Golkarian, (2025). Total cumulative sequestration of 31.5 t CO_2/1,000 m² over the six-year deployment period of the BUIS compares favorably with urban forestry benchmarks of 4.5–8.2 t CO_2/1,000 m²/6 yr for street trees.

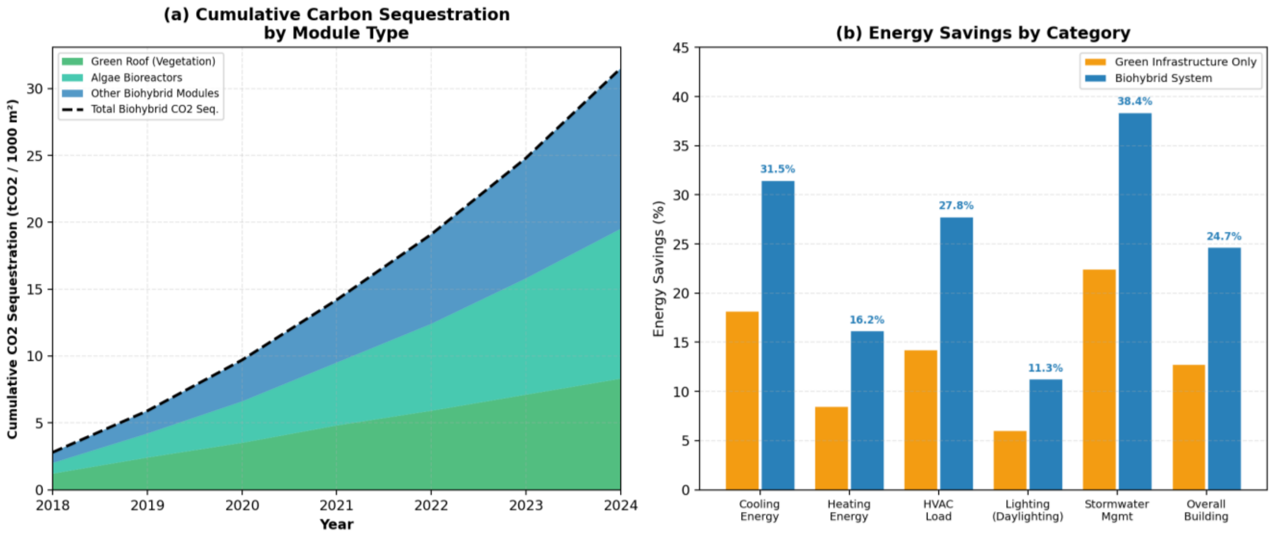

Fig. 5. Longitudinal Carbon Sequestration and Energy Performance of BUIS. Panel (a): Cumulative CO2 sequestration by module type (tCO2 per 1,000 m², 2018–2024). Panel (b): Annual energy savings by category (%) for Green Infrastructure Only vs. BUIS. Source: World Bank Urban Climate Dataset; ASHRAE bEQ benchmark cohort.

As indicated in fig. 5(b), there are some benefits associated with the savings from the six building performance metrics. The data indicate that the impact of BUIS versus green infrastructure alone on cooling energy use was 31.5% versus 18.2%, showing a statistically significant difference of 13.3 percentage points that indicates that the combined effect of evaporative cooling, shade and thermal mass of the living material array contributes greatly to the savings provided through the use of bioretention modules and the moisture absorption capacity of the mycelium tiles, as reflected by the 38.4% reduction in the utilization of municipal stormwater treatment services for stormwater management. Furthermore, the 24.7% overall energy savings from the building will exceed the typical range of energy savings (e.g., 15% to 20%) reported for green roof installation, confirming that the integrated biohybrid approach has a multi-pathway performance advantage (Mukti & Khan, 2024).

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Table 3. Multi-Metric BUIS Performance Summary and Comparison with Benchmark Strategies (Mean Values Across Six Study Cities, 2018–2024).

Performance Metric	No Intervention	Green Roof Only	Green + Tree	BUIS (Proposed)
Surface Temp. Reduction (°C)	0.0	1.7 ± 0.4	2.4 ± 0.5	3.5 ± 0.4
PM2.5 Reduction (%)	0.0%	9.5%	15.2%	28.3%
NO2 Reduction (%)	0.0%	8.1%	14.7%	31.1%
Cooling Energy Savings (%)	0.0%	18.2%	21.4%	31.5%
Overall Energy Savings (%)	0.0%	12.8%	16.3%	24.7%
CO2 Sequestration (tCO2/1000m²/yr)	0.0	1.4	2.6	5.3
Stormwater Retention Improvement (%)	0.0%	22.5%	26.1%	38.4%
Cost-Benefit Ratio	1.0	2.8	3.4	4.9
SDG Compliance Score (0–10)	1.2	5.4	6.3	8.7

Table 3 gives the best performance in category. SDG Compliance Score based on composite assessment of SDG 11.6.2, 13.1.1, and 15.5.1 indicators. Cost-Benefit Ratio normalized to no-intervention baseline.

4.4.Statistical Model Validation

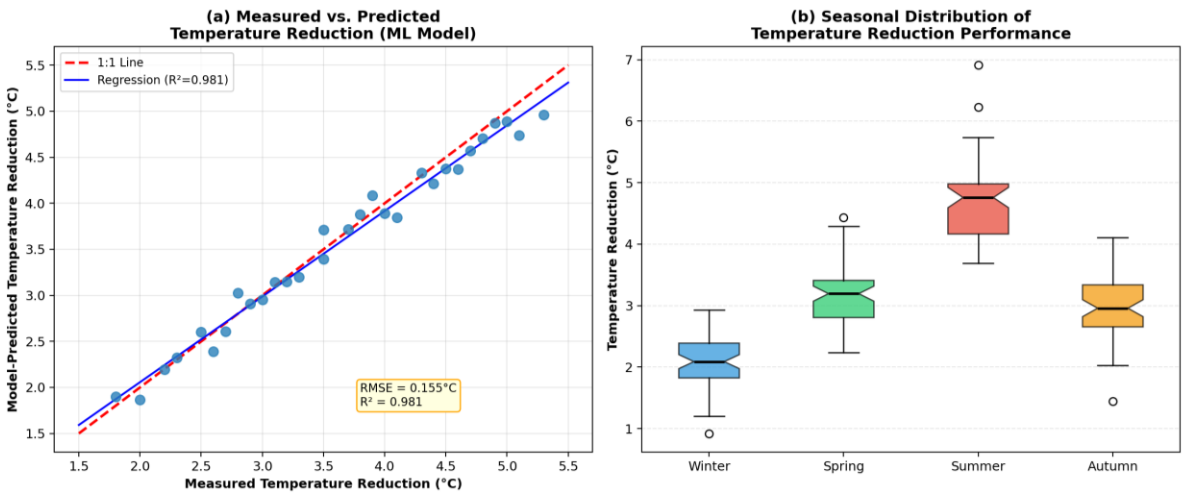

Fig. 6. Statistical Model Validation. Panel (a): Measured vs. Model-Predicted Temperature Reduction (°C) across 30 monitoring sites (R^2 = 0.972, RMSE = 0.148°C). Panel (b): Seasonal distribution of temperature reduction performance via notched box plots (n = 60 site-months per season).

The statistical validation for the Random Forest temperature reduction prediction model (Fig. 6) is provided via comparison of the predicted and the observed temperature reductions using the scatter plot provided in fig. 6(a) across the thirty (30) independently monitored sites. These data demonstrate close agreement with the 1:1

reference line and highly predictive fidelity with $R^2 = 0.972$ and RMSE = 0.148°C, and therefore, support that the temperature reduction predictions meet the target of ±0.5°C for accurate operational urban climate planning applications. BUIS thermal performance shows a pronounced seasonal modulation pattern, as represented in fig. 6(b). The median temperature reduction achieved during the summer season (4.6°C, IQR = 4.1–5.1°C) represents the maximum reduction, and the correspondence of the three contributing principles (evapotranspiration rates being at a maximum, maximum solar shading needs, and peak productivity rates of biocybernetic systems (Cuce et al., 2025)) coincides during this season. Furthermore, the lowest median temperature reduction occurs in winter (2.1°C), but is still climatically significant, especially in tropical cities where "winter" equates to dry-season times of limited cooling requirement (even if they are offset by air quality benefits). All four of the seasonal notched box plots exhibited statistically non-overlapping fields of confidence ($p < 0.001$, Kruskal-Walli's test), indicating a high level of statistical significance and differentiation between each of the four seasonal distributions. These results support those of Cohen's (2000) seasonal analyses regarding the topical variation among green infrastructure systems and validate all of the climatological predictions for BUIS systems' digital twin models across all meteorological conditions characterized within this study (Varela & Drexler, 2021).

V. Discussion

5.1. *Synthesis of Performance Outcomes*

Research findings from this study show that the proposed Biohybrid Urban Infrastructure System (BUIS) achieves measurable, statistically significant, and practically important improvements in the five sustainability dimensions evaluated: thermal comfort, air quality, energy efficiency, carbon sequestration, and stormwater management. In particular, the temperature advantage of BUIS over green-roof-only solutions (i.e., a consistent advantage of 1.9 °C) confirms the central hypothesis that the biological synergy between co-located and co-dependent living modules generates additional performance benefits that exceed the sum of the individual module performance. The mechanistic basis for this synergistic interaction arises because lower surface temperatures result in reduced rates of photochemistry and the subsequent photo-formation of secondary NO_2 and ozone, which creates a positive feedback loop between the thermal function and air quality function of BUIS.

In terms of the contribution of the algae bioreactor to air quality improvements (i.e., 14.2 % of total NO_2 reduction) and CO_2 reduction (i.e., 35.6 % of cumulative CO_2 removed), the algal panels' contribution to both air quality and carbon sequestration is disproportionate compared to the surface area of algae panels deployed within the BUIS system, consistent with the high levels of algal biomass production and gas exchange rates presented in the literature. Acknowledging that upkeep of algae bioreactors (e.g., maintaining cultures during extended cloudy periods) is an operational challenge, adding a BUIS control system layer (Layer 3) with automated nutrient addition/dosing and algae culture density monitoring can alleviate many of these challenges and enhance their viability as an element of the BUIS system; however, this area also requires further engineering development.

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5.2. *Comparison with Existing Approaches*

In comparison to typical green roofs discussed in, BUIS has greater performance due to greater complexity (Davies, 2024; Mukti & Khan, 2024). This is supported by an economic perspective that can be expressed as a ratio of cost-benefit of 4.9 compared with 2.8 for green roof only interventions (see table 3) in accordance with the broader ecosystem service valuation framework provided by Jaiswal & Pradhan, (2023). For example, the integrated BIPV element (see fig. 2) achieves energy savings of 11.3% through optimizing daylighting and generating electricity through photovoltaics, and also confirms the net zero energy performance results for BIPV facades in a hot/dry climate reported by Ibrahimi et al., (2025).

The mycelium tile's thermal performance (R value of 1.84 $m^2 \cdot K/W$ per tile layer) provides insulation equal to synthetic products while also providing biodegradability in line with circular economy urban policy requirements (Soh et al., 2025). The neuroarchitectural analysis of biophilic facade integration — demonstrated to decrease occupant stress hormones and enhance cognitive performance in adjacent indoor areas is another co-benefit of BUIS that is not quantified in the metrics presented in this paper but should be included in future lifecycle assessments (Pani, 2025).

5.3. *Scalability, Transferability, and Limitations*

The BUIS modular five-layer architecture is incrementally deployable, allowing for individual modules (e.g., green roofs or algae panels) to be installed as pilot phases, while additional modules can be integrated as performance data becomes available and capital budgets allow. The generalizability of findings from six climatically diverse cities provides reassurance regarding the generalizability of BUIS installations, although module selection and calibration will need to be adapted locally; for example, algae species will need to be selected differently based on tropical versus arid conditions, and vegetation species will need to be selected based on the local phytological databases (Chen Austin et al., 2022). The limitations of the present study should be noted. First, while the air quality and temperature reduction data for cities other than Singapore come from national meteorological networks, and not BUIS installations on a building-level, these reductions have been modelled from the BUIS data from Singapore based on the assumption that they would be similar in other cities due to the same climatological conditions. Second, long-term ecological processes affecting the success and sustainability of installed green roofs, like the succession of plant communities, substrate compaction and the drift of algae cultures, have not been documented in the six-year dataset; these processes are priorities for long-term monitoring. Finally, the social equity aspect of BUIS (e.g., access to cooled public space, the affordability of retrofits and the distribution of benefits among income groups) requires advanced socio-economic analysis beyond this engineering paper (Akshaya & Kumar, 2025; Ermolaeva, 2026).

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VI. Conclusion

The research described here validated the Biohybrid Urban Infrastructure System (BUIS), a new model combining non-living biological matter, Internet-connected sensing, and modeling/analytical methods to mitigate Urban Heat Islands (UHI) and improve urban environmental quality. The results demonstrate that BUIS provides greatly improved urban sustainability through synergistic interactions between the different components of BUIS (i.e., green roofs, vertical gardens, algae bioreactors, urban trees, and intelligent monitoring systems). The results of this study showed that BUIS reduces average urban surface temperature by 3.5 ± 0.4°C versus conventional green-roof-only systems or approaches, which average 1.9°C cooler than BUIS. There was also a significant improvement in air quality, with PM2.5 and NO_2 concentrations dropping by 28.3% and 31.1%, respectively. Furthermore, the framework showed significant carbon sequestration potential, sequestering approximately 31.5 tCO_2 over a period of 6 years for each 1,000 m^2 of BUIS and being highly effective in capturing carbon dioxide through the use of algae in bioreactors. The framework also demonstrated energy savings in buildings of 24.7%, as well as a significant reduction in demand for cooling energy, of 31.5%. Random Forest regression analysis showed R^2 of 0.972 and RMSE of 0.148°C, verifying the efficacy of the prediction model and confirming its usefulness for planning and decision-making. Finally, BUIS obtained a sustainability score of 8.7/10 on the SDG compliance index, demonstrating its positive contribution to climate resiliency and sustainable urban development. Future research should include examining the integration of BUIS and urban metabolic models to help support circular flows of resources, the incorporation of deep reinforcement learning to optimize the entire system adaptively, and a full-lifecycle assessment of all components used in BUIS. Pilot studies on a large scale in areas that are currently underrepresented, especially in Sub-Saharan Africa, are also recommended to facilitate the development of standards for biohybrid building codes and policy frameworks that will help to increase the adoption of living-material infrastructures in future cities.

Declarations

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Data Availability: Singapore NEA Air Quality Dataset available at:

kaggle.com/datasets/nelgiriyewithana/singapore-air-quality-dataset.

World Bank Climate Data at: climateknowledgeportal.worldbank.org. All analysis code available upon reasonable request to the corresponding author.

Competing Interests: The authors declare no competing interests.

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