This is the Accepted Manuscript version of an article published by Elsevier in the journal *Energy and Buildings* in 2025,which is available at https://doi.org/10.1016/j.enbuild.2025.116061
Cite as: Lu, Y., Tan, C. L., He, Y., Biljecki, F., Tay, S. E. R., & Lau, S. K. (2025). Multi-objective optimization of food, energy, and carbon for vertical agrivoltaic system on building façades. *Energy and Buildings*, 345: 116061.

Multi-objective optimization of food, energy, and carbon for vertical agrivoltaic system on building façades

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Abstract

Climate change and urbanization present critical challenges to cities, requiring innovative energy and food security strategies. This study introduces a novel agrivoltaic system for building façades in Singapore's dense urban context, addressing the trade-off between photovoltaic (PV) electricity generation and plant growth under shared solar exposure. By combining field experiments and advanced simulations, a genetic algorithm was employed to optimize PV arrangements, balancing solar exposure conflict for energy production and crop cultivation while also reducing building cooling load. Lettuce (*Lactuca sativa*) grown under PV shading yielded up to 120 g per plant, meeting commercial standards. Simulations revealed significant building energy benefits, with approximate annual savings of 50 kWh/m^2 and CO_2 reductions of 35 kg/m^2 for every 100 m^2 building block. This innovative system integrates renewable energy generation, urban agriculture, and passive cooling, maximizing the utility of vertical surfaces. By efficiently utilizing building surfaces, this approach offers a land-efficient strategy for integrating sustainable food and energy solutions in dense urban areas, contributing to urban resilience and further supporting sustainable development goals.
Keywords: Agrivoltaic system, Building integrated photovoltaics, Urban agriculture, Multi-objective optimization, Building energy performance, Low carbon emissions

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1. Introduction

1.1. Background

Climate change, characterized by long-term shifts in temperature and weather patterns, has become one of the most significant challenges facing humanity, affecting the stability of the environment. According to the United Nations (UN), human activities, particularly fossil burning and carbon emissions, have primarily driven climate change, resulting in a 1.1 °C global temperature rise since the 1800s and a projected upward trend to 1.5 °C by 2030 [1]. The temperature rise, along with increased greenhouse gas emissions, contributes to more extreme climate variations, accelerating melting of glaciers and sea level rise, all of which pose serious threats to human living environments [2].

Meanwhile, global energy consumption continues to rise owing to strong economic growth and urban development, with projections indicating a 50 % increase from 2020 to 2050, according to the U.S. Energy Information Administration [3]. In the composition of energy consumption, more than 80 % of energy is still generated by fossil fuels, which is the primary source of CO2 emissions [4]. The Paris Agreement, announced at the UN Climate Change Conference in 2015, calls for a 45 % reduction in greenhouse gas emissions by 2030 and net-zero emissions by 2050 to limit global temperature rise to 1.5 °C [1]. Furthermore, the 2030 Agenda for Sustainable Development was endorsed by the UN General Assembly in 2015, and 17 sustainable development goals were proposed [5].

The UN Food and Agriculture Organization projected a 70 % increase in global food production requirements compared with 2007, to meet the anticipated demand by 2050 [6]. Additionally, the world population is growing at a rate of 0.84 % per year [7], which progressively exacerbates the challenges associated with food production. Agricultural operations and food production are vulnerable and easily affected, particularly by climate change. For example, extreme weather events such as floods and droughts, which are intensifying on account of climate change, have detrimental effects on plant growth, survival rates and soil pollution [8]. Rising temperatures and changing rainfall patterns also impact the resistance of crops to pathogens and pests [9]. The production of crops was found to be directly impacted by global warming, with an estimated 3.1–7.4 % loss in agricultural yield for every 1 °C increase in the world's average temperature [10].

The UN-Habitat has identified a triple 'C' crisis—climate change, COVID-19, and conflicts—as among the most pressing global challenges in recent years [11]. The COVID-19 pandemic intensified vulnerabilities in food supply chains by disrupting farm labor, shipping and logistics, leading to significant fluctuations in food demand [12]. Lockdown measures further destabilized food security, with lingering effects even in the post-pandemic period [13]. Urban agriculture contributes minimally to local food self-sufficiency, accounting for less than 1 % [14]. Additionally, ongoing conflicts exacerbate food and economic instability. Therefore, it is crucial to allocate more urban space for self-sufficient farming to enhance the city's food resilience.

Singapore, one of the smallest and most densely populated countries in the world, faces significant challenges due to its scarce land and high demand for resources [15-17]. Singapore heavily relies on imports, with over 90 % of its food [18]and more than 95 % of its energy supply sourced from overseas [19]. The country's land scarcity and population density heighten the urgency of achieving food and energy security. Addressing the dependence on imports through innovative solutions is crucial for long-term sustainability. Moreover, Singapore has been renowned for its commitment to transforming into a “City in Nature”. The Singapore Government emphasized the importance of sustainable development with the Singapore Green Plan 2030, aiming to enhance the resilience of the food and energy sectors [20]. Numerous urban farming initiatives in Singapore include home gardening on high-rise residential buildings [21] and productive façade testing in laboratory [22]. Considering its resource demands, the abundance of solar irradiation and government support, Singapore is an ideal location to develop and test new solutions, such as the prototype agrivoltaic façade system explored in this study.

1.2. Literature review

Agrivoltaic systems, as the combination of agriculture and photovoltaics, integrate crop cultivation and solar power generation on the same land, optimizing both energy and food production [23]. Traditionally, PV panels on farms provide solar energy while shading crops below [24]. To explore agrivoltaic scalability, Dinesh and Pearce [25] developed a model simulating both PV and agricultural outputs, showing that integrating shade-tolerant crops with solar panels can increase economic value by over 30 % compared to conventional farming. Additionally, agrivoltaic systems could improve global land productivity by 35–73 % [23].

Urban agriculture, a form of edible greenery, involves cultivating and delivering food within or near cities. As urbanization intensifies and land becomes scarcer, urban agriculture faces increased pressure, driving the demand for innovative technologies to enhance food production [26]. Building-Integrated Agriculture (BIA) addresses this by incorporating hydroponic farming systems into urban structures, such as balconies, rooftops, and walls [27]. Building façades utilized in vertical farming allow leafy greens and vegetables to grow within cities [28, 29], reducing the resource demands of urban food supply and minimizing fossil fuel use by decreasing food transport distances [30]. Moreover, Building-Integrated Photovoltaics (BIPV) provide flexible, integrated solar energy solutions within the building envelope, including roofs, walls, and windows [31]. BIPV systems generate electricity while reducing CO2 emissions and contribute to substantial energy savings. Together, BIA and BIPV represent sustainable and multifunctional strategies for food and energy production within dense urban areas.

BIPV can generate electricity for buildings while reducing carbon emissions associated with energy derived from fossil fuels. The Energy Market Authority (EMA) reported that Singapore's national electricity structure contained natural gas (94.1 %), petroleum products (0.3 %) and coal (0.9 %) in 2024, and the remaining portion representing some clean energy (e.g., municipal waste, biomass and solar) [32]. The electricity from fossil fuels has 2.5 % electricity losses during transmission, with carbon emissions of 601.0 kg CO2 per MWh [33]. BIPV systems that utilize solar energy to convert electricity and provide electricity directly to the building can avoid transmission losses associated with the national electricity grid [34]. Should BIPV successfully supply the entire electricity demand of a building, there stands the potential for an 80 % reduction in carbon emissions compared to reliance on electricity sourced from fossil fuels [35].

The common type of BIPV is the sloping panel with silicon solar panels on the rooftop, which has efficient electricity production with a conversion efficiency of around 15–20 % [36]. With recent developments in technology, the average panel conversion efficiency has increased from 15 % to over 22 % over the years [37]. The efficiency of PV on façade will be reduced by less than 40 % when compared to rooftop installations [38]. For instance, monocrystalline silicon solar cells utilized on facades have undergone testing, revealing an efficiency of 15.2 % [39].

Emphasizing PV storage technology is essential, as it enhances electricity reliability during power outages and contributes to building self-sufficiency. The battery is the core component of a PV storage system, with different functional types. There are two main types of storage systems. The first type stores electricity generated by the PV system, charging during periods of solar production and discharging during peak demand. In this case, the stored electricity is used solely for on-site consumption and cannot be exported to the grid [40]. The second type allows for both on-site usage and export to the grid, typically operated with an optimal self-consumption strategy. Battery material selection is also critical [41]. Lead-acid batteries are among the most commonly used in PV systems due to their low cost and long service life, despite having the problem of low energy density, moderate efficiency, and high maintenance requirements [42]. However, the development of advanced battery materials, such as lithium–sulfur batteries, sodium-ion batteries, and zinc–air batteries, is essential to enhance storage capacity, efficiency, and safety in PV systems [43-45].

1.3. Research objectives

Previous studies have assessed the effects of PV panels on horizontally distributed ground crops and livestock breeding in traditional farming, potentially impacting crop productivity from PV shade, reducing solar radiation [46]. Strategic PV placement can enhance yields, as many edible, shade-tolerant vegetables thrive under reduced sunlight [47]. Nonetheless, a significant research gap remains regarding this potential synergy. The other research gap exists regarding the application of agrivoltaic systems on buildings in urban environments, where their impact on buildings and the surrounding urban context remains unexplored.

This study seeks to explore how to strategically lay out the agrivoltaic pattern to address the conflicts of solar resource and achieve the maximum benefits via optimization to balance PV energy generation and vegetation growth on shared building surfaces. In addition, the second objective is to evaluate the influence of agrivoltaics on building energy consumption, cooling effects, and carbon reduction through simulation and field experiments.

Previous research supports traditional farmland agrivoltaic systems as economically and environmentally beneficial, highlighting the need for further development and promotion [48]. This study explores a potential solution for urban environments by integrating vertical agrivoltaic systems on building façades. A prototype and pilot study in Singapore aims to enhance resilience in energy and food security by balancing photovoltaic electricity generation with edible plant cultivation. The research also establishes a replicable methodology applicable to dense urban contexts globally, which allows other regions to adopt a similar framework by utilizing simulation and optimization algorithms.

2. Methodology

This hybrid system "Sunbox" integrates PV panels with greenery on building façades, with PV panels positioned in front of vegetation attached to the building wall. A significant challenge arises from the shading effects of PV panels on greenery, creating a conflict over solar resource allocation. To resolve this sunlight conflict, a novel framework is developed, combining validated simulations and empirical data to evaluate and optimize PV panel arrangements. This approach not only mitigates the trade-off between energy generation and plant growth but also establishes a scalable solution for maximizing energy, food production, and environmental benefits in urban settings.

The data preparation phase involved creating a 3D digital model using Rhinoceros software and setting up the Sunbox field experiment (Fig. 1). Solar radiation simulations were validated using experiment sensor data, which also captured microclimate parameters such as air temperature between the PV panels and greenery. Internal and external sensors were deployed to monitor and compare microclimatic conditions within the Sunbox and its surrounding environment. After the field experiment tests, simulations were conducted for the parametric Sunbox system across 200 PV arrangement patterns to analyze solar irradiation on PV panels and greenery. Building energy performances were simulated with different façade types and Window-to-Wall Ratios (WWR) to achieve variable results on electricity costs and CO_2 emissions. A Multi-Objective Optimization (MOO) approach using genetic algorithms was applied to maximize electricity generation, enhance solar exposure for vegetation, and minimize the system's carbon emissions. This comprehensive methodology ensures an optimized balance between energy production, plant growth, and environmental sustainability.

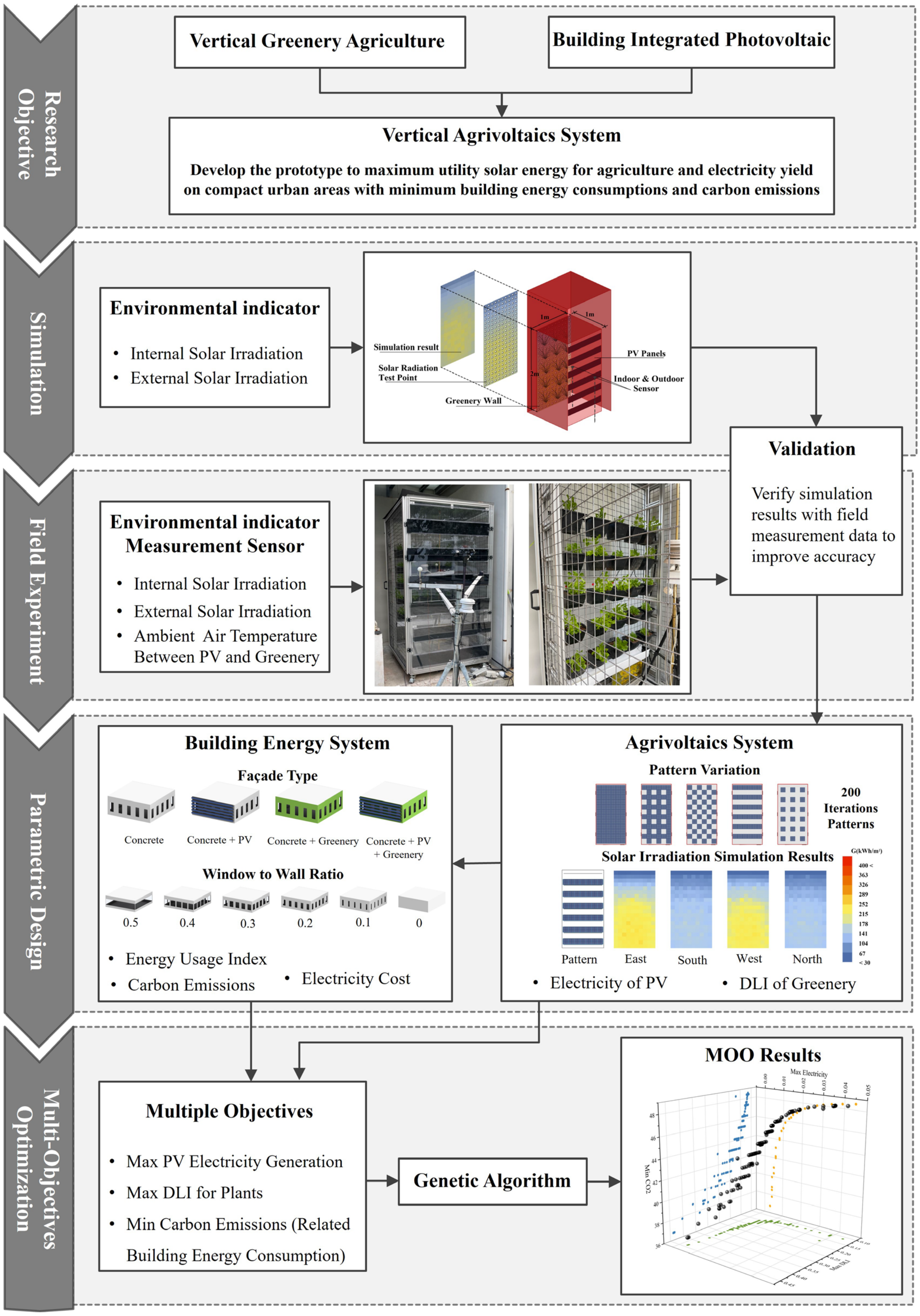


Fig. 1. Research workflow for Multi-Objective Optimization of vertical agrivoltaics.

2.1. Field experiment setting

Field experiments were conducted at the Tropical Technologies Laboratory (T[2] Lab) at the National University of Singapore (Latitude 1°30′N, Longitude 103°77′E). Experimental installations, referred to as the "Sunbox," were positioned at all four corners of the building to facilitate directional measurements and capture microclimatic variations across orientations. The Sunbox measured 1 m × 1 m × 2 m and comprised a metal structure frame with a mesh grid surface (Fig. 1). The back mesh surface provided the capability for 0.2 m × 0.2 m × 0.2 m plant pots to be securely attached. Additionally, the front wall of Sunbox was specifically designed to accommodate 84 PV cells, each measuring 0.15 m × 0.15 m, allowing the cells to be arranged in various array patterns. Solar cells were employed as patterned sunshades for greenery, and their impact on solar access was systematically evaluated. Therefore, black opaque acrylic sheets were used as a substitute for actual PV cells due to the limitation of site usage. Selecting appropriate crop species, such as lettuce, has shown promise for enhancing food production in shaded environments [49]. Lettuce (*Lactuca sativa*) was cultivated as a tested edible vegetation species in the soil-based planting pot with automatic drip irrigation in the Sunbox.

The experiment was conducted over two years (Oct 2021–Oct 2023) under Singapore's hot and humid climate (Zone 1), using baseline conditions characterized by high temperature and humidity. Comparative measurements were taken under scenarios with and without greenery in the East, North, West, and South orientations. Clear and sunny days were selected for analysis to effectively capture the impact of PV panels and greenery. In addition, minute-level collection data were aggregated into hourly intervals, minimizing noise and enhancing data fidelity.

In this experiment, HOBO sensors were deployed to monitor key microclimate metrics, including solar irradiance, Photosynthetically Active Radiation (PAR), and air temperature, both internal and external the Sunbox (Table S1). Sensors within the Sunbox served as the target group, specifically measuring the microclimatic interactions between PV panels and vegetation. (Fig. 2). Meanwhile, sensors outside the Sunbox, positioned at the same height as the internal sensors, served as a control group to record external environmental conditions.

Fig. 2. Photographs of the field experiments: a) external setup; b) internal setup; c) T^2 Lab.

2.1. Modeling and simulation

The experimental structures and surrounding environments were modeled in Rhinoceros 3D software for simulation [50, 51]. The 3D models were developed to replicate the real-world prototype used in the field experiment, with dimensions of 1 m × 1 m × 2 m. Sensor locations were accurately represented based on their actual placement. In the simulated environment, both horizontal internal and external sensor points were included, along with the vertical PV panel and internal greenery wall, to evaluate their respective global solar irradiation levels (Fig. 3). The study explored around 200 iterations of PV patterns, categorized into separate PV cells, horizontal rows, vertical columns, and scattered arrangements. These patterns were controlled parametrically and managed using the Grasshopper plugin [52], enabling precise adjustments and streamlining the modelling process. The local climate and corresponding International Weather for Energy Calculation (IWEC) weather files were obtained from the EnergyPlus [53]. The building wall was modeled as concrete walls with a 20 % reflectance rate for the Honeybee setting. Using "RunDaylightSimulation [54]" and "RADIANCE [55]" simulation programs, geometries were exported to the selected sky to run the yearly average cumulative radiation simulation. The annual cumulative solar radiation received by the internal greenery wall and the external PV cell was calculated based on the hourly global solar radiation data from the weather file.

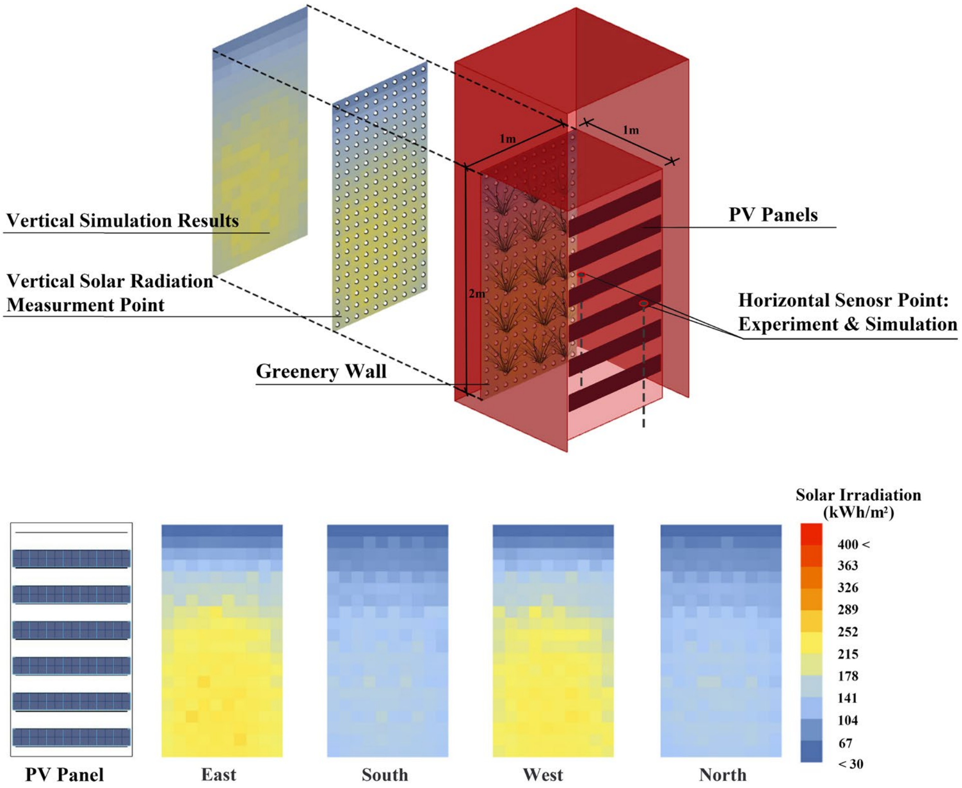


Fig. 3. Simulation setting and results.

Energy simulations were conducted to assess the building performance when vertical agrivoltaic system is applied to building facades. The standard building configuration was modeled as a 10 m × 10 m block with a height of 4 m to estimate average energy consumption in the building floor scale (Fig. 1). Four wall types were analyzed: concrete, concrete with integrated PV panels, concrete with greenery, and concrete with a combination of greenery and PV panels, each subjected to six WWR ranging from 0 to 0.5 as energy-saving conditioning. According to the Singapore Building and Construction Authority (BCA), the grading system for the green building certification, called "Green Mark" awards 2 points when the WWR is less than 0.5 [56]. This research identified a suitable WWR range of 0 to 0.5 to achieve the sustainable building.

Thermal and energy simulations were executed using "OpenStudio [57]" and "EnergyPlus [58]" with a Package Single-Zone Air Condition (PSZ-AC) system as the standard Heating, Ventilation, and Air Conditioning (HVAC) configuration. The PSZ-AC system, recommended in ASHRAE Baseline System 3, is applied in non-residential buildings under 25,000 square feet [59]. It is

designed for smaller spaces where each zone requires independent heating, cooling, and ventilation. The analysis focused on Energy Use Intensity (EUI) for cooling and fan energy for Singapore climate, alongside calculations of electricity costs and corresponding CO_2 emissions.
The wall material was defined as a 200 mm concrete wall (Table 1). Crystalline silicon photovoltaic panels were modeled to include shading effects and a photoelectric conversion efficiency of 20 % [60]. Simulating the impact of greenery involved a more complex setup to capture its cooling effects. Only one greenery setting was used as an example for the simulation to get the general idea of greenery's shading and solar radiation impact on building energy performance. For vegetation with a height of 0.20 m, parameters included a leaf area index of 3, leaf reflectivity of 0.50, leaf emissivity of 0.95 and minimum stomatal resistance of 180 m/s.

Table 1. Input parameters for energy simulation.

General Setting	**Location**	Singapore (Latitude 1°30′N, Longitude 103°77′E)
	Weather Data	Singapore annual weather data from EnergyPlus
	Analysis Grid	200 measuring points with a grid resolution of 0.1 m × 0.1 m at a distance of 0.01 m between the vegetation wall
	Simulation Indicator	Cumulative Radiation
	Analysis Period	1 Year
PV Material	**PV Efficiency**	20 %
Wall Material	**Wall Construction**	8 in. (~20.3 cm) Concrete
	Wall Reflectance	20 %
	Glass Visible Light Transmittance	90 %
Energy System	**OpenStudio HVAC System**	Package Single-Zone AC
Greenery Material	**Height of Plants (m)**	0.20
	Leaf Area Index	3
	Leaf Reflectivity	0.50
	Leaf Emissivity	0.95
	Minimum Stomatal Resistance (s/m)	180
	Roughness	Medium Rough
	Conductivity of Dry Soil (W/m K)	0.35
	Density of Dry Soil (kg/m^3)	1100
	Specific Heat of Dry Soil (J/kg K)	1200

Thermal Absorptance	0.90
Solar Absorptance	0.70
Visible Absorptance	0.75
Saturation Volumetric Moisture Content of the Soil Layer	0.30
Residual Volumetric Moisture Content of the Soil Layer	0.01

2.3. Multi-objective optimization

The MOO process required the identification of three objective indices: maximizing PV electricity generation, maximizing solar light for plants, and minimizing carbon emissions. These indices were integrated into the optimization framework and analyzed using genetic algorithms to derive the optimal Pareto front solutions. The basic genetic algorithm applied in MOO is based on Pareto Optimality, which identifies a set of alternative solutions that form the Pareto front, representing the optimal trade-offs [61]. Whether maximizing or minimizing objectives, the values are initially transformed into a positive minimum for optimization. The Pareto front delineates the boundary of optimal solutions from the generated dataset, aggregating a set of optimal solutions [62]. Pareto Optimality enables the identification of solutions that best balance multiple conflicting objectives [63].

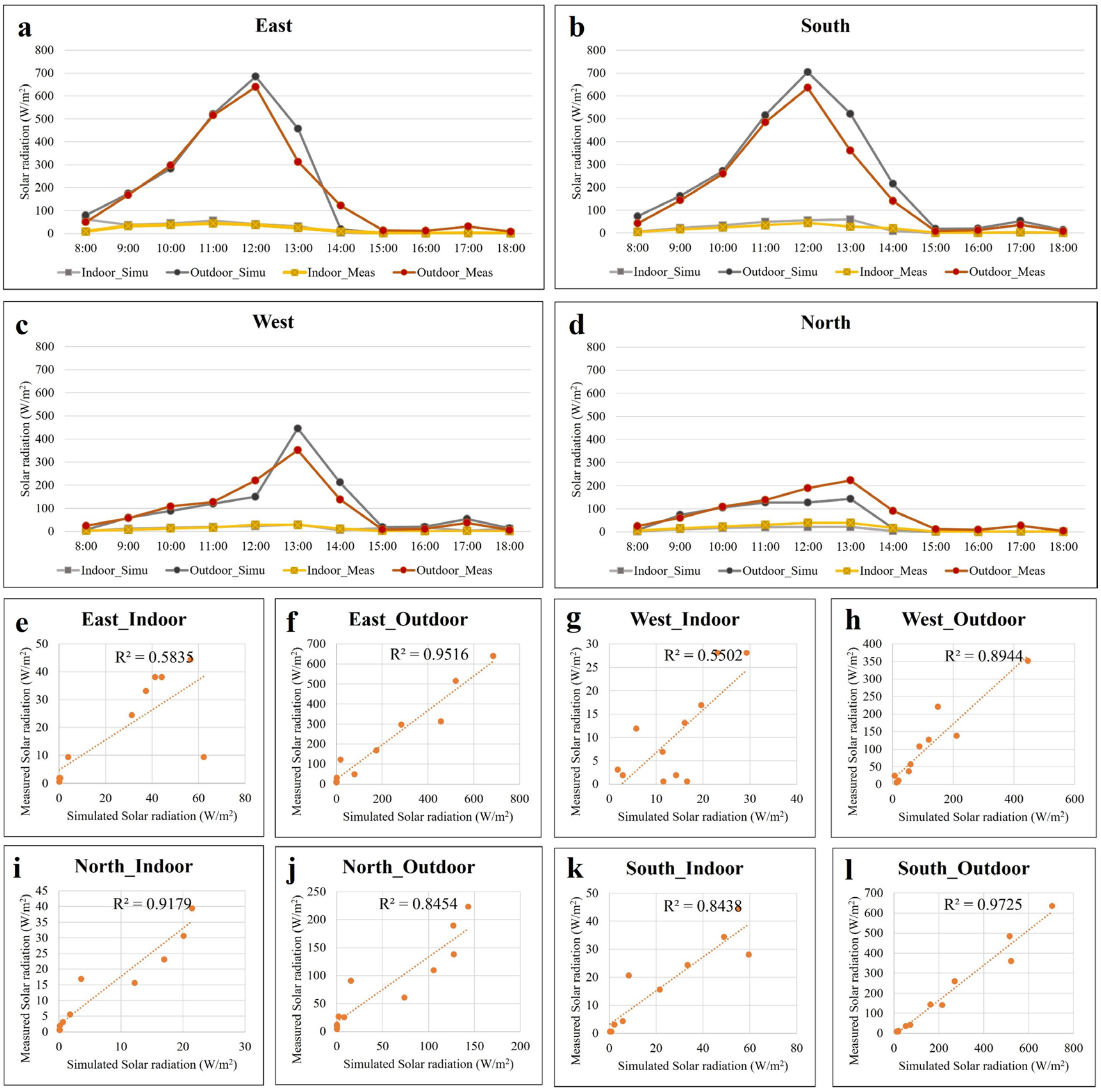
3. Results and analysis

3.1. Validation

Validation was conducted in this research for the simulation accuracy. Even "RADIANCE", the software we applied for solar irradiation simulation, is well-validated with a relative error below 10 % [64-66]. This comparison was conducted to validate both the accuracy of the input weather file and the solar irradiation simulation results with the measurement data of Sunbox. The Global Horizontal Radiation data from the EPW file were validated using measurements from external solar irradiation sensors. For the internal Sunbox solar irradiation, simulation outputs were compared with readings from internal solar sensors. A validation comparison was conducted for December 30, 2021 (a clear and sunny day) to assess the accuracy of the simulated and measured solar radiation data.

The predictive performance is shown in Fig. 4, Root Mean Square Error (RMSE) and R^2 results reveal that Honeybee can effectively capture the temporal variations of solar radiation for both indoor and outdoor sensors. The outdoor simulation yielded better prediction accuracy than indoor, with higher accuracy outdoors ($R^2 = 0.91$) compared to indoors ($R^2 = 0.7$). This indicates that the weather file for simulated outdoor solar irradiation closely aligns with real-world measurements. Although the RMSE for indoor conditions remains relatively high, it falls within an acceptable range for solar irradiation analysis and is sufficiently robust for running the simulation program.

The close alignment between simulated and observed data confirms the model's validity for future solar radiation studies.



RMSE	East (W/m^2)	South (W/m^2)	West (W/m^2)	North (W/m^2)	Average Value
Indoor	16.74	12.01	7.77	9.56	11.52
Outdoor	56.97	59.7	43.26	39.71	49.91

R^2	East	South	West	North	Average Value
Indoor	0.58	0.84	0.55	0.92	0.72
Outdoor	0.95	0.97	0.89	0.85	0.92

Fig. 4. Validation results of simulated solar irradiation against measured data: a-d) comparison of simulation and observation solar irradiation value of Sunbox indoor and outdoor in four orientations throughout the day; e-l) scatter plots with R-values illustrating the comparison of the values; and a summarized overview at the bottom.

3.2. Impact on plant growth

3.2.1. Solar irradiation

Environmental factors influencing plant growth include light, water, nutrients, and the cultivation medium [67]. Light plays a crucial role in plant growth, as photosynthesis relies on light energy to stimulate enzymatic processes [68, 69]. Solar irradiation provides the necessary photochemical energy for plant growth [70].

Solar irradiation data was collected from field experiments between November 2021 and September 2022, quantifying solar irradiance both outside and inside the Sunbox. PAR denotes the spectral range of solar radiation falling on plants (400–700 nm) per second. Daily Light Integral (DLI) is a cumulative measure of the total PAR received over a 24-hour period, serving as a key indicator of light requirements for plant growth [71]. Hourly measurements showed that the east-facing direction experienced a peak in PAR during the morning, while the west-facing direction peaked in the afternoon (Fig. 5a-b).

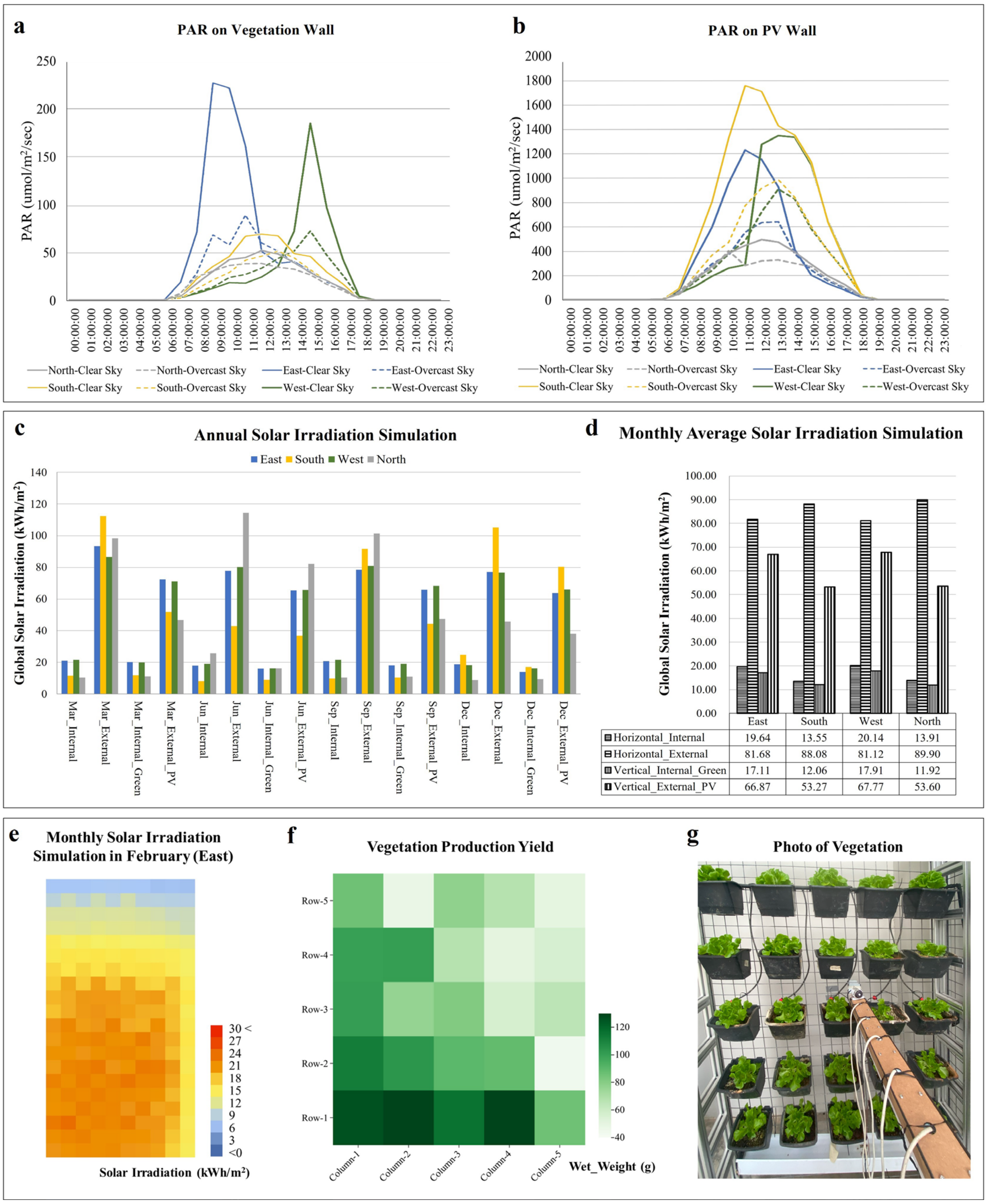


Fig. 5. Field measurements and simulation of solar irradiation and plant growth: a) PAR on

vegetation wall; b) PAR on PV wall; c) annual solar irradiation simulation; d) monthly average solar irradiation simulation; e) monthly solar irradiation simulation on east façade in February; f) vegetation production yield; g) photo of vegetation.

Annual simulations were also done simultaneously (Fig. 5c-d). Based on monthly simulations, sun path variations showed that solar irradiation was highest on the northern side in June and on the southern side in December for both PV panels and greenery (Fig. 5c). During the remaining months, east and west orientations demonstrated superior performance. These variations correspond to the sun's trajectory, significantly affecting solar irradiance intensity and angle. Fig. 5d presented the simulated average monthly solar irradiation for internal and external horizontal surfaces, as well as for the vertical PV panel and greenery wall. Although north and south orientations showed significant seasonal variation, monthly average east and west orientations consistently received higher solar irradiation on both the vertical internal greenery wall and external PV panel throughout the year. These foundings aligned with the intended design objectives, making them advantageous for year-round solar optimization for both energy generation and vegetation growth.

Field experiments indicate that lettuce cultivated in the Sunbox environment survived well, as the common edible vegetation in Singapore, even under partial shading from PV panels (Fig. 5g). The experiment conducted between February and March 2023 coincided with the sun's position near the equator. However, lettuce yield in the field experiment was influenced by various environmental factors. As an inherent limitation of outdoor studies, the production results cannot fully replicate those of ideal simulated conditions. In February 2023, one harvest was obtained from the field experiment. Despite the variability, the yield trend aligned with the February monthly cumulative solar irradiation distribution predicted by the simulation. Optimal solar irradiation conditions were observed in the bottom and left columns and each plant achieved similar and favorable harvest weights around 120 g (Fig. 5f).

3.2.2. Air temperature

Air temperature measurements were conducted between the plants and the PV panel at a distance of 0.1 m in Sunbox setup with PV panel installed, capturing conditions with and without greenery. Due to the long duration required for greenery cultivation, data collection was conducted one year apart, with both datasets analyzed under clear and sunny conditions in May (2022 and 2023). However, differences in weather conditions between the two years may still introduce discrepancies, even within the same month. Nevertheless, the study effectively captured the overall impact of greenery on this Sunbox microclimate.

Fig. 6b presents the daily average temperature data from all sunny days in May, with the Sunbox oriented East. Sensor A01 was positioned closest to the plants, with subsequent sensors spaced 0.1 m apart. A distinct temperature gradient was observed across each 0.1 m interval, showing that areas closer to the vegetation are cooler, particularly around 10:00 hrs. A comparison between greenery and non-greenery conditions at sensor A01 at the average of clear days in May (Fig. 6c) revealed consistently lower daytime temperatures in the presence of greenery, especially between 9:00 hrs and 11:00 hrs, leading to the selection of 10:00 hrs for detailed analysis (Fig. 6d).

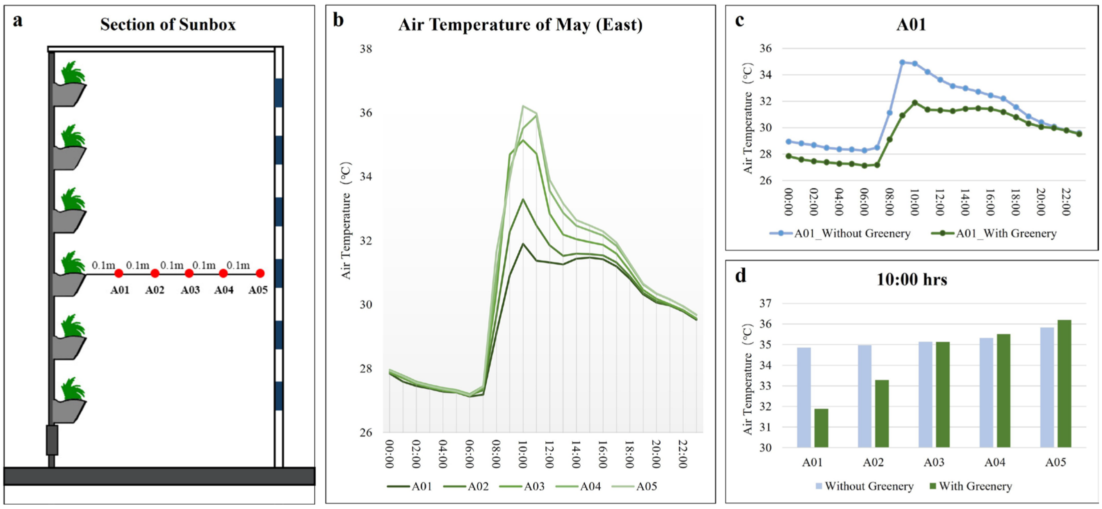


Fig. 6. Field measurements of air temperature within an agrivoltaic system: (a) the section of Sunbox; (b) air temperature recorded by five sensors within the Sunbox (with greenery); (c) comparison of air temperature measured by Sensor A01 under conditions with and without greenery; (d) air temperature comparison across five Sunbox sensors under conditions with and without greenery at 10:00 hrs.

The data in Fig. 6d indicates that the presence of greenery reduces air temperature by up to 3 °C compared to non-greenery conditions and by as much as 4.5 °C compared to outdoor conditions during the experiment period. Transpiration from greenery effectively lowers ambient temperatures, which not only cools the surrounding environment but also reduces the temperature on PV panels and building facades, thereby reducing overall building energy consumption.

3.3. Impact on energy

3.3.1.Energy consumption

The EUI was simulated using EnergyPlus to quantify the energy consumption of a standardized building block (10 m × 10 m × 4 m) in Singapore's tropical climate. This simulation incorporated a PSZ-AC system as the HVAC configuration, capturing both cooling loads and fan electricity consumption. Additionally, this study explores the impact of variations in the WWR from 0 to 0.5 on a building facade agrivoltaic system, analyzing how these variations influence building energy performance.

The energy results, depicted in Fig. 7a, demonstrate a distinct correlation between increased WWR and elevated EUI values, attributed to a reduction in thermal insulation and greater heat exchange with the outdoor environment. Each 0.1 rise in WWR corresponds to an estimated rise of 20 kWh/m^2 in annual EUI, primarily due to the increased U-value of the wall with more window exposure. More heat transfer into the building leads to an increase in the cooling demand.

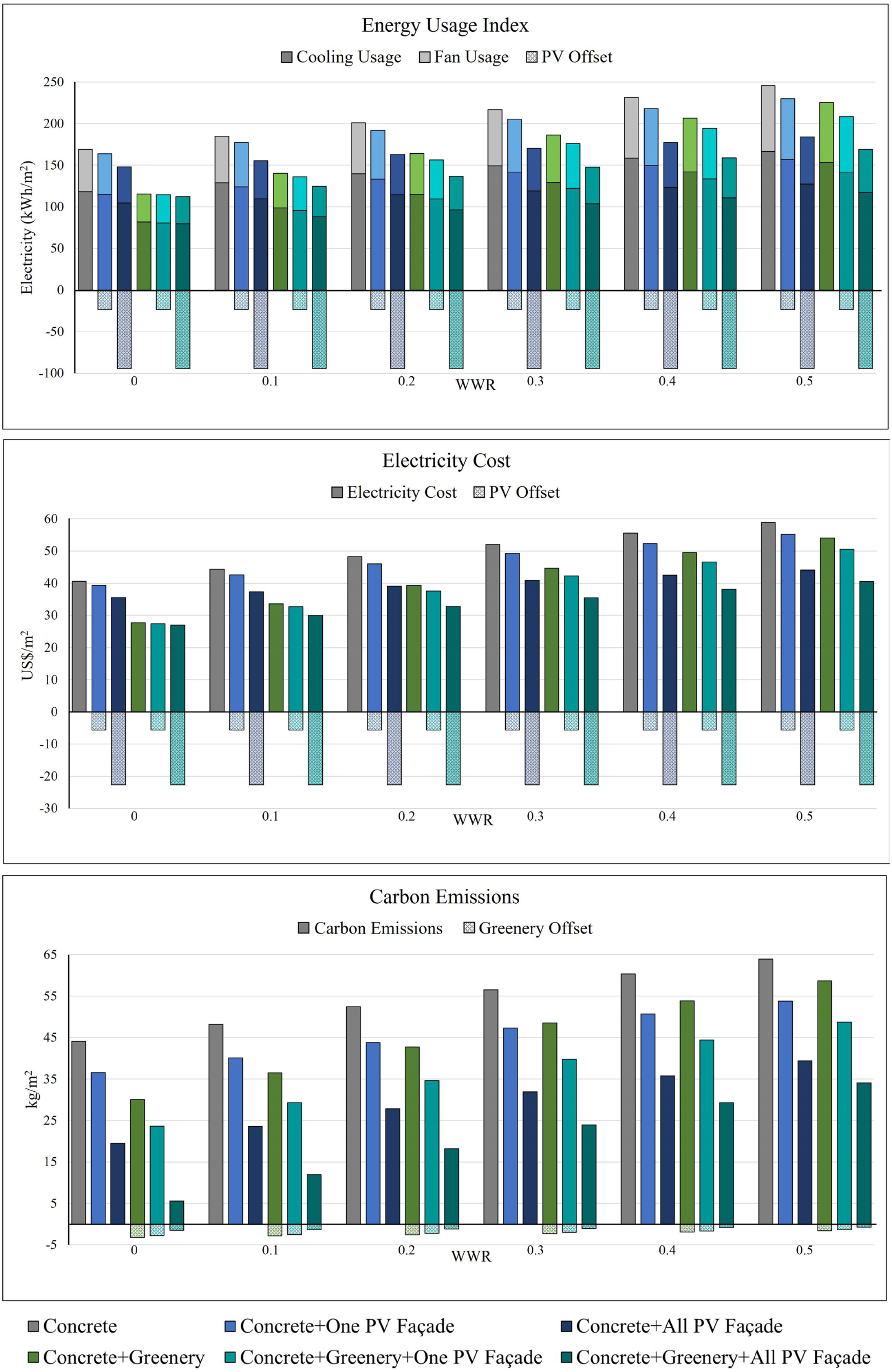


Fig. 7. Simulation results of building energy performance applying the agrivoltaic façade: a) energy usage index; b) electricity cost; c) carbon emissions.

The results indicate that vertical greenery can significantly reduce EUI, achieving annual savings of up to 54 kWh/m^2 compared to concrete walls when the WWR is 0. This reduction is attributed to the combined effects of cooling shade and the insulation provided by the vegetation layer. However, as WWR increases, the cooling efficacy of greenery diminishes due to reduced green wall coverage. In contrast, vertical PV panels offer moderate EUI reductions, primarily through shading rather than direct renewable energy generation. When PV panels covered all four façades in this case study, they reduced EUI by 21 kWh/m^2. Increased reductions in EUI were observed at higher WWR values, reaching up to 54 kWh/m^2 at a WWR of 0.5. This improvement is attribute to the enhanced shading effect, which becomes more impactful as window exposure increases and the baseline energy load rises. The combined application of PV panels and greenery maximized these benefits, providing EUI reductions of 57 kWh/m^2 at WWR 0 and up to 73 kWh/m^2 at WWR 0.5. This synergy highlights the potential of integrating greenery and PV systems to optimize both cooling and shading impacts for improved energy efficiency. The associated simulated economic and carbon reduction benefits of renewable energy from PV panels are addressed separately, highlighting the complementary roles of PV and greenery in enhancing building energy performance.

3.3.2. Renewable energy generation

In the agrivoltaic system, clean electricity generated by solar panels contributes to reducing the building's grid electricity consumption (Fig. 7a). In simulations using a PSZ-AC system, PV panels with a 20 % conversion efficiency received an average annual solar irradiance of 560 kWh/m^2 for vertical walls, compared to 1580 kWh/m^2 annually in Singapore [72]. With 50 % PV coverage on each wall (20 m^2), electricity generation amounted to approximately 2240 kWh per wall or around 9000 kWh for all four walls. This resulted in a reduction of approximately 23 kWh/m^2 in electricity consumption per wall, thereby decreasing reliance on the public grid. This shift not only reduces the need for fossil fuel-based electricity but also contributes to lower carbon emissions.

3.3.3. Cost implications

The cost analysis was based on the electricity consumption associated with air conditioning and fan usage, alongside the offset provided by renewable solar electricity, as reflected in electricity bills (Fig. 7b). By incorporating the cooling effects of greenery and the shading from PV panels, the EUI was reduced by 73 kWh/m^2, with 95 kWh/m^2 reduction for the solar power generation (with PV and greenery applied to all four walls with WWR 0.5). This led to a reduction in total electricity consumption from 246 kWh/m^2 to 75 kWh/m^2. Based on an electricity tariff of US \$ 0.24 /kWh, this setup achieved annual savings of approximately \$59 /m^2, with only \$18 /m^2 remaining in energy costs.

Additionally, the carbon and cost expenditure on vegetation can be reduced. Considering Singapore's high reliance on imported food due to low local agricultural production, there is a reduction in transportation costs and associated carbon emissions when food is grown locally on the vertical wall. As a result, the economic benefits include savings in vegetation procurement and reductions in carbon emissions linked to food imports.

3.4. Impact on carbon emissions

In the building operational phase, carbon emissions are mainly produced for regulating the interior environment, including heating, air conditioning, lighting, ventilation, etc. The carbon aspect of this research focuses on carbon emissions associated with energy consumption during the building operation stage, specifically related to HVAC systems. Compared with traditional buildings, this integrated agrivoltaic system on facades offers significant reductions in CO_2 emissions through several mechanisms. First, the decreased energy consumption via shading during the operational phase results in lower energy requirements. For grid electricity, the emission factor is approximately 0.4168 kg of CO_2 per kWh. With less electricity consumed, fewer CO_2 emissions are emitted due to building operations. Second, clean energy generation from solar panels can supplement electricity consumption and further reduce the carbon emissions associated with using the electricity grid. Third, the integration of greenery provides carbon offsetting through vegetation photosynthesis. Vertical greenery can offset approximately 0.43 kg of CO_2 per square meter annually, given a sufficient DLI [73]. It is important to note that the carbon offset efficiency of the greenery is diminished by the shading effect of the PV panels. Solar irradiation on the greenery, as determined from simulation results, is included in the calculations. All relevant indices have been factored into the overall analysis.

In this study's simulation, applying vertical PV panels resulted in an average annual CO_2 reduction of 10 kg/m^2 on a single wall and 25 kg/m^2 on all four wall, compared to a bare conrete wall. This reduction was primarily due to the combined effects of surface shading and on-site renewable energy generation, which decreased electricity consumption (Fig. 7c). Additionally, vertical greenery attached to the wall contributed approximately 12 kg of CO_2 per year, driven by cooling and shading functions. The integrated system, combining both PV panels and greenery, achieved a total carbon reduction of 35 kg per square meter, demonstrating significant effectiveness in carbon offsetting.

3.5. Optimization of plant growth, energy production, and carbon emissions

3.5.1. Sunbox simulation results

The solar irradiation and energy simulations of Sunbox were conducted with parametric PV pattern designs, accommodating 200 PV arrangement patterns across four orientations within the Singaporean context. Simulations and calculations mapped electricity production on PV panels, DLI for greenery, and CO_2 emissions per square meter for building energy operation when Sunbox facade was applied (Fig. 8a). Results indicate that annual average DLI and electricity production are higher for east and west orientations compared to north and south orientations.

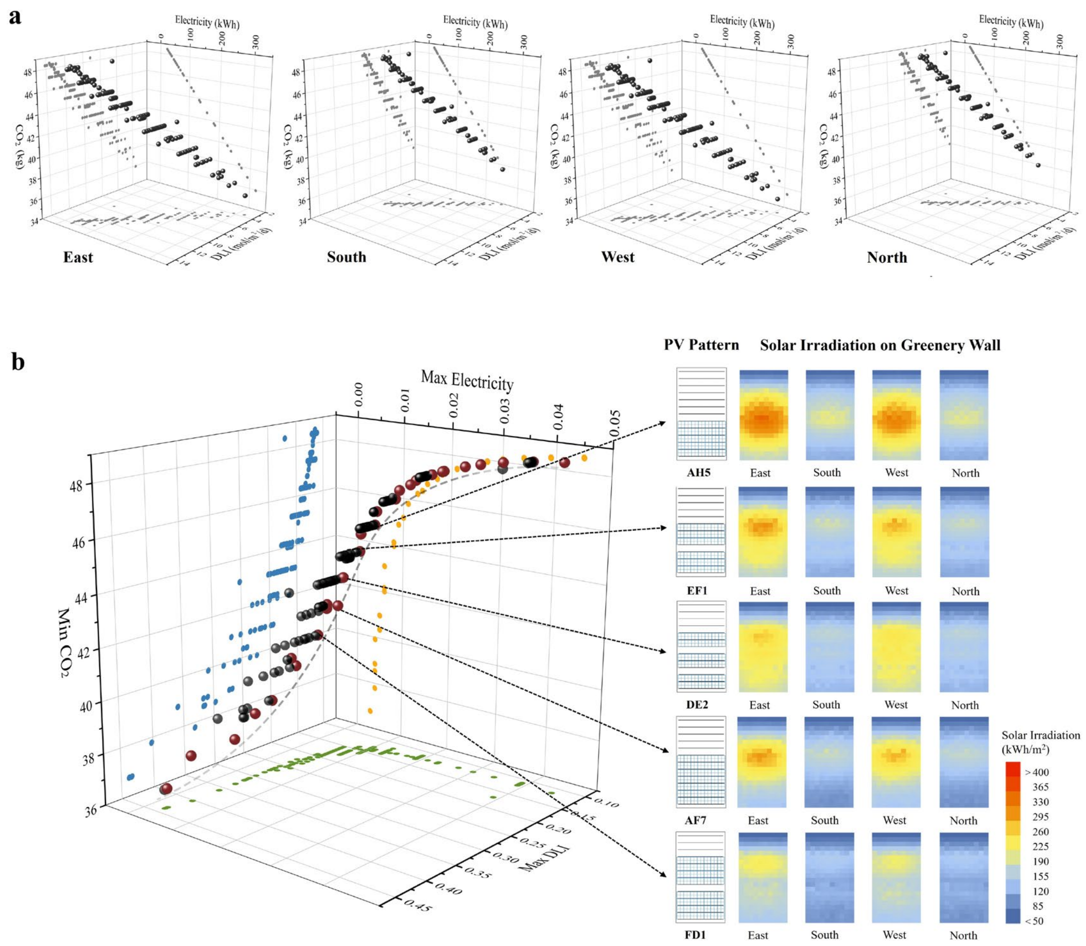


Fig. 8. PV optimal patterns in MOO: a) performance of different PV patterns in four orientations; b) MOO optimal results and the solar irradiation distribution on the vegetation wall.

Additionally, inversely proportional relationships are observed between electricity generation and both DLI and CO_2 emissions. As more PV panels are applied, more electricity will be generated, and shading will reduce the building's cooling load and associated carbon emissions, though it will also mean that vegetation receives less light. Therefore, a direct linear relationship exists between DLI and CO_2 emissions. A lower DLI for interior greenery is linked to more PV panels and reduced CO_2 emissions. This trade-off highlights the need to balance the competing priorities of maximizing energy generation, reducing carbon emissions, and maintaining adequate conditions for vegetation growth.

3.5.2. MOO results

A genetic algorithm was utilized to achieve MOO with the aims of minimizing CO_2 emissions, maximizing electricity generation, and optimizing the plant's DLI. In this model, convergence toward zero signifies proximity to the target objectives, with an inverse relationship between increases in electricity production and DLI concerning the represented target values in MOO.

Each solution in Pareto line is retrievable based on its parameter properties, facilitating pattern identification within the program. MOO results indicate that although performance metrics differ across various orientations, spatial distribution and optimal pattern configurations remain consistent, as demonstrated by the alignment of the Pareto line (Fig. 8b). Although performance varies across different orientations, there is no influence of spatial patterns in MOO, enabling average data to represent all orientations and streamline further analysis reliably.

The optimal PV panel configurations enhance both solar radiation penetration for greenery and energy efficiency, as indicated in red on the Pareto line (Fig. 8b). When observing patterns arranged in rows, configurations like AH5, featuring four rows of panels positioned at the bottom, allowed more solar radiation to reach the greenery wall, thereby maximizing internal radiation for plant growth. The scattered configurations, EF1 and DE2, achieved an even but less concentrated solar irradiation distribution on the greenery wall while maintaining high electricity generation. From left to right on the Pareto line, it becomes evident that DLI moved further away from the zero point, with solar irradiation results decreasing. In contrast, CO_2 and electricity values approached the origin of coordinates, indicating improved performance, as seen with AF7 and FD1, which had more PV coverage. Therefore, a suitable PV option would be provided depending on varying objective weight requirements. DE2 striked an ideal balance across three key objectives: maximizing solar panel utilization, ensuring even and sufficient internal radiation for greenery, and minimizing CO_2 emissions, making it a comprehensive solution for sustainable energy and environmental performance.

The selection of five optimal solutions highlights the effectiveness of the genetic algorithm in generating reasonable outcomes, enabling the efficient identification of solutions that address diverse optimization objectives. Beyond these five selected options, additional suitable solutions can be identified based on varying objective requirements, further demonstrating the flexibility and adaptability of the approach. Experimental and simulation data indicate higher PAR values within the Sunbox in the east and west orientations. Similarly, the genetic algorithm identifies an optimal solution with PV panel patterns arranged on the bottom side in rows, presenting high overall performance.

4. Discussion

Light is a critical factor for vegetation growth and significantly influences plant morphology, flowering patterns and biomass accumulation [74]. High DLI levels correlate with enhanced greenery growth [75]. However, upon reaching the peak value of greenery absorption, an increase in the DLI yields a diminishing return on plant growth [76]. Moderate solar exposure is ideal for vegetation growth, supporting healthier cultivation and harvest outcomes [77]. In tropical climates like Singapore, excessive solar irradiation and dry conditions pose challenges for cultivating leafy vegetables [78]. In the agrivoltaic simulation, the vegetation wall behind the patterned PV panels achieved a DLI of approximately 10–20 mol/m^2, effectively meeting the light requirements for healthy lettuce cultivation.

The vertical greenery in this experiment demonstrated an effective reduction of air temperatures within 30 cm. Bachir et al. [79]showed that increasing urban vegetation can improve thermal comfort and mitigate urban heat island effects. In our experiment, air temperatures near the vegetation were reduced by 4.5 °C compared to the ambient environment (Fig. 6). This is due to the presence of the vegetation layer, intercepting sunlight, with only around 2 % utilized for photosynthesis, while 48 % permeates the leaves and is stored in the plant's water system. About

30 % is converted into heat through transpiration and 20 % is reflected [80]. On green surfaces, temperature reduction reduces latent heat, such as evapotranspiration, which decreases sensible heat [81]. Additionally, vertical greenery provided shading and thermal insulation, reducing building surface temperatures by up to 17 °C [82]. This shading effect was significant in the study's simulation. Previous research also demonstrated that it can reduce energy demand for cooling and fans by approximately 23 % and 20 %, respectively, resulting in overall annual energy savings of around 8 % [83].

With rapid urbanization and population growth, buildings and construction have become significant resource stocks [84]. Building façades and rooftops are the main surfaces in compact cities and there is potential to maximize the utilization of these surfaces as productive areas for the production of both energy and food [85]. While the irradiation levels on facades are lower than those on roofs, the large surface area compensates for this difference, making facades significant [86]. Façade orientation plays a crucial role in optimizing the performance of the Sunbox system. Our observations indicate that east and west orientations achieve higher efficiency in Singapore's equatorial context. Due to these annual sun path shifts at the equator, east–west-oriented buildings are better suited for continuous vegetable cultivation, particularly in simpler building designs without self-shading features [71]. In Singapore, the optimal orientation for buildings with windows and balconies is north–south. Shifting windows from east–west to north–south orientations can reduce cooling loads by 8.57–11.54 % [87]. To prevent overheating and discomfort from solar gain, maintaining a low WWR on east and west façades is essential [88]. In this context, integrating a vertical agrivoltaic system on East and West façades offers multiple benefits, maximizing space utilization while reducing overheating and discomfort from excessive sun exposure.

Solar photovoltaic electricity has the potential to replace a substantial portion of fossil fuel-based energy, thereby reducing emissions of carbon dioxide, nitrogen oxides and sulfur dioxide. One square meter of solar panel surface can offset 200–300 kg of CO_2 annually compared to fossil fuels [89]. Previous research has demonstrated that BIPV systems on double-skin façades reduced building energy consumption by 34.1 % in hot and humid climates, such as Darwin, Australia [90]. In this study, results indicated that an agrivoltaic system integrating PV and greenery on four façades achieved even greater energy savings. For a WWR of 0.5, energy consumption savings reached 45 % in Singapore, while a WWR of 0 yielded savings of 85 % when accounting for both renewable energy generation and façade cooling effects (Fig. 7). These findings suggest that agrivoltaic systems can offer superior energy savings combined solar energy production in hot climate zones.

Green certification systems differ by region in sustainable building design, but energy performance is emphasized worldwide. In Singapore, the Green Mark is the primary certification, utilizing EUI as a key index, with energy efficiency comprising over 60 % of the Green Mark Framework [91, 92]. For small office buildings with a gross floor area under 15,000 m^2, the EUI thresholds are as follows: less than 135 kWh/m^2 for Gold Plus, less than 120 kWh/m^2 for Platinum, and less than 100 kWh/m^2 for the Super Low Energy certification [56]. Currently, buildings have not incorporated greenery or photovoltaic PV systems on their façades. This research demonstrated that integrating PV systems can achieve an EUI of 54 kWh/m^2 when accounting for renewable energy generation and shading effects. When combined with greenery, the EUI can be reduced to 115 kWh/m^2 compared to the original all concrete baseline of 170 kWh/m^2. These values already met the Green Mark requirements for low-energy buildings, with the PV and greenery combination capable of achieving the Super Low Energy certification. Additionally, this integration results in significant reductions in associated carbon emissions, further supporting sustainable development goals.

The carbon emissions in this research, included in the MOO calculations, emphasize the building operation stage and the energy consumption associated with HVAC systems, particularly for cooling to maintain thermal comfort in Singapore's climate. As building operations represent the largest portion of carbon emissions, they are a key component of this analysis [93]. However, a comprehensive assessment of carbon impacts for agrivoltaic systems requires a broader scope. Life Cycle Assessment provides a comprehensive framework to trace carbon emissions across the entire lifecycle, encompassing manufacturing, transportation, installation, operation, maintenance, and waste disposal [94]. For PV systems, material production and manufacturing significantly contribute to embodied carbon, with emissions reaching high values of 60 g for CO_2 annually per kWh of electricity generated [95]. Furthermore, disposing of PV components leads to increased emissions, highlighting the necessity for careful and efficient use of PV systems to reduce their overall carbon footprint.

The coupling effect between PV panels and greenery can better improve both performances. While previous studies have explored the impact of PV panels on ground crop development, primarily with panels positioned horizontally, they have also demonstrated the potential benefit of coexistence [96]. An experiment in Italy found that agrivoltaic systems offered better stability in soil temperature, evapotranspiration, and soil water balance compared to full-sun cultivation. This agrivoltaic system not only supports plant growth but also enhances crop resilience and reduces the impact of drought stress exacerbated by climate change [97].

The results in this study confirmed the cooling effect of greenery in the agrivoltaic environment. However, the heat transfer dynamics between PV panels and vegetation were not extensively analyzed, though preliminary evidence indicated this cooling effect may enhance PV efficiency [98]. Solar panels are most efficient at around 25 °C, with each 1 °C increase reducing efficiency by approximately 0.45 %, potentially resulting in an annual energy loss of 71 kWh [99]. Vegetation has been shown to lower the temperature of PV panels, thereby enhancing their efficiency [100]. There was a study that found that green roofs with photovoltaic panels increased annual PV efficiencies by 1.3 % in Colombia, 1.8 % in Switzerland, 3.3 % in Spain and 8.3 % in Hong Kong compared to conventional roofs [99]. Addressing this limitation of the detailed coupling effect is essential, which requires new experimental setups and advanced simulation models in future research.

5. Conclusion

In Singapore, which is characterized by heightened demand and resource constraints, leveraging solar energy is an effective strategy for mitigating food and energy challenges. The Sunbox is an innovative agrivoltaic façade prototype that integrates PV panels with vertical greening on building facades. The optimized model was applied to address the conflict of resources and achieve maximum benefits, maximizing solar energy utilization for efficient electricity generation while also providing sufficient sunlight exposure for plant growth with lower building energy carbon emissions. Consequently, this research contributes to the advancement of urban resilience and sustainability.

There are some limitations to this study, which could pave the way for future work. Firstly, the selection of vegetation species was restricted by Singapore's climate, with leafy vegetables such as lettuce chosen for the experiment. Future research could explore a broader range of greenery species to assess growth potential. Secondly, in this experimental stage, the PV panels were used solely as shading elements and were not operational for electricity generation due to the experimental field limitations. As a result, the thermal environment in the field experiment may lack accuracy due to heat gain by the operating PV panels. Lastly, while the findings are most directly applicable to Southeast Asian regions with climates similar to Singapore, solar irradiation levels and energy simulation outcomes may vary across different climatic zones. Nevertheless, the study has introduced a replicable methodology adaptable to urban contexts in diverse climate conditions. This research will take future steps to address these limitations by testing diverse species, heat gain of operational PV panels, and varying climatic conditions to enhance this agrivoltaic system's generalizability and applicability.

In conclusion, this study highlights the potential of vertical agrivoltaic system on building façades, offering a novel contribution to sustainable urban development and urban agriculture research. Future exploration will focus on investigating more microclimatic variables in urban contexts and developing adaptable and scalable prototypes for broader regional implementation. In this context, efficient resource utilization will be key to addressing energy and food security, contributing to a more sustainable future.

Authorship contributions

Yijun Lu: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Chun Liang Tan:** Writing – review & editing, Software, Resources, Project administration, Methodology, Conceptualization. **Yang He:** Writing – review & editing, Validation, Investigation, Data curation. **Filip Biljecki:** Writing – review & editing, Supervision, Investigation. **Stephen En Rong Tay:** Writing – review & editing, Supervision, Investigation. **Siu-Kit Lau:** Writing – review & editing, Supervision, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Singapore Ministry of Education (MOE) Academic Research Fund Tier 1 research project titled "Solar and Crop Yield Optimization for the Tropical Building Envelope" [A-0008249-00-00]. The authors would like to thank MOE for their support and Mr Wilfred Yeo Renjie for assisting with data collection. We would also like to acknowledge the support of City Developments Limited (CDL) for the establishment of the NUS-CDL Tropical

Technologies Laboratory (T^2 Lab).

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