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Review article

Green roofs and facades with integrated photovoltaic system for zero energy eco-friendly building – A review

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ABSTRACT

The greening of urban environments plays a crucial role in mitigating the adverse effects of urbanization, such as air pollution and the urban heat island effect, and can provide numerous benefits to residents, including opportunities for leisure and improved mental health. On the other hand, there is a great demand to utilize renewable energy systems in cities to mitigate greenhouse gas emission. Building-integrated photovoltaic (BIPV) technology is one of the most promising solutions to harvest clean electricity on-site and support the zero carbon transition of cities. The combination of BIPV and green spaces in urban environments presents a mutually advantageous scenario, providing multiple benefits and optimized land usage. However, despite its promising potential, there is a dearth of scientific research systematically examining this integrated strategy. This paper investigated three key aspects related to the integration of BIPV systems and greenery in urban environments. Specifically, the paper aimed to explore: 1) the overall design considerations and performance impacts of integrated BIPV systems and greenery; 2) the challenges involved in integrating these two systems; and 3) the prospects of this integrated approach. The methodology of this paper involved a comprehensive review and analysis of the integration of BIPV systems and greenery in urban environments. This examination was conducted from various perspectives, including shading, irrigation, energy performance, aesthetics, materials, and installation. The principal findings of this research are twofold: firstly, the integration of BIPV and greening can yield mutually beneficial outcomes; and secondly, the cooling effect of greening on photovoltaic systems primarily hinges on the distance between the two components and the surrounding microclimate. These research findings underscore the potential of coupling BIPV systems with greening, positioning it as a sustainable and advantageous approach for future building design and development.

Introduction

The Paris Agreement has set concrete goals to control global warming with international cooperation, [1]. There is an urgent demand to promote renewable energy systems in replacing traditional fossil energy systems globally. Solar PV is now the main supplier in the renewable energy market and is expected to continue its dominance in the future [2]. During the period from 2010 to 2020, the compound annual growth rate of the photovoltaic technology market amounted to approximately 34% [3]. Compared to centralized photovoltaic plants which take large areas of land, BIPV systems primarily utilize building envelopes to harvest solar energy is a rapid growing trend in cities [4].

Apart from the usage of clean energy, to increase urban greening is also essential for urban renewals. Cities need more urban greening spaces to address the challenges of environmental degradation, and to benefit the well-beings of citizens. A modern compact city is typically characterized by high-density, mixed-use patterns, with features that contribute to a functional urban design prioritizing sustainability and emphasizing ecosystem services. In high density urban context, integrating greening into buildings such as green roofs and green facades are attractive solutions for architects. Besides of the ecological and social benefits, building integrated greening also has potentials to enhance the BIPV efficiency by providing cooling effects in microclimate [5,6]. However, current research lacks a comprehensive examination of the design analysis of photovoltaic-integrated green systems and the reciprocal performance impact between the two from an urban perspective. This paper entails a literature review on urban greening with integrated PV systems, encompassing green roofs and PV systems, as well as green

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facades with PV systems, to thoroughly understand the environmental and contextual factors that contribute to the sustainable performance of each system. The objective is to propose more targeted approaches for achieving aesthetic design and efficiency in these two systems.

Research methods and research questions

A two-stage research methodology was employed in this study. In the first stage, an exhaustive literature review was conducted to examine all existing publications related to the integration of BIPV with green building elements. The Web of Science (WoS) was chosen as the primary indexed electronic database for this purpose. A consistent set of search terms was utilized, comprising "solar green roofs", "solar green facades" and "PV greening". The search parameters included all relevant studies published up until late 2022, ensuring a comprehensive understanding of the most recent developments in the field. More than 800 related publications were found. Subsequently, duplicate entries, non-English publications, books, and brief notes were filtered out to exclude articles deemed unsuitable for the review. The selected articles were then categorized based on their thematic focus, facilitating the identification of key research areas within the field. These articles were divided into six distinct categories, including aesthetics, air quality, energy, materials, water efficiency, and irrigation systems and 83 publications were selected for in depth review.

In the second stage, a case study of an award-winning architectural concept design was analyzed, aiming to explore the effectiveness of such integration in reducing the building's energy consumption and enhancing the efficiency of photovoltaic panels. Key components of the methodology included: 1) Selection of the case study: The treehouse was chosen based on its innovative design, recognition in the architectural field, and relevance to the research objectives. 2) Collection of design details and performance data: Comprehensive information about the treehouse design, such as layout, materials, and the incorporation of BIPV and vegetation, was gathered. Relevant data on energy consumption and photovoltaic panel performance were also obtained. 3) Data analysis and comparison: Quantitative and qualitative analyses were performed on the collected data to evaluate the treehouse's performance against conventional building designs. This comparison allowed for the assessment of the impact of integrating BIPV and green elements on energy efficiency.

This study aims to answer the following questions:

1. What are the key functions, interactions, and synergistic benefits of BIPV integrated with greening systems, specifically in solar green roofs, solar green facades, and their combined application?
2. Through an exploration of design opportunities and a selected case study, how can BIPV-greening systems be effectively implemented and optimized for maximum performance in sustainable urban development?

Findings: A descriptive overview

Our research findings present a detailed examination of the BIPV systems and their synergistic integration with greening strategies. This overview encapsulates various aspects of these innovations, including traditional and solar green roofs, solar green facades, and the potential of leveraging these integrations for sustainable architectural solutions. Additionally, a SWOT analysis further enriches our understanding of these systems.

BIPV system

Various countries have introduced relevant measures to accelerate the application of solar energy. For example, the Italian government has offered a tax deduction of 110% over 5 years for the implementation of new PV residential plants [7]. Solar PV systems were mandatory for new buildings in China after April 1, 2022 [8]. In Germany, since 2015, electricity prices have continued to fall to promote grid connections to PV power generation [9].

Solar energy offers significant advantages as it is a pollution-free, sustainable source with relatively short payback periods. A common application of solar energy is in PV systems. PV systems comprise PV modules and various components. There are three primary PV module types available in the market: polycrystalline, monocrystalline silicon, and thin film. The battery efficiency of monocrystalline silicon cells stands at 26.1%, while the module efficiency is 24.4% [10]. But the drawback was its cost and its thickness. Although marginally less efficient than crystalline silicon solar cells, thin-film technology holds considerable potential for advancements in solar and renewable energy technologies due to its reduced production costs and appealing manufacturing methods [11]. All three main PV technologies are employed in BIPV. Recent research revealed that the global compound annual growth rate for BIPV was 40% from 2009 to 2020. In most European countries, the new regulations on energy performance in buildings have been translated into national regulations/laws, indicating that energy performance regulations are now becoming the main driving factor for the BIPV market [12]. BIPV can be integrated into the building envelope (roof or façade), replacing traditional building envelope materials, and making a significant contribution to achieving net-zero energy buildings.

Factors affecting the performance of BIPV systems encompass parameters such as inclination, mounting structure, shadow effects, and more [13]. In addition to these factors, environmental pollution impacts the output power of PV panels. Urban areas generally exhibit lower wind speeds compared to rural areas, leading to reduced convective heat transfer coefficients between PV modules and the surrounding environment [14]. Aerosol pollution scatters and absorbs sunlight, significantly diminishing PV power generation. In areas with air pollution, aerosols can decrease irradiance on optimally inclined fixed panels by up to 1.5 KWh/m^2 per day, resulting in an approximate 25% reduction in irradiance in polluted areas [15]. The significance of environmental factors is evident in both urban and rural contexts. Various studies have indicated that the aesthetics and environment of buildings had an impact on the psychology and physiology of humans [16]. The primary function of architecture extends beyond efficiency, as aesthetics play a crucial role. BIPV feature flexible component designs catering to diverse functions, thereby offering considerable application potential. Neglecting aesthetics during the design phase of a BIPV may result in a less visually appealing building.

The appraisal of BIPV potential is an integral instrument for policymakers and investors, enabling a comprehensive understanding of the feasibility, scalability, and prospective hurdles associated with the deployment of photovoltaic technologies within the architectural milieu. Within the urban sphere, strategic decisions regarding the placement and methodology of photovoltaic system installations bear significant ramifications for energy efficacy, environmental impact, and economic yield. Approaches to assessing the potential of BIPV are diverse and encompass several methods including: (a) sampling method [17], which extrapolate key variables from selected sample points to the entire area; (b) geostatistics method [18], for analyzing and predicting values related to spatial or spatio-temporal phenomena, thereby enabling the construction of more accurate interpolation and uncertainty models; (c) machine learning algorithms[19,20], that aid in making predictive models based on past and current data; and (d) physical method[21], which incorporate 3D modelling to consider spatial relationships and shading effects among buildings and other structures. Each of these methods presents its own unique strengths and limitations, and their selection often hinges upon the specific characteristics of the area under study and the goals of the assessment.

The greening integrated with the BIPV system

Green roofs

A green roof is a building rooftop partially or entirely covered with vegetation and additional layers of supplementary materials. Green roofs typically comprise vegetation, fabric filters, drainage elements, root barriers, insulation, and waterproofing layers [22]. Green roofs are classified into intensive and extensive categories. Extensive roofs, in contrast to intensive roofs, feature a shallow base, necessitate no additional structural reinforcement, demand minimal maintenance, and are less costly [23]. Green roofs yield environmental, social, and economic benefits such as reducing stormwater runoff, providing thermal insulation, delivering psychological advantages, enhancing air quality, prolonging roof lifespan, augmenting urban food productivity, and preserving urban biodiversity [24–29]. Consequently, green roofs are gaining popularity due to their favourable impact on energy efficiency and ecological conservation.

In examining the potential of green roofs, a multifaceted methodological approach is usually adopted. The evaluation process involves determining the public's perception and understanding of green roof implementation, typically conducted through survey questionnaires. This aspect of the study provides insights into the societal and psychological factors that can influence the adoption and acceptance of green roofs in urban settings. Simultaneously, the evaluation of green roof energy performance is often conducted through a combination of modelling approaches (e.g.,EnergyPlus) and on-site measurements. In Table 1, we collate and summarize key literature that employs these methods in assessing the potential of green roofs.

Solar green roofs

Highly efficient zero-carbon structures possess the capacity to harness existing low-cost technologies to curtail emissions, concurrently fostering the health of the surrounding communities. Recent research elucidates that in the realm of commercial buildings, the implementation of active design measures can yield up to 90% of the potential for emission reductions. Sole reliance on passive design measures, including envelope insulation and natural ventilation, proves to be inadequate for the realization of carbon neutrality within commercial buildings[37]. Overcoming these limitations necessitates exploring innovative design solutions.

Integrating BIPV and greening systems not only represents a mutually beneficial solution but also addresses challenges faced by these systems when implemented independently, such as evapotranspiration from plants, which can decrease the temperature of PV panels and consequently enhance energy output. Installing a green roof on a conventional solar array can potentially increase the energy output of the system by 23.88 kWh and reduce greenhouse gas emissions by 0.019 t e-CO_2 [38]. Fig. 1 illustrates the working principle of a BIPV-green roof system.

Numerous research studies have demonstrated the efficacy of BIPV green roofs in enhancing the performance of PV modules, though the extent of improvement exhibits considerable variability. Multiple scholars have investigated the efficiency of BIPV-green roof systems within tropical environments and discovered that the presence of vegetation can augment the performance of PV panels by approximately 2% [39,40]. Table 2 provides a comprehensive analysis of BIPV-green roof systems, taking into account factors such as plant species and the positioning of PV panels.

Species selection and appropriate installation play crucial roles in the life cycle of a BIPV-green roof system. Sedum plants, in comparison to other plant species, exhibit a higher thermal compensation rate, thereby leading to their growing popularity in green roof applications [41,42]. [43] found that sedum plants demonstrated superior growth and coverage when planted at substrate depths of either 7 cm or 10 cm.

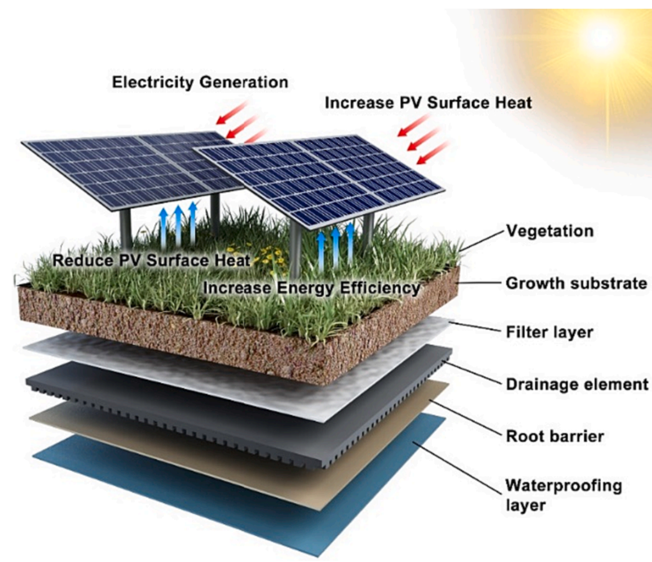

Fig. 1. Working principle of a BIPV-green roof (source: by author). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Green roof's energy saving capacity in different climates.

Ref.	Location	Climate	Type	Methodology	Findings
[30]	Portugal	Mediterranean	Intensive Semi-intensive Extensive	Experimental and numerical	Without insulation, extensive green roofs consumed 20% less energy than black roofs. Compared to black and white roofs, the energy consumption of semi-intensive green roofs was 60–70% lower, and intensive green roofs were 45–60% lower.
[31]	Greece	Mediterranean	Extensive	Experimental; EnergyPlus	Annual energy saving of 15.1%.
[32]	India	Tropical	N/A	DesignBuilder	Reduced the total energy consumption of the building by 10.5%.
[33]	Italy	Mediterranean	N/A	Artificial neural network	Predicted the thermal performance of green roofs based on monthly values of climatic variables.
[23]	Spain	Mediterranean	Extensive	Experimental	Extensive green roofs allowed for good thermal performance in summer and did not provide any thermal benefits in winter.
[34]	Cyprus	Mediterranean	Extensive	Experimental	In summer, the average indoor temperature of the green roof huts was lower than that of the cabins without vegetation roofs.
[35]	Saudi Arabia	Arid hot	N/A	Survey	Nearly 94% of respondents had agreed that green roofs enhanced the aesthetics of a building, 91% of those surveyed identified the local climate as the greatest challenge to implementing green roofs.
[36]	Japan	Humid subtropical	N/A	Survey	Most respondents agreed on the contributions of green roofs to thermal comfort and the environment, but recognition of other potential benefits was weaker. Therefore, a bottom-up strategy is needed to increase public awareness of green roofs.

Table 2
Key factors related to the performance of BIPV-green roofs.

Authors and year	Climate	Species of plants	Types of PVs	Mounting height of PV	PV module orientation	PV panel inclination (degree)	Increase in efficiency
Chila Kaewpraek et al., 2021 [39]	Tropical	Calico	Polycrystalline silicon	Unknown	Southeast	15	2%
Vanisha Arenandan et al.,2022 [40]	Tropical	Sedum	Polycrystalline silicon	1.01 *m*	South	3	1.6%
Mohammed J. Alshayeb et al., 2018 [47]	Temperate continental climate	Sedum	Polycrystalline silicon	0.2 *m*	South	10	1.4%
D. Chemisana et al., [44]	Mediterranean	Gazania rigens & Sedum	Polycrystalline silicon	0.02 *m*	South	33	1%-3%
German Osma-Pinto et al., [46]	Subtropical	Sedum	Polycrystalline silicon	0.5 m, 0.75 *m*	South	10	1 ± 0.4%
Hamid Ogaili et al., [48]	Mediterranean	Dianthus	Monocrystalline silicon	0.18 *m* 0.24 *m*	South	30	1.2%

Adequate plant coverage safeguards the roof against detrimental external environmental factors, such as wind erosion, ultimately prolonging the roof's lifespan. [44] selected sedum and *Gazania* plants to test the performance of an integrated BIPV-greening system and showed that in comparison to *Gazania,* sedum plants increased the incident irradiance of the modules throughout the day, with an average increase of 1.41%. However, most experiments with integrated BIPV-green roofs using sedum plants have been carried out in tropical regions, and the heat flux from a roof varies under different weather conditions. Moreover, the moisture content of the growing substrate and precipitation have been correlated with heat flux. Consequently, herbaceous roofs outperformed sedum roofs during winter, owing to the elevated volumetric moisture content found in herbaceous plants [45].

The installation height and surrounding wind speed of a building are pivotal factors influencing the performance of a BIPV-green roof system. Research findings indicated that in warm tropical climates, PV panels installed at heights of 50–75 cm above the green roof surface, and with wind speeds exceeding 1 m/s could enhance average daily power generation by 1±0.4% [46]. Furthermore, several studies have concentrated on determining the optimal inclination of PV panels to maximize efficiency. Typically, PV panels possess a south-facing orientation, with varying inclinations contingent upon geographical location and climate variation. Overall, the enhancement of BIPV-green roof system efficiency relies on an array of factors, including climate, PV panel height, plant species, and plant density. BIPV-green roof systems demonstrate greater advantages in tropical regions than in other regions. Excessive growth of roof vegetation may obstruct the PV panels, leading to a reduction in electricity generation efficiency. Simultaneously, the height of the PV panels dictates the airflow rate between the panels and the plants. Consequently, during the design phase of BIPV-green roof systems, it is imperative to identify the optimal PV panel positioning and appropriate plant species to fully capitalize on the advantages offered by BIPV-green roof systems.

Solar green facades

Vertical greening technology has emerged as a popular method of cultivating plants in a vertical orientation. This technology primarily encompasses climbing style, container style, hydroponic style, moss style, and module style systems. Green plants are nurtured in a growing medium, such as packaged soil, fiber mats, or other substrates, and furnished with an integrated irrigation system for hydration. The climbing-type vertical greening approach is comparatively straightforward, as it does not necessitate supporting structures and offers lower management and maintenance costs, as well as broader coverage areas. Typical climbing-type vertical greening plants include climbing species such as wall creeper and ivy. In contrast, living walls consist of plants cultivated in containers, which can be engineered into modular systems independent of ground soil and featuring automated irrigation.

Walls represent the exterior surfaces with the largest sunlight exposure area, and when compared to rooftop PV systems, BIPV facades present increased energy potential. Solar green facades not only enhance architectural aesthetics [49] and urban productivity [50], but also contribute to energy efficiency and environmental protection, thereby fostering the growing popularity of BIPV vertical greening. The operating principle of solar green facades parallels that of solar green roofs, wherein vegetation on the building facade lowers the temperature of PV panels, consequently reducing cooling energy demands [51,52]. Research has demonstrated that solar green facades decrease facade temperatures by an average of 21.4℃ to 30℃ during summer, while in winter, with air temperatures below 0 °C, the system mitigates heat loss on facades by up to an average of 3℃ on average [52]. Nonetheless, it should be acknowledged that facades of high-rise buildings in densely populated urban areas are significantly shielded from one another, and facade shading may generate hotspots and potentially cause fires. Fig. 2 illustrates the various prevalent types of solar green facades.

Harnessing the synergistic potential of BIPV and greening strategies for sustainable architecture solutions

BIPV systems and greening initiatives individually contribute significantly to addressing societal energy and environmental challenges. However, their integration engenders a synergistic relationship characterized by mutually beneficial outcomes. As outlined in the methodology section, the interplay between BIPV systems and greening initiatives is evident in various dimensions, including shading and cooling, water management through irrigation, air quality improvement, ecological enhancement, energy performance optimization, aesthetic considerations, material usage, and mounting angle adjustments (refer to Table 3 and Table 4). This comprehensive classification facilitates a comparative analysis and evaluation of distinct combinations of the two systems, thereby assisting in informed decision-making for sustainable development.

SWOT analysis

To fully consider the potential of integrated BIPV-greening systems, the main internal strengths and weaknesses and external opportunities and threats closely related to the research object were analysed and summarized using a strengths, weaknesses, opportunities, threats (SWOT) matrix. The SWOT matrix was established according to a literature review. The established matrix for the SWOT analysis of the integrated BIPV-greening system is shown in Fig. 3.

BIPV-greening systems offer a promising approach to enhancing energy efficiency and mitigating urban heat islands. Nevertheless, the maintenance and performance of BIPV-greening systems across various climates remain inadequately explored. Although some literature posits that innovative tools, such as mowing robots [74], can be employed for BIPV-greening system maintenance, the system's upkeep is inherently

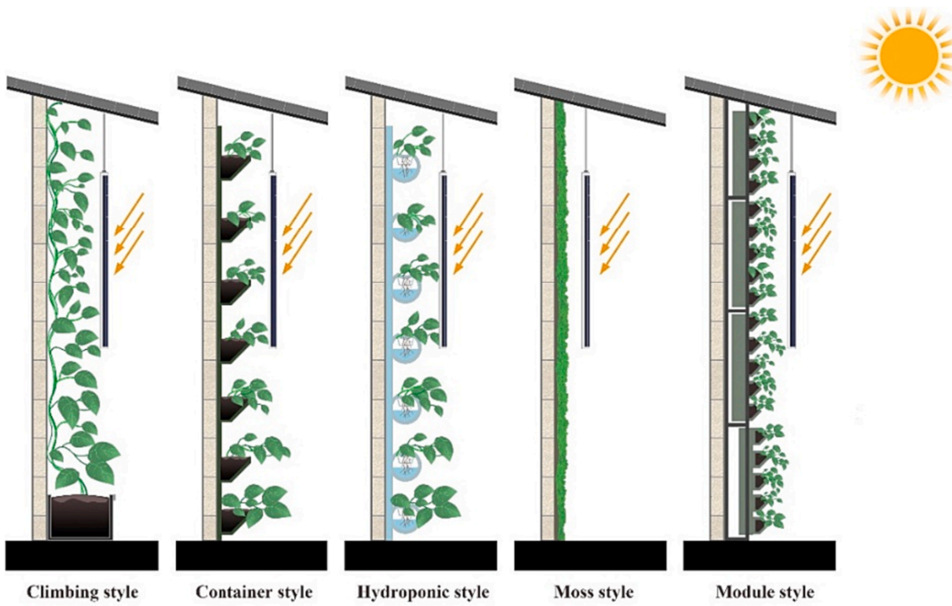

Fig. 2. Working principles of various BIPV-facade types (source: by author).

Table 3
Impact of green roofs and facades.

Factors affected	Green roofs	Green facades	Ref.
Aesthetics	Experience aesthetic reactions positively correlated with attitudes and importance placed on the benefits of green roofs.	Psychological impacts related to the phenomenon of biophilia.	[53]
Air quality	Mitigate air pollution by fine particle matter.	Decreases in particulate matter (PM2.5) concentration up to 15%.	[54–56]
Ecology	Facilitate biological invasions. Can partially mitigate the loss of habitat due to increasing urbanization.	Balances in urban ecology. Possible increases in insects and pollen.	[49,57–59]
Energy	Consume less energy than traditional roofs in the summer, with decreases of 2.2–16.7%.	Decreases the indoor operative temperature by up to 3.6 °C. 28.5% annual energy saving.	[60–62]
Water management	Reduce stormwater flow. Reduce stormwater runoff by approximately 4%.	Reduces peak flows within urban drainage infrastructure. Reduces stormwater runoff by approximately 6%.	[63–66]
Materials	Select the appropriate substrate material/depths to improve rainwater retention capacity.	Selection of suitable irrigation systems, growing media and plant varieties, leaf density, etc., according to the different climatic zones.	[67,68]

Table 4
Impacts for integrated BIPV-greening systems.

Topic	Integrated PV-green roofs & facades	Ref.
Aesthetics	Operation, accessibility and security are easy.	[69]
Air quality	Renewable energy improves air quality	[70,71]
Ecology	The vertical gap between the PV panels and the green roof enhances the system's biomass performance.	[72,73]
Energy	The efficiency of PV panels can be increased by the distribution of plants.	[44,46]
Water management	The installation of green roofs has the ability to remediate trace metal pollution, thereby reducing the impact of rainwater runoff on aquatic environments. In contrast, PV-green facade systems exhibit a lesser degree of effectiveness in reducing both rainwater runoff and peak flow rates.	[64,72]
Materials	Crystalline silicon photovoltaic cells.	[51]

complex, encompassing multiple facets such as pest control, substrate addition, and filter replacement [75]. Another challenge faced by BIPV-greening systems is the scarcity of comprehensive performance studies in diverse climatic conditions. While the literature [76] compares the life cycles of green roofs and BIPV roofs in cold climates, it does not address the relationship between plants and PV systems in such environments. As shown in Table 2, the majority of experimental sites were situated in tropical regions, with studies predominantly conducted during summer months and only a few investigations involving cold

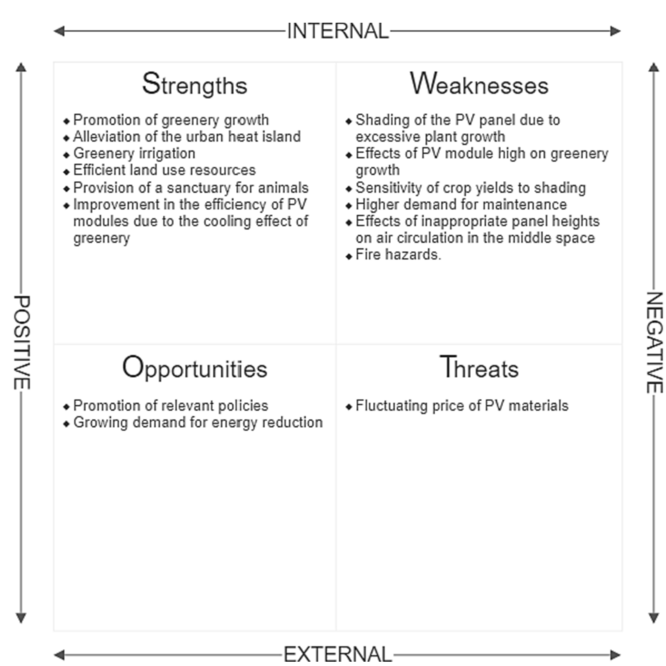

Fig. 3. SWOT analysis of integrated BIPV-greening systems.

climate conditions. Additionally, policy uncertainty presents both opportunities and challenges. Generally, the initial cost of BIPVs is high, and the price of solar panels is determined by local living expenses and labor costs [77]. However, the economic payback period for solar panels is typically short, ranging from approximately 10 to 15 years [78].

Discussion

Sustainable design is a crucial consideration throughout a building's entire life cycle. However, approximately 80% of its consumption is determined during the design phase [79]. Consequently, it is imperative for architects to prioritize sustainability in this phase to mitigate the adverse impacts of the building. For the design that integrates both BIPV and greening, the following principles are recommended: (1) to ensure plant survival in buildings, it is advisable to select plant varieties that are well-suited to local climate and soil conditions. Plants exhibiting drought and cold tolerance, along with high leaf reflectivity, are optimal choices. (2) An integrated BIPV-greening system has a certain load on a facade and roof, which will be influenced by external factors such as wind, especially on high-rise buildings. The load design should consider the influence of various factors, such as plant media and carrier weight, PV module gravity factors, wind loads, and seismic effects. (3) A reasonable arrangement of the distance between PV panels and plants should be considered. If the distance is too close, the restricted space may hinder the ventilation of the intermediate layer, leading to an increase in plant surface temperature and affecting the evaporation process. Conversely, if the distance is too great, the cooling effect of plants on PV panels may be diminished. PV panels are commonly installed at distances ranging from 0.18 cm to 1 m from the roof plane, with their performance contingent upon factors such as roof wind speed, selected plant species and height, and PV module material. (4) Greywater encompasses a higher nutrient content than rainwater, and certain components within greywater can promote plant growth while reducing the need for fertilizers. In the design of an integrated BIPV-greening system, utilizing rainwater or greywater irrigation should be prioritized to conserve water resources. (5) PV module spacing is a critical factor that influences fire propagation [80]. Fire passages are required around the BIPV-greening systems to avoid the spread of fire. Simultaneously, the distance between photovoltaic modules should be rationally designed, and weeds should be routinely pruned.

In addition to generating electricity, BIPV facades serve an additional significant function: they improve the building's thermal comfort and provide shading. Emerging designs have introduced the integration of greenery into BIPV facades using opaque crystalline silicon solar panels. Existing literature has mostly concentrated on exploring the energy potential of these designs, providing us with a conceptual understanding. However, these studies generally fail to differentiate between transparent and opaque photovoltaic (PV) panels, a distinction that is vital considering the light requirements of certain sun-loving plant species. For these plants, semi-transparent PV panels may offer a more suitable option than their opaque counterparts. A review of the existing literature reveals a common application of translucent PV panels in agricultural greenhouses, but there is a distinct lack of research concerning the incorporation of greenery with coloured PV panels. This gap limits our comprehension of the potential advantages and drawbacks of integrating coloured PV panels into greening systems. To address this lacuna, future studies should focus on exploring the potential of integrating coloured PV panels with greening systems. A crucial factor that needs consideration in this respect is the specific light spectrum requirements of different plant species or crops. Such research will provide valuable insights into optimizing greening systems integrated with BIPV technology.

Regarding the additional weight and maintenance challenges posed by the combined system on the building façade, incorporating plants alongside PV panels increases the overall load on the structure, while the maintenance of greenery in such configurations can be complex, requiring specialized care and attention. To address these limitations, it becomes crucial to explore lightweight materials and employ modular construction techniques. By utilizing lightweight materials specifically designed for BIPV integration with greenery, it is possible to minimize the additional load on the building without compromising structural integrity. Additionally, modular construction methods can facilitate easier maintenance by allowing for the individual replacement or adjustment of components, thereby reducing the need for extensive and costly interventions.

As previously mentioned, rooftop gardens can attract a variety of insects and birds, which may lead to an increased accumulation of bird droppings on the components. If this debris is not promptly cleaned, localized shading may occur, thus reducing the energy output. This can potentially lead to hot-spot effects, further compromising the safety of photovoltaic modules, and in extreme cases, it can even cause fires. The predominant current methods for cleaning solar panels are manual water washing and using industrial cleaning equipment, but these methods are challenging and expensive. Therefore, future research will aim to develop self-cleaning coatings for photovoltaic panels to mitigate the hotspot effects caused by surface dust and debris, particularly suitable for application in high-rise buildings.

Conclusions

In the rapidly evolving domain of BIPV technologies, there is a discernible uptick in academic interest concerning the integration of BIPV with greenery. This review has undertaken a comprehensive exploration of the manifold applications of this integration, illuminating its substantial implications for architectural sustainability. As we ventured into the effects and possibilities of green roofs, green facades, and photovoltaic systems, the paper critically assessed their compositional elements, as well as their respective energy performance metrics. From the vast repository of extant literature, we discerned six distinct categories pertaining to these integrative systems. A deeper, more granular categorization of these systems can augment our comprehension of their intricate sustainability parameters. Our study underlines that the conjunctive implementation of BIPV and greening systems holds enormous potential. However, it's imperative to underscore a noticeable limitation in the current discourse. Much of the existing literature emphasizes the integration of PV systems with green roofs, leading to a notable gap in thorough studies that address the fusion of plants and PV facades. This research gap becomes more pronounced when considering the intricate classifications of BIPV facades. Elements such as transparency, the specific PV technology employed, module operating temperatures, and mounting techniques can all significantly shape their integration possibilities and outcomes. As a result, a pressing need arises for more in-depth research into the interplay between various solar facade types and greenery.

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.

Data availability

Data will be made available on request.

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