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From Flora to Solar Adaptive Facades: Integrating Plant-Inspired Design with Photovoltaic Technologies

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Abstract: Recognizing the significance of solar energy as a vital renewable energy source in building envelope design is becoming more and more important and needs urgent attention. Exploring solar adaptation strategies found in plants offers a wide range of effective design possibilities that can substantially improve building performance. Thus, integrating solar technologies with biomimetic solar adaptive solutions could establish a suitable combination towards a sustainable design. In this context, this study follows an interdisciplinary approach to provide a link between plants' solar adaptation strategies, building integrated photovoltaics and building envelope design. To do so, a framework has been presented using data synthesis and classification to support the potential integration of three photovoltaic (PV) technologies with plant-inspired building envelope design, facilitating a harmonizing approach between biomimetic design and the application of photovoltaic technologies in buildings.

Keywords: biomimetics; building envelope; facade; architecture; energy; building integrated photovoltaics (BIPV); nature; adaptation

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1. Introduction

Exploring natural adaptation strategies to seek proven technical solutions emerged as a discipline named biomimetics [1]. Adaptive skin is not a new notion for sustainable building envelopes [2], yet integrating adaptive strategies from nature into architecture is a rapidly developing field [3] facilitated by emerging computational methods. The increasing number of researchers and designers using the approach of biomimetics to solve technical problems proves the applicability and premise of biomimetic solutions for the design of adaptive facades [4,5].

The concept of 'adaptive facade' not only defines aesthetic features but also the building envelope's capacity for serving as an interface between the outdoor and indoor environment and responding to different fluctuations in environmental characteristics such as solar radiation, temperature, wind and precipitation. In this regard, adaptive facades may adjust to various design criteria like shading, solar gain, privacy and ventilation [6,7]. As one of the important renewable resources, solar energy can be harvested and regulated through the building envelope with principles inspired by strategies from nature [5].

Investigating innovative techniques to enhance the performance and multifunctionality of adaptive solar envelopes is a continuously evolving area of research [8]. Such innovations were investigated in the study by Premier [9] that focused on integrating smart materials like photovoltaics (PVs) with solar shading devices. Another study proposed an adaptive and reflective solar facade for multi-building energy management, utilizing adaptive reflective panels to optimize solar resource use in urban areas. This innovative system aims to reduce waste energy and mitigate the urban heat island effect by efficiently sharing solar radiation among building surfaces [10]. The potential of an adaptive solar facade (ASF) for comfort-centric design was explored in another study using parametric tools [2]. It demonstrated the ASF's ability to improve shading system flexibility and enhance visual comfort in a single office space in Tehran [2,4,11–16]. A recent advancement in the integration of PV technologies into facade shading devices is also showcased through the strategic use of advanced canopies. For instance, in Soft House I, designed by Kennedy and Violich, photovoltaic ribbons create a canopy on the southern facade of the building, adjusting and moving in accordance with sunlight variations to maximize energy harvesting to power various small devices such as laptop computers, phones and LED lighting. Another example for such applications is Soft House II which utilizes semi-transparent and highly reflective PTFE bands incorporated with thin-film PV strips, which are employed on a solar tracking system so that the PVs' orientation faces toward the sun constantly. While researchers have widely investigated solar facades [11–15], a promising avenue for enhancing adaptive efficiency could involve applying biomimetic principles and integrating PV technologies [16]. This aspect has recently attracted attention among various researchers and designers [4], signalling an emerging focus on combining biomimicry and PV integration to optimize the performance of these facades. Exploring adaptation principles from nature within the expanding realm of biological knowledge has the potential to inform novel design solutions that are adaptable, flexible and efficient [17].

In this study, the term used to describe bio-inspired facades or roofs designed to efficiently regulate or harvest solar radiation, or fulfil both functions, is "biomimetic adaptive solar building envelopes" (Bio-ASBEs). This research delves into the concept of Bio-ASBEs, with a specific emphasis on the solar adaptation strategies found in plants for controlling and harnessing solar radiation. This is due to the fact that buildings share similarities with plants; they are affixed to a specific location [18] and exposed to solar radiation that can be regulated and harvested for energy purposes. This study also illustrates how the integration of PV technologies can unlock significant potential for biomimetic design in this context.

Some characteristics of building integrated photovoltaics (BIPVs) can enable their seamless integration into Bio-ASBEs [16] and offer various visual and physical features [19]. As alternative solar cell technologies continue to emerge, the question arises as to which photovoltaic solutions are better suited for integration into building envelope designs inspired by the forms, functionalities and behaviors observed in plants and how this could happen.

To this end, this research provides an overview of how plants adapt to varying levels of solar energy. It outlines key methods for both regulating and harvesting solar radiation. This information is presented with a designer's perspective in mind, making it applicable for translation to the field of architectural design. Additionally, after providing a review of BIPVs and particularly the potentials of organic photovoltaic cells (OPV), perovskite solar cells (PSCs) and crystalline silicon (c-Si) PV cells, this study links the design possibilities of each of the examined PV technologies to plant-inspired solar adaptive design principles through developing a novel structured framework called PV-integrated Bio-ASBE. The research objectives include:

- To present a comprehensive overview of solar adaptive facades and building integrated photovoltaics (BIPVs) while offering a design-focused discussion on the strengths and weaknesses of three selected PV technologies;
- To extract and present solar adaptation aspects in plants;
- To explore the integration of photovoltaic (PV) technologies with plant-inspired solar adaptive design for building envelopes.

2. Research Methodology

This research follows an interdisciplinary approach [20] for the development of a PV-integrated Bio-ASBE design framework by integrating plant-inspired design principles and the possibilities that building integrated photovoltaics offers for the design of adaptive building envelopes (Figure 1).

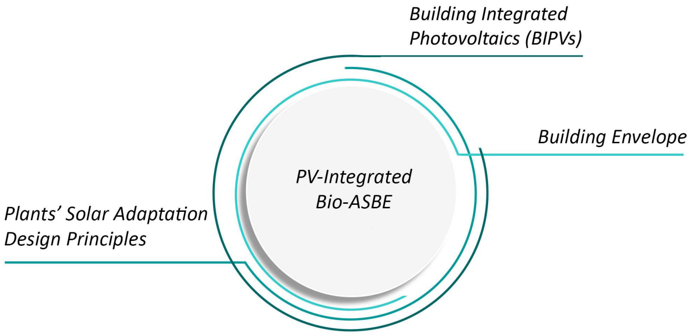

Figure 1. Research context.

To develop the integrated framework, this study aims to identify the correlation between the design characteristics of some BIPVs and design principles from features found in plants that respond to different solar radiation conditions. This work focuses on a further discussion of earlier review work [16] and preliminary guidelines on design lessons from plants [5]. First, the literature review was expanded to identify overlaps between PV characteristics (Section 4) and plants' solar adaptation strategies (Section 5) for potential integration. Second, a new classification was established to facilitate associations between the different temporal and spatial aspects. Third, by synthesizing current elaborated study findings, this paper proposes a novel framework (Section 6), referred to as the PV-integrated Bio-ASBE. The primary objective of this framework is to provide guidance to seamlessly incorporate advanced PV technologies into adaptive solar design solutions, drawing inspiration from strategies employed by plants.

Three photovoltaic technologies were considered as examples, crystalline silicon (c-Si) PV cells, perovskite solar cells (PSCs), and organic photovoltaic cells (OPVs), according to their potential for bio-adaptive building envelope integration. The selection of these three solar cell technologies as examples was based on their potential of "alignment with plant-inspired design principles and building envelope integration", "market dominance" and "applicability and efficiency" [16].

3. Solar Adaptive Facades

There is an increasing need to design more adaptable buildings and environmentally responsive building envelopes, providing not just static shelters with separate components but rather incorporating advanced materials and systems to regulate their internal environment based on external changing conditions, potentially even generating energy [21].

One of the first studies that utilized the term "adaptive facade" (AF) was [22] in its first edition in 2007 [6]. It has been followed by the concept of the adaptive building envelope in the literature which is defined by different terminologies such as "adaptive building skin" [23], "adaptive building facade" [24], "climate adaptive building envelope" [25] and so forth. "Climate adaptive building shell" was introduced by Loonen et al. [26]. It refers to a building shell that can adjust its functions, features or behavior in response to varying conditions and changing performance requirements aiming to enhance overall building performance.

Solar access and regulation are crucial factors for the wellbeing and comfort of buildings' occupants [27]. Building envelopes, referred to as solar facades, have the capability to regulate and generate solar energy. These solar facades can be classified into two primary categories, as outlined by Quesada et al. [11]. One is termed "opaque", while the other is referred to as "transparent and translucent". Within these categories, both active and passive approaches can be found. Opaque solar facades predominantly reflect and absorb incoming solar radiation, whereas transparent solar facades have the capacity to directly transfer solar heat gain into the building. In terms of passive solar strategies, three crucial objectives have been identified by Gosztonyi et al. [28] for future facades:

1. Maximal light transmission—this aims to optimize the entry of natural light into the building.
2. Selective transmission of thermal solar radiation—this focuses on allowing specific wavelengths of solar radiation that contribute to heating while blocking others.
3. Selective transmission of light and the guidance/tracing of light—this involves controlling the passage of light to enhance daylighting and visual comfort, and reduce the need for artificial lighting, thus improving thermal comfort [28].

Badarnah and Knaack [29] proposed a design concept for an adaptive shading system that applies orientation, distribution and flexibility principles to enable sun tracking to provide shading and generate energy through PV cells simultaneously [30]. Another example of an adaptive solar facade is the experimental house designed for the 2007 United States Solar Decathlon Competition which features an external cladding composed of wooden slats housing integrated photovoltaic panels. This system is managed by an intelligent control system, enabling both energy generation and mitigation of solar heat gains [31] as cited in [32] (Figure 2). Nagy et al. [15] also introduced a prototype of the concept of adaptive solar facade (ASF). This innovative, modular building facade system is designed to dynamically respond to solar radiation, harnessing it to generate electricity. Furthermore, an integrated simulation framework was presented in [33] which achieves both energy conservation and photovoltaic electricity generation through adaptive shading. Another example of adaptive solar skin is the ICT Media Building in Barcelona, Spain which employs pneumatic actuation to react by inflating or deflating, effectively reducing UV rays and heat by 85% [34]. Investigating innovative techniques to enhance the performance and multifunctionality of adaptive solar facades is a continuously evolving area of research [8]. A promising strategy involves the application of biomimetic principles and PV integration [16] in the design of these facades. The exploration of biomimetics in architecture has attracted the attention of several researchers and designers [4]. Yet, the integration of biomimetic design with photovoltaics remains scarce.

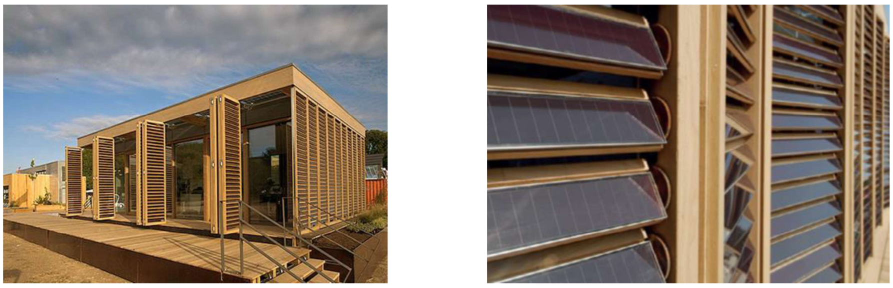

Figure 2. The integrated PVs in the louvre system at the Technische Universität Darmstadt's 2007 Solar Decathlon House, reproduced with permission from MDPI [32].

4. Building Integrated Photovoltaics (BIPVs)

A variety of physical and visual characteristics of PV technologies for building integration emerge from the literature on BIPVs. Photovoltaic modules integrated into the structural components of a building, commonly referred to as building integrated photovoltaics (BIPVs), have taken the place of conventional building materials [16,35].

The BIPV system serves a dual function, functioning as both a power generator and a component of the building envelope. By producing electricity on-site, the PV modules can significantly reduce overall building material costs and lead to significant savings in installation expenses. This is particularly noteworthy because BIPVs eliminate the necessity for additional assembly components such as rails and brackets [36]. The integration of BIPVs into building envelopes presents numerous benefits compared to non-integrated systems, as it eliminates the necessity for separate installations or dedicated land allocation, resulting in cost-effectiveness across various aspects [35]. Furthermore, as an extra benefit of this system, airflow behind the solar cells reduces their temperature which improves their longevity and efficiency [37], which can be achieved through PV integration into ventilated facade and external shading systems.

As highlighted by Lai and Hokoi [13], in considering solar technologies beyond photovoltaics, PV solutions for building integration can serve as transparent, semi-transparent, or opaque elements of the building envelope [13]. PVs can also be integrated into shading devices [33].

Numerous examples demonstrate the possibilities for integration of photovoltaics into building facades. For instance, Jayathissa et al. [33] enhanced building energy efficiency by implementing a dynamic photovoltaic system for adaptive shading. This system effectively regulates natural lighting and solar heat gain while simultaneously generating electricity. In a similar research work, Xu et al. in 2008 introduced the concept of a photovoltaic thermo-electric window (PV-TE), which not only produces but also stores electricity [38]. Another innovation in building integrated photovoltaics (BIPVs) involves a component that combines insulation properties, structural functionality and clean energy production. This versatile element is particularly suitable for retrofitting projects and constructing translucent facades in high-rise buildings across various climatic zones [39]. Likewise, Lee et al. [40] suggested implementing a photovoltaic double-skin (PV-DSF) system to enhance the efficiency of building envelopes. This innovation resulted in a decrease of 0.5 °C and 2 °C in air and wall temperatures during the summer, consequently reducing energy consumption [40].

The unique attribute of photovoltaics (PVs) designed for integration into buildings is their capacity to offer various functions, including energy generation, shading and aesthetic improvements. This allows for a seamless blending of sustainable technology with architectural design. In the following, a brief overview of three chosen photovoltaic technologies and their comparison has been provided to pave the way for a more detailed examination of their integration potential with Bio-ASBEs.

4.1. Crystalline Silicon (c-Si) PV Cells

Traditional crystalline silicon (c-Si) PV cells (Figure 3a) have maintained a dominant presence in the market, to the point that today they constitute more than 90% of the worldwide photovoltaic (PV) market [41]. This is especially true in the use of rigid BIPV panels designed to serve as roofing tiles and exterior cladding [42]. From the 1990s to the early 2000s, innovations like “passivated emitter rear contact”, “surface texture”, “firing technology” and “screen printing” were introduced. These advancements significantly improved power conversion efficiency and reduced manufacturing costs, thus promoting the industrialization of silicon photovoltaics (PV) [43]. Their non-toxicity, good stability and cost-competitiveness [41] make them a good candidate for application. Their material features are characterized by flatness, opaqueness, significant weight and rigidity. One of the main drawbacks of these PV cells is their poor performance under high temperatures and shading caused by chimneys, neighboring structures or other obstructions [44], although (c-Si) solar cells are a well-established technology [45]. Thin-film photovoltaics provide greater adaptability for building integration since they can be lightweight and flexible, as opposed to being supplied as rigid modules with glass covers [36].

The integration of crystalline silicon (c-Si) modules with Bio-ASBEs would pose challenges due to their opaque, rigid and heavy nature. On the other hand, achieving semi-transparency with c-Si modules involves increasing the spacing between solar cells and reducing the overall active PV area, which in turn results in reduced energy generation. These aspects should be considered in architectural design, specifically in biomimetic applications.

4.2. Perovskite Solar Cells (PSCs)

Perovskite solar cells (PSCs) (Figure 3b) have attracted significant attention as a promising energy-harvesting technology primarily due to their remarkable power conversion efficiency (PCE) as highlighted in various studies [46–48], uncomplicated solution-based fabrication and suitability for lightweight and portable applications [49]. They also offer other advantages such as flexibility, foldability, printability, semi-transparency and color variation, as demonstrated by Ref. [50], among other potentials. The most significant advantage of perovskite materials compared to traditional photovoltaics is their capacity to respond to a broader range of light wavelengths, maximizing the conversion of incident radiation into electricity. Moreover, their flexibility in fabrication on various substrates allows for their application in different ways. Additionally, perovskite solar cell manufacturing relies on a simple wet chemistry process without the need for an evacuated environment, compared to silicon solar cells, which require subjecting materials to extremely high temperatures exceeding 1000 °C in a highly evacuated chamber [51]. However, there are some concerns surrounding their toxicity, production costs and stability. To make perovskite solar cells practical for real-world applications, we must address several scientific challenges and issues like reducing charge separation, collection and transportation losses [49]. Despite these limitations, integrating PSCs into building envelopes represents a holistic and promising approach, positioning them as the next generation of building integrated photovoltaics (BIPVs), as discussed by Roy et al. [52].

4.3. Organic Photovoltaic (OPV) Cells

Over the last two decades, organic PV technologies (OPV) (Figure 3c) have emerged as a promising option for building integrated applications and mass production. This is primarily attributed to their cost-effective manufacturing through mechanical routes, innovative design and the use of non-toxic materials, as underscored by Ahmad et al. [53]. However, a significant challenge in OPV technology lies in its long-term stability, a concern that can be mitigated by effectively covering and encapsulating OPV solar cells, as explored by Kuhn et al. and Hinsch et al. [19,54].

Despite the commercial challenges, such as relatively lower power conversion efficiency compared to other competing technologies, it is worth mentioning that Darling and You [55] believed that OPVs had made substantial progress in terms of efficiency, surpassing the improvements achieved by other technologies in recent years [55]. Additionally, technologies like OPV, characterized by their distinct absorption band, have the capability to allow transparency in the visible region by concentrating light absorption in the near-infrared (NIR) and ultraviolet (UV) regions [56]. Despite existing limitations in the design of semi-transparent OPV modules, it seems that they are on track for use in skylight and smart window applications in the near future [56,57]. Due to their remarkable flexible and adaptable nature, they can provide promising opportunities for biomimetic designs.

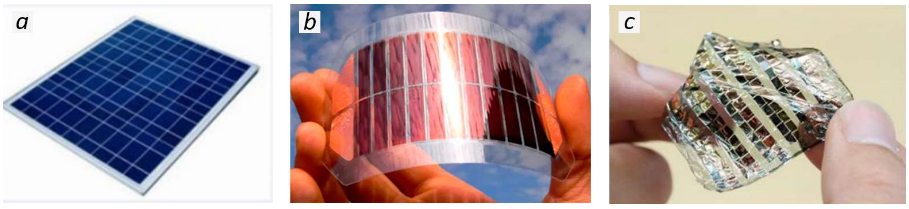

Figure 3. Three chosen photovoltaic technologies: (**a**) crystalline silicon (c-Si) solar cells [58], (**b**) perovskite solar cells (PSCs) [59], (**c**) organic PV technologies (OPV) (stretchable and washable type) [60].

4.4. Summary—Comparative Analysis of Crystalline Silicon, Perovskite and Organic Solar Cells

An analysis of the technologies introduced in the literature reveals their respective advantages and disadvantages, which are summarized and compared in Table 1. This comparative analysis centers on the design possibilities afforded by photovoltaics in architecture, particularly their potential for integration into Bio-ASBEs.

Table 1. Comparative analysis of crystalline silicon, perovskite and organic solar cells, adapted from [16].

PV Cells	Advantages	Disadvantages	Design Potentials for Integration with Bio-ASBEs
Crystalline silicon (c-Si) solar cells [41,44]	- High efficiency - Dominance in the market - Lower cost - Non-toxicity - Good stability	- Mostly not transparent and do not allow window integration - Mostly rigid, flat, heavy and opaque panels - High temperatures and shading cause a loss of performance	Crystalline silicon PVs' integration with Bio-ASBEs would pose challenges due to their opaque, rigid, heavy nature. Nevertheless, depending on the design concept, their advantages can outweigh their disadvantages.
Perovskite solar cells (PSCs) [49,51,58,61]	- High efficiency in power conversion (PCE) (main advantage) - Flexibility - Simple manufacturing process - Foldability - Light weight - Semi-transparency - Printable - Color variation	- Toxicity - Material production - High cost - Low stability	Perovskite cells demonstrate the capacity to integrate with Bio-ASBEs, aligning effectively with the adaptability demanded by Bio-ASBEs due to their flexible, printable, semi-transparent nature.
Organic solar cells (OPV) [19,42,53–56,60]	- Mechanical flexibility - Design flexibility - Mechanical cost-effective routes - Non-toxicity in some cases - Transparency/semi-transparency - Stretchable and washable (some types)	- Short-term stability - Low efficiency - Low strength	The potential offered by integrating the lightweight, flexible, semi-transparent/transparent and reconfigurable attributes of OPVs with the adaptable features of Bio-ASBEs is highly promising.

5. Solar Adaptation in Plants

Nature showcases remarkable adaptive approaches for controlling light and temperature under different intensities and across various timeframes, achieved by illuminating, filtering or harnessing it [62]. Plants, even though they appear still, have impressive ways to adjust to different light levels using various methods [63] and while lacking muscles, plants exhibit a range of movements that occur over various timescales, spanning from hours or days to milliseconds. Therefore, studying their adaptation strategies can offer insights into designing facades that efficiently manage light and generate energy in architecture [5]. However, building facades have distinct requirements compared to plants, including the need for user comfort and different shapes and layouts. Thus, there is a need to integrate plant mechanisms with the specific demands of building facades [29]. In the process of bio-inspiration, it is crucial to acknowledge the significance of biological characteristics and their relevance to achieving successful integration [64]. Plants exhibit remarkable abilities to control solar radiation through three key adaptive strategies: light harvesting (optimizing sunlight exposure), light regulation (minimizing sunlight exposure) and thermoregulation (temperature control). These strategies may intersect depending on the plant species, its specific climate and its natural habitat.

5.1. Light Harvesting—Maximizing Light Exposure

Plants employ diverse strategies and incorporate various features to harvest solar radiation and optimize its utilization when required [64]. Esteso-Martínez et al. [65] identified numerous structural and morphological characteristics related to light harvesting in certain plant species. These traits encompass stem inclination, leaf rotation, petiole enlargement and branching [5,65]. Badarnah and Knaack [29] outlined plants' organizational features and their attributes for maximizing light exposure, which include leaf distribution (e.g., the Fibonacci series for compact pattern packing), dynamics (e.g., increasing leaf area while reducing mass per unit) and orientation (e.g., facing perpendicular to sun rays) [29]. In another study, Badarnah [62] explains remarkable natural adaptive mechanisms for controlling light by either illuminating, filtering or capturing it [62]. Jalali et al. [5] built upon this by revealing unique strategies used by plants in environments with scarce solar radiation or high light demands. These strategies include large surface area, monolayer leaf arrangement, self-shading minimalization and reflective properties of the leaf's back surface [5].

5.2. Light Regulating—Minimizing Light Exposure

Plants employ various methods to respond to high solar radiation. In environments with intense radiation, such as deserts, plants face the challenge of minimizing direct tissue exposure to maintain survival and productivity. To address this, they use metabolic adaptations to function properly at higher temperatures and mechanisms that lower tissue temperatures. Leaves employ various strategies to reduce solar radiation absorption resulting in mitigating excessive heating. These strategies include increasing reflectivity through the presence of epidermal hairs or a waxy cuticle, providing shade to sensitive tissues with the help of a layer of hairs or spines, altering the angle of leaves relative to the direction of the sun and decreasing the surface area-to-volume ratio of leaves [66].

Prisco et al. [67] classify plants' adaptation types, one of which is morphological/anatomical modification [67] which could be a suitable source of inspiration in architecture. For instance, in harsh desert environments, deep rooting helps plants avoid surface drought and improves water uptake from deeper layers; induction of root hairs also helps water uptake; appropriate leaf orientation prevents receiving excessive radiation, heat and freezing; and leaf folding lowers light capture [5,67,68].

5.3. Thermoregulation

Nature's solar adaptation strategies are intrinsically linked to organisms' ability to regulate heat and include heat gain, retention, prevention and dissipation [7] in response to varying solar conditions and the natural organism's demand [5]. One approach in plants involves maximizing transpiration rates by increasing the surface area relative to volume, facilitating heat dissipation. Additionally, some plants reduce boundary layer resistance to heat transfer, often through the development of dissected or narrow leaves, which enhances sensible heat loss. Another strategy is thermal moderation, as observed in certain plants like cacti and desert succulents. They utilize thermal mass to buffer against temperature fluctuations, enabling them to withstand both cold nights and hot days. Some desert species employ different tactics, such as positioning themselves above or below ground level to benefit from the thermal damping the soil offers [66].

On the other hand, avoiding low temperatures in plants falls into two classes: mechanisms that raise tissue temperatures to support growth and methods to prevent tissue from being damaged by cold or freezing. In cold places like the Arctic, many plant species employ a combination of strategies to conserve heat and harvest solar energy. They can act as solar reflectors or collectors, concentrating sunlight on their sensitive reproductive tissues. Additionally, their short stature reduces heat loss since they are less affected by wind, resulting in lower heat loss rates. Another mechanism involves the release of heat, known as a freezing exotherm, when external water or tissue freezes, releasing latent heat [66].

5.4. Summary: Solar Adaptation Factors in Plants

Over time, plants have evolved a set of strategies to adapt to the specific climatic conditions of their native habitats [5]. Several common adaptive features have been identified among the selected plants, each of which is strategically aligned with the climatic challenges they face (Figure 4). For example, plants such as *Hellebore*, *Phlomis* and olive trees, indigenous to the Mediterranean climate characterized by hot summers and wet winters, have evolved similar mechanisms to avoid excessive summer heat. One shared mechanism is adjusting reflectivity [69–71], a vital strategy these plants employ to prevent overheating and water loss. Furthermore, in addition to material characteristics like the presence of hairy or waxy layers, these plants exhibit morphological adaptations. At the leaf level, adaptations to light often entail changes in stomatal density and leaf size. Sun-exposed leaves tend to be thicker and have a greater mass per unit area compared to shaded leaves [72]. These morphological adaptations also include the development of curled or twisted leaves, which effectively reduce excessive light absorption [5]. Conversely, some plants like Fatsia japonica have adopted large leaves [73] to maximize light harvesting.

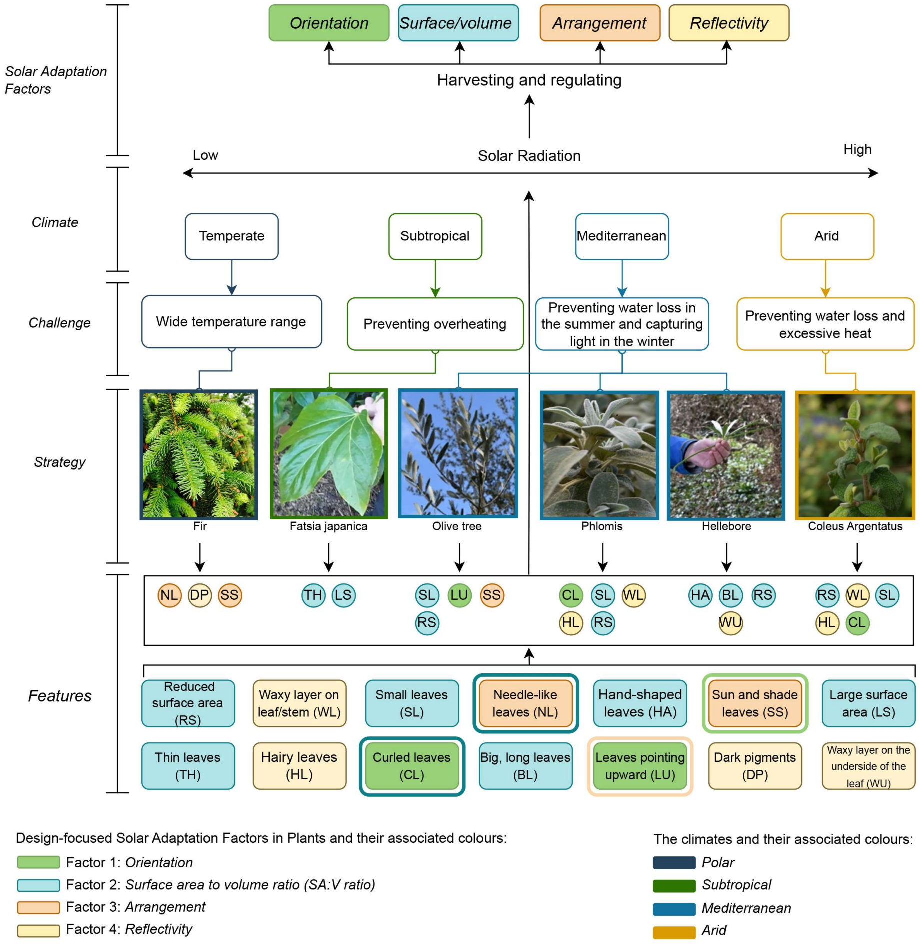

Figure 4. Solar responsive aspects—features, strategy and factors in plants. The features that exhibit analogies to multiple factors are illustrated with multiple lines.

The leaves' arrangement and orientation also play a critical role in shaping solar adaptation principles [74]. Baldini et.al. [74] emphasized that the leaf area index (LAI) and the specific spatial arrangement of leaves are the primary influences determining how radiant energy is distributed within the olive tree [75]. Certain olive tree leaves orient themselves nearly parallel to the direction of sunlight, thereby mitigating excessive light exposure [5,71,74]. On the other hand, firs have developed a different strategy to survive under low temperatures, with small, needle-shaped leaves surrounded by thick waxy coatings [76].

In this context, the solar adaptation features of the chosen plants including *Hellebore*, *Phlomis*, *Fatsia japonica*, fir and olive tree are systematically categorized and structured, drawing upon their rational connections (Figure 4). This approach enables designers to better comprehend the information and discern meaningful parallels [3,77]. This classification encompasses key factors including *"Orientation", "surface area to volume ratio", "Arrangement" and "Reflectivity" outlined in* Figure 4.

Below is a list of the plants' identified features along with their corresponding main solar adaptation factors:

1. ***Orientation**:* Curved leaves (CL), Leaves pointing upward (LU);
2. ***Surface area to volume ratio*** (SA:V ratio): Reduced surface area (RS), Thin Leaves (TL), Needle-like leaves (NL), Big, long leaves (BL), Hand-shaped Leaves (HL), Large surface area (LS);
3. ***Arrangement**:* Needle-like leaves (NL), Sun and shade leaves (SS);
4. ***Reflectivity**:* Waxy layer on the leaf/stem (WL), Hairy leaves (WL), Waxy layer on the underside of the leaf (WU).

This study builds on plants' solar adaptation principles [5]; a hierarchical framework for designing solar envelopes, taking inspiration from how plants manage sunlight, was developed. The preliminary framework [5] consists of four key elements, including *Principles*—the fundamental solar management features observed in plants; *Strategies*—the mechanisms plants employ to control the amount of solar radiation they receive; *Design factors*—various aspects that can be considered during the development of solar envelope designs; *Design*—where we put these ideas into practice to create the actual solar envelope. Each design factor corresponds to specific plant-inspired strategies, allowing designers to select and apply them as needed to bring their solar envelope concept to life [5].

The four solar adaptation factors presented in this study are the outcome of synthesizing and classifying new data obtained from a literature review, along with the results of the preliminary framework of our previous study where strategies related to two identified solar management principles, including avoiding excessive solar energy intake and optimizing light harvesting, were presented [5]. Moreover, the solar responsive features associated with each of the four factors that have been presented in this study serve as a more detailed and comprehensive version of the preliminary adaptive solar framework [5].

The rational link between each plant's climate, the challenges they face, the strategies employed and the solar responsive features they exhibit is clearly illustrated in Figure 3. For example, Fatsia japonica is indigenous to a subtropical climate characterized by humid and hot summers and cool to mild winters. The challenge in this climate is the need to prevent overheating. Consequently, this plant has developed features such as *thin leaves (TH)* and a *large surface area (LS)* to enhance evaporation while still receiving adequate light [78]. These two features are linked to *Surface area to volume ratio (SA:V ratio)* as one of the four solar adaptive factors identified in plants, showing the rational connection and similar strategies found in nature.

Additionally, in this study, a narrower yet integrative approach is adopted to investigate how the four identified solar adaptation factors (Figure 4) can be abstracted and translated for the design of PV-integrated Bio-ASBEs.

6. Integrated Approach—From Flora to Solar Facades

Both plants and buildings face the challenge of effectively managing their interactions with the environment to maintain ideal internal conditions. This shared need has led to the development of numerous valuable strategies which can be drawn from plants' adaptation strategies and applied to architectural components [79]. To translate biological concepts into technology, a process of interpretation or abstraction becomes essential [79–81].

Here, an integrative hierarchal approach is adopted to translate biological data to a design language [5,64,82] and link it to the properties of PV technologies to present a PV-integrated Bio-ASBE framework (Figure 5).

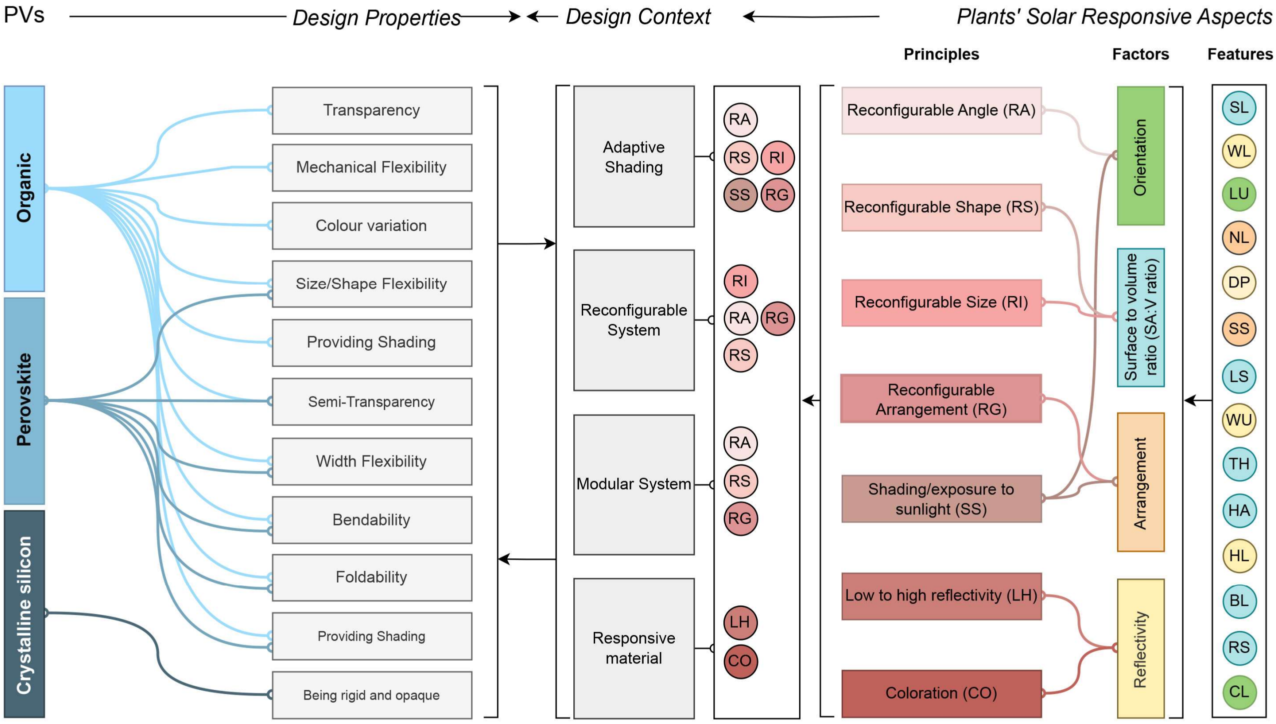

Figure 5. PV-integrated Bio-ASBE framework.

This approach encompasses two interconnected facets. On one side, it begins with "*Plants' Solar Responsive Aspects*" culminating in the formation of "*Design Context*". On the other side, the approach explores three selected photovoltaic technologies, encompassing crystalline silicon (c-Si) solar cells, perovskite solar cells (PSCs) and organic PV technologies (OPVs), culminating in presenting their "*Design Properties*" (Figure 5).

Plants' solar responsive aspects encompass "*Features*", "*Factors*" and "*Principles*", respectively. Building on the foundation laid out in Section 5, which identifies solar adaptation factors in plants through the classification of their features, the subsequent step involves defining the principles that further abstract the concept to inform the design context. These principles include: "*Reconfigurable Angle (RA)*", "*Reconfigurable Shape (RS)*", "*Reconfigurable Size (RI)*", "*Reconfigurable Arrangement (RG)*", "*Shading/Exposure to Sunlight (SS)*", "*Low to High Reflectivity (LH)*" and "*Coloration (CO)*". These principles are explained by plants' morphological characteristics, like size, shape, width and behavioral traits such as material properties (e.g., reflectivity), which can be dynamic and changeable over different timeframes—ranging from hours to seasons. The characteristics are adapted in order to harvest solar radiation effectively by maximizing exposure to sunlight, as well as to mitigate excessive solar energy absorption, drawing inspiration from natural plant strategies [5].

This abstraction process has yielded four fundamental design contexts: "*Modular system*", "*Adaptive shading*", "*Responsive material*" and "*Reconfigurable system*", all derived from the classification of plants' solar responsive principles. The design of *Pho'liage* [83], for example, aligns with principles including "*Reconfigurable angle (RA)*" and "*Shading/exposure to sunlight (SS)*". These principles relate to the solar responsive factors in plants, including "*orientation*" and "*arrangement*". As a thermoregulating facade element, Pho'liage incorporates an open/close configuration, drawing inspiration from the behavior and mechanics of plants' stoma cells. This prototype serves as an illustration of the integration of the four design contexts introduced in Figure 5 into the design. It showcases "*Adaptive shading*", a "*Reconfigurable system*", a "*Modular system*", and the utilization of "*Responsive material*".

As shown in Figure 5, the design contexts derived from plants' solar responsive factors have been associated with the design properties of photovoltaic technologies extracted from

Table 1. The demonstrated connections emphasize how photovoltaic technologies can play a pivotal role in achieving solar responsive functions by integrating solar cells into Bio-ASBEs.

The *Reconfigurable Angle (RA)* design principle is highly relevant to the positioning of PV modules with optimal orientation and tilt. In the application of the identified solar adaptive factors in design, careful consideration is required for the positioning of components. The PV-integrated shading devices are predominantly positioned externally to the building. This is due to the fact that the optimal performance of solar shading is achieved in this way as they block the sun's rays before entering the building [84]; more importantly, the sun's rays should be captured to generate electricity [84]. It can also be observed that placing PV modules externally can facilitate the cooling of solar cells through ventilation for improved performance. The design principle of "*Reconfigurable arrangement (RG)*" is closely linked to the adaptability of the "*Reconfigurable angle (RA)*". This connection is evident in the dynamic behaviors of folding, bending, rolling and other adaptive movements observed in plants. These flexible movements, changing orientation and angles, enable plants to achieve optimal arrangements, maximizing or minimizing solar energy capture depending on the climatic conditions. This design principle can be utilized in the design of PV-integrated Bio-ASBEs, especially by the development of new flexible PV technologies. The dynamic behaviors exhibited by plants, such as changing shape and size (Figure 4), find their design counterparts in the principles of "*Reconfigurable Size (RI)*" and "*Reconfigurable Shape (RS)*". These design principles play an important role in biomimetic design development and PV integration considerations; for instance, the auxetic behavior found in certain cell structures [85] enables them to undergo changes in both shape and size while maintaining structural integrity. This characteristic can be applied in architecture for the design of shading systems where the reconfigurable shape and size of the system by manipulation of aperture size provide a flexible means of controlling heat and light as demonstrated by [86]. Additionally, the scale of the concept must be clearly defined, determining whether the envelope integration relates to a roof, wall, window or specific facade element. The purpose of responsiveness should be carefully considered, whether it focuses solely on energy harvesting or includes a multifaceted combination of objectives such as thermal comfort, visual comfort, daylighting and energy harvesting.

The integration of biomimetic principles with photovoltaic technologies opens exciting possibilities for real-world applications in architectural design. Such integration offers the potential to both generate electricity and enhance energy efficiency through adaptive shading relevant *to "Shading/exposure to sunlight (SS)"* design principle, as demonstrated in Nagy et al. [15], and aligns closely with several UN Sustainable Development Goals (SDGs) [87]. PV-integrated Bio-ASBEs mainly address SDG 7 by supporting clean energy generation and reducing reliance on fossil fuels. PV-integrated Bio-ASBEs may also contribute to achieving SDG 11 (*Sustainable Cities and Communities*). As noted in the explanation of this goal [88], an impact on transforming cities is recognized to influence several other SDGs. The potentials of the proposed approach also encompass long-term economic efficiency as adaptive building envelopes can have the capacity to enhance building energy efficiency and consequently economic performance by dynamically adjusting their behavior in response to real-time outdoor and indoor conditions [89]. Solar envelopes inspired by plants can also give rise to kinetic design, thanks to their flexible and adaptive characteristics. These kinetic functions are not only visually and aesthetically striking, resembling their natural counterparts, but can also offer additional benefits such as fostering social acceptance of novel technologies due to their appealing attributes [90]. The study by Khosromanesh and Asefi [90] exemplifies a responsive facade inspired by the ice plant seed capsule. It creates an adaptive system responsive to fluctuating environmental conditions, reducing energy consumption and improving building performance. The study explores design factors for hydro-actuated facades, promoting deformable and sustainable architectural systems. The bio-inspired responsiveness in this study is suggested to be coupled with the energy generation potential of PVs as outlined in the PV-integrated Bio-ASBE Framework (Figure 5).

Low–high reflectivity (LH) as a design principle is another aspect that needs careful consideration. Reflectivity is generally considered an unwanted characteristic in BIPVs, unless it meets certain criteria. Favorable instances include reflecting more light onto solar cells instead of directing it away as reflective glass covers do, which reduces energy generation [91], or selectively reflecting away certain wavelengths such as those in the infrared spectrum responsible for heat as noted in a study about spectral beam splitting technology [92]. Selectively reflecting solar radiation enables directing onto photovoltaic cells the portion of the spectrum they can generate electricity from. At the same time, it prevents their overheating by directing radiation away onto thermal devices that may use it as heat. This approach to reflecting the solar radiation spectrum can maximize the exploitation of solar energy as both electricity and heat. Additionally, reflectivity may be acceptable if it introduces color effects pertinent to the design principle of "*Coloration (CO)*". Integrated concentrating solar facade (ICSF) serves as an exemplary model for addressing these considerations by minimizing reflectivity losses and optimizing the concentration of sunlight onto the PV cells. It is a building integrated responsive system that integrates translucent concentrator modules into double-skin curtain wall assemblies [93,94].

Based on the plant-inspired solar responsive design context outlined in Figure 5 and its link with PV design properties, it can be concluded that crystalline silicon (c-Si) solar cells are not the most suitable choice for integration with Bio-ASBEs. This conclusion arises from the limited adaptability and flexibility of c-Si cells, which are essential qualities for effective integration with Bio-ASBEs. In contrast, perovskite solar cells (PSCs), organic PV technologies (OPVs) and other PV technologies with similar characteristics such as flexibility and transparency or semi-transparency emerge as more promising candidates for harmonious integration with Bio-ASBEs; for instance, certain thin-film solar cells, including cadmium telluride (CdTe), can offer transparency [95] as a design potential.

While the suggested technologies provide promising design-related possibilities, considering the stability and toxicity of PVs is also crucial in building integration approaches, as they represent a limitation. Si-based conventional PV devices are integrated into building envelopes to provide high-power and stable conversion efficiencies (PCEs). Nevertheless, their transparency and aesthetics confine their integration into electronic devices and city landscapes. Dye-sensitized and organic PV devices offer more effective transparency but are restricted by low PCEs for large areas and poor stability [96,97] as cited in [98]. One action that has been taken to overcome these boundaries is the improvement of stable transparent PV (TPV) devices. TPVs represent an energy conversion technology designed to convert light into electricity while allowing visible light to pass through. This capability facilitates on-site power generation and incorporates transparent device features. TPV devices exhibit considerable potential, making them a suitable choice for integration in building applications [99–101] as cited in [98], which can be the focus of future research for integration with biomimetic designs.

7. Conclusions

Extensive research exists on biomimetics and BIPVs separately; yet, a significant research gap persists in the exploration of their integration. The novelty of this research lies in exploring the integration of photovoltaic (PV) technologies with plant-inspired solar adaptive design for building envelopes, leading to the creation of a comprehensive framework called PV-integrated Bio-ASBE. In pursuit of our research objectives, a wide spectrum of potentials for their linkage has been identified emphasizing the design possibilities that PV technologies can offer for a biomimetic design. New advanced PV technologies can offer diverse design possibilities, including coloration, flexibility, transparency/semi-transparency, printability and so forth. All these features enhance their suitability for biomimetic design and integrated building applications. Building upon our previous work, this study provides a review of BIPVs and three selected photovoltaic technologies as examples, perovskite solar cells (PSCs), crystalline silicon (c-Si) PV cells and organic photovoltaic cells (OPVs). Furthermore, this study has reviewed and discussed strategies for solar adaptation in plants and their potential contribution to the development of adaptive solar envelopes. Taking these into consideration, this study proposes the framework and discusses PVs' potential integration with plant-inspired building envelope designs, highlighting different technologies' potentials and drawbacks. In line with the plant-inspired principles, it is evident that crystalline silicon (c-Si) solar cells are the least suitable choice for incorporation into Bio-ASBEs. Instead, thin-film and transparent/semi-transparent solar cells can be more suitable for mimicking solar strategies found in plants. Nature's solar adaptation solutions are vast, and this study concentrates on investigating solar adaptation strategies found in plants. Expanding the research to include other plant species and natural organisms could further build on the findings on plants' solar responsive factors and their analogous architectural solutions. Additionally, the examined photovoltaic technologies have limitations, including toxicity, efficiency and cost. To address these challenges, future research could explore alternative options like hybrid photovoltaic/thermal (PV/T) or concentrating photovoltaic (CPV) technologies also with transparent and semi-transparent PVs.

While this study delves into the solar adaptation strategies relevant to Sustainable Development Goal 7 (SDG 7) primarily by seeking to provide clean and sustainable energy, there are additional facets that demand attention to comprehensively address the challenges associated with achieving this goal. Future research initiatives could extend their focus to explore the affordability of solar technologies, considering the economic implications for diverse communities and regions. This encompasses not only upfront costs but also long-term accessibility and affordability to ensure equitable energy distribution. Additionally, a critical area for investigation lies in conducting detailed lifecycle analyses of the materials integral to photovoltaic technologies. Understanding the environmental impact throughout the entire lifespan of these materials, from extraction to disposal, is crucial for assessing the overall sustainability of solar adaptation solutions.

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