

Review

Biomimetic approaches to “transparent” photovoltaics: current and future applications

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Abstract: There has been a surge in the interest for (semi)transparent photovoltaics (sTPVs) in recent years, since the more traditional, opaque, devices are not ideally suited for a variety of innovative applications spanning from smart and self-powered windows for buildings to those for vehicle integration. Additional requirements for these photovoltaic applications are a high conversion efficiency (despite the necessary compromise to achieve a degree of transparency) and an aesthetically pleasing design. One potential realm to explore in the attempt to meet such challenges is the biological world, where evolution has led to highly efficient and fascinating light-management structures. In this mini-review, we explore some of the biomimetic approaches that can be used to improve both transparent and semitransparent photovoltaic cells, such as moth-eye inspired structures for improved performance and stability or tuneable, coloured, and semi-transparent devices inspired by beetles' cuticles. Lastly, we will briefly discuss possible future developments for bio-inspired and potentially bio-compatible sTPVs.

Keywords: transparent photovoltaics; semi-transparent photovoltaics; biomimetic

1. Introduction

Finding suitable renewable energy sources is one of the key challenges faced by humanity, mainly because of the impellent need to reduce green-house gases (GHGs) emissions and thus minimise climate change, even before the finite nature of fossil fuels becomes an issue [1].

Among renewables, solar energy is probably the one with the highest potential, based on consideration of the total radiative power reaching our planet. More solar energy hits Earth in one hour than the entire annual energy consumption on the planet in 2010 (4.3×10^{20} J vs 4.1×10^{20} J) [2]. Over a whole year, the solar energy received on Earth is ten times larger than all of the known reserves of energy coming from oil, coal, natural gases, and uranium combined [2].

Even though the amount of energy potentially harvestable is so incredibly vast, many challenges still remain for the large-scale exploitation of solar energy as a substitute to fossil fuels, resulting in only 3.27 % of the total electricity produced coming from solar power in 2020¹.

Some of these challenges are hard to address. One of these relates for example to the sizeable portion of solar energy being absorbed or reflected by Earth's atmosphere. In principle, this problem can be solved by extra-terrestrial solar power generation, which however still requires significant development, both in terms of subsequent transfer to Earth installations, and of orbital positioning, maintenance, and repair costs.

Other challenges are easier to address, as related to the specific current development of the relevant technology, such as limitations in energy storage and distribution [3, 4]. A

¹ Source: <https://ourworldindata.org/renewable-energy>

possible solution to this challenge could be found in increasing the amount of PV energy produced directly where it is needed by utilising building-integrated photovoltaics (BIPVs) or building-applied photovoltaics (BAPVs), because buildings account for around 40 % of the world's energy consumption [5].

The first category (BIPVs) describes PV devices used to substitute traditional building materials during the construction of the building itself (usually for its façade), while the second (BAPVs) describes devices added to the building after its construction (usually on its rooftop) [6]. BIPVs using a variety of technologies (including those based on dye-sensitised cells, DSSCs [7], as well as organic [8] and/or perovskite photovoltaics [9, 10]) have already found successful demonstrations. A recent demonstration is the building resulting from the collaboration between Skanska and the PV manufacturer Saule technologies².

Exploitation of the lateral surfaces of buildings for solar energy harvesting, for example by introducing windows with PV capabilities, can increase the area of usable surfaces for this purpose, consequently leading to more than doubling the amount of solar energy produced by buildings [6]. This, however, would require a different approach to PV devices.

Traditional, opaque PVs, in fact, can be unsuitable for many building-related applications, as is the case for implementation in windows: for these purposes, transparent and/or semi-transparent PVs are the required solution.

Semi-transparent photovoltaics can in principle also be of interest in so-called "agri-voltaics" applications, where solar panels are distributed in agricultural settings either in the open fields or integrated in the greenhouse architecture. In either case careful consideration of cost/performance factors is required to ensure the sacrifice of the cells efficiency stemming from (semi)transparency is justified in terms of agricultural yields.

TPVs can also be used outside of large-scale energy harvesting, as in the field of vehicle-integrated PVs (VIPVs), where transparent solar panels built into the roofs, wind-screens or windows of electric vehicles can improve their range or feed some of their less power-intensive equipment [11].

Last but not least, nanostructured, biomimetic surfaces of windows can act as antireflective coatings and thus reduce both "light-pollution" effects on the surroundings, and even thermal loading on front-facing buildings [12].

2. Key Challenges

TPVs and sTPVs have different requirements than traditional PV devices. As their names suggest, transparency in the visible range of the electromagnetic spectrum is a key aspect for these devices, measured by their (spectrally) averaged visible transparency (AVT). In principle one could envisage the possibility of only exploiting the non-visible portion of the solar spectrum (either or both ultraviolet, UV and near-infrared, NIR), however, this is far from trivial with currently available semiconductors. The easiest solution would be to use semiconductors with bandgaps > 3.1 eV or so, but this would severely limit the power conversion efficiency (PCE) of the resulting cells, because of the spectral distribution of solar radiation. In practice, it is therefore necessary to seek a compromise between transparency and absorption (necessary to generate excitons or free carriers and eventually a current), and even those cells that are indicated as TPVs are in fact partially absorbing in the visible.

There is no clear consensus on the threshold in transparency separating TPVs and sTPVs, with certain authors categorising devices with an AVT of 60 % as semi-transparent [13] and those with an AVT of 65 % as transparent [14]: in this review, we will therefore consider an AVT of 60 % to be the border between the two categories.

Furthermore, achieving high AVT inevitably decreases the device's PCE, so a compromise between the two should be found: for example, smart windows usually require

² Source: <https://sauletech.com/saule-technologies-and-skanska-change-construction-industry/>

an AVT of around 50 % and a PCE between 2 and 5 %, whereas it is generally accepted that mobile displays need an AVT of around 80 % and a minimum PCE of 5-10 % [6]. In light of this, a new figure of merit has been proposed by Traverse et al. for evaluating the performance of this kind of PV cells: the light utilisation efficiency (LUE), given by the product $PCE \times AVT$ [6].

For BIPVs, there is also the requirement of the devices being aesthetically pleasant, especially in residential or urban contexts, which is not a concern for most PVs utilised in solar farms.

These three key factors (AVT, PCE, and aesthetics) are the most important ones to consider when developing transparent or semi-transparent photovoltaics (Figure 1).

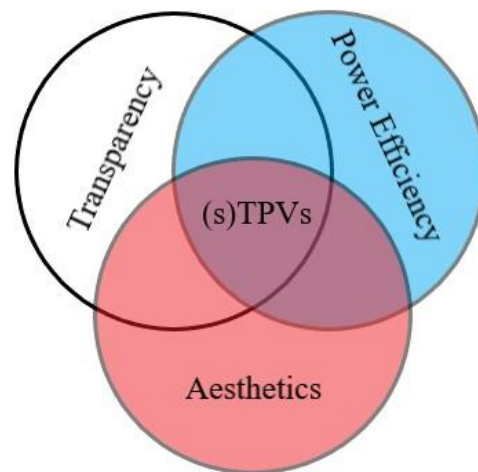


Figure 1. Visual schematisation of the three key factors in the design of TPVs and sTPVs.

Another key characteristic relevant to TPVs and sTPVs is their ability to accurately transmit colours, especially for windows and vehicle applications. This is measured by their colour rendering index (CRI), which quantifies the accuracy with which an object's colour is rendered from a light source or through a transparent medium compared to a reference light source (e.g., a black body at a certain colour temperature). For windows applications, the AM1.5G spectrum is considered to be the best standard to use [6]. CRI can assume values from 0 to 100, with higher values representing more accurate colour-rendering capabilities (Figure 2): a light source with a CRI of 70-90 is considered to be of good quality [15] and the same is true for TPVs or sTPVs.



Figure 2: Difference in colour-rendering capabilities between high and low CRI. Reprinted by permission from Springer Nature: Nature Energy [6], copyright 2017.

Furthermore, as is the case for every type of PV expected to operate outside of a controlled environment, stability and resistance to deteriorating factors such as rain, humidity, and bacteria are also required in order to obtain high quality devices [16].

One might hope that many of these challenges might be addressed by looking at the natural world, where animals and plants have evolved a plethora of solutions to light-management and stability problems over millions of years of evolution, ranging from structural colour aimed at camouflage or at attracting a mate, to photosynthesis-enhancing structures, to super-hydrophobic leaves [16-19].

3. Current State

Including biomimetic or biological elements in the design of TPVs and sTPVs can be a way of finding solutions to the many challenges that are typical of such devices: such challenges relate to either or both the aesthetical and performance aspects (including stability), as the two are often closely related (a device with an AVT of 80 % or more would have the same impact on the façade of a building as regular transparent glass, for example [6]).

In this section, we will present the latest research involving biomimetic solutions that have enabled improvements to TPV and sTPV devices.

3.1. Optical Performance and Aesthetics

In general, (s)TPVs intended for building-integrated applications are expected to meet the additional requirement of not detracting from the aesthetics of the building on which they are placed. How this issue is handled, however, depends on the specific application in question.

In warmer regions of the World, the highest demand for electricity is registered in correspondence to higher cooling demand within buildings [13]: in such a scenario, switching from highly transparent conventional glass to sTPVs with lower ATV would decrease the amount of cooling required to keep the internal space at a comfortable temperature, which in turn could lead to a saving of energy of up to 12 %, as shown by Li et al in a study based on field measurements obtained in Hong Kong during the month of July 2007 [20], as well as generating energy.

The minimum AVT required for windows is usually accepted to be at 20-30 % [21], so sTPVs within this range would be ideal candidates for these applications.

Examples of semi-transparent devices with low AVT and good aesthetics have been developed by Wang et al. by reproducing light-management strategies from beetles' cuticles in the fabrication of spectrally selective electrodes [22]. Some beetles exhibit bright structural colour by stacking layers of materials with different refractive indices in the same way as a Bragg mirror [19] (Figure 3a). More specifically, by combining stacks composed of several layers of LiF and N,N'-bis(naphthalen-1-yl)-N,N'-bis(phenyl)benzidine (NPB) with metal films, an anti-reflecting coating, and a hydrophobic external layer for improved stability (Figure 3b), devices with a PCE of 15.07 % and peak transmittance of ~30 % were fabricated (with a corresponding LUE of around 452).

Furthermore, by modifying the thickness and the number of dielectric layers, it is possible to tune the colour of the resulting devices with a colour purity of almost 100 % (Figure 3c). This allows for BIPVs that may require a surface of a specific colour to be used in buildings so that the intended aesthetically pleasing effects can be created without limitations.

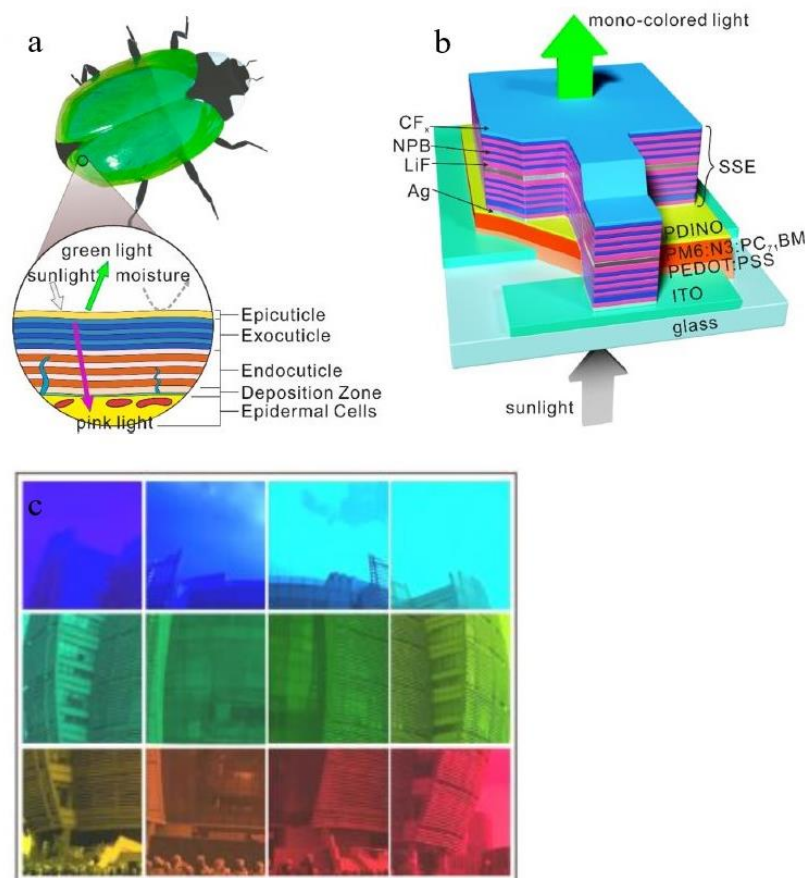


Figure 3. Beetles' cuticle inspired sTPVs. (a) Schematic of a beetle's cuticle. (b) Schematic of the spectrally selective electrodes. (c) Montage showing spectrally selective electrodes of different colours. Adapted with permission from [18]. Copyright 2020 American Chemical Society.

Another biological structure that has been successfully replicated in the field of bio-inspired PVs is the moth-eye. The corneas of many species of butterflies and moths exhibit nanostructures consisting of millions of nanometric-sized bumps (Figure 4), which act as a layer with gradually changing refractive index [23]. This structure provides them with anti-reflection capabilities, which improve their camouflage and night vision, and reduce eye wettability [23, 24]. By mimicking such structures, it is possible to improve the PCE of PV devices while also reducing light reflection, which in turn also lowers their light pollution impact for BIPV applications, as shown by the work of Zheng et al. [12].

In this study, they integrated a moth-eye biomimetic nanostructure into an organic semi-transparent solar cell, which resulted in a relative decrease of reflectance of 28 % (from 14.3 % for a flat device to 10.3 %) and an increase of PCE from 3 % to 3.4 %, with an AVT of 46.1 % (LUE=156.74).

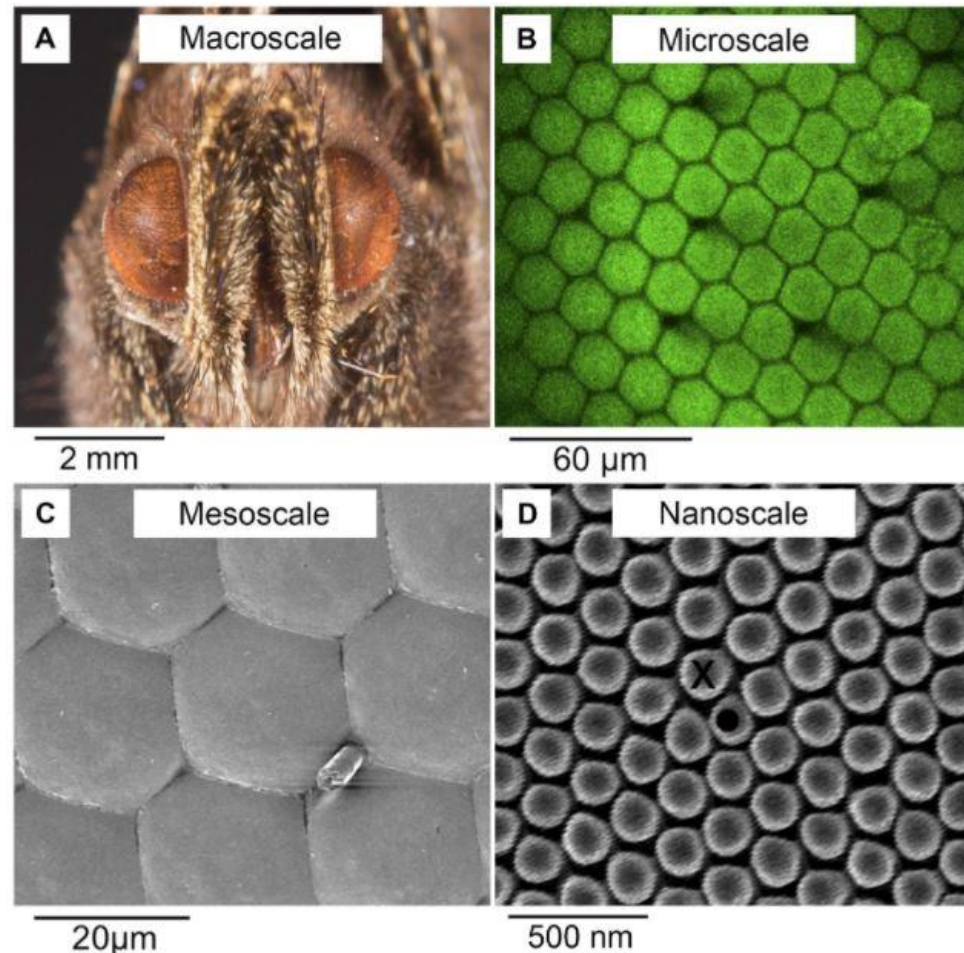


Figure 4. Structure of the eye of a Mourning Cloak butterfly (*Nymphalis Antiopa*). Image reprinted from Lee et al. [24] under license CC BY 4.0³

Another successful implementation of the moth-eye nanostructure in the development of an sTPV device has been presented by Zhu et al., who applied it to a perovskite solar cell [25]. In this work, the authors have developed a moth-eye inspired structure with light-trapping capabilities and reduced reflectance in the spectral region where the human eye is more sensitive (Figure 5).

By utilising this structure, a PCE of 10.53 % at an AVT of 32.5 % was achieved: this yields a LUE of 342.23, the state of the art for perovskite sTPVs as of May 2021. For comparison, the best non-transparent perovskite-based solar cells afford a PCE well over 20 % under AM1.5G illumination⁴.

In comparison, organic-based sTPVs can reach a PCE as high as 10.8 % with an AVT of around 50 % (which yields a LUE of 540), but the issue of photostability at higher temperatures might make them less well-suited for applications in warmer and high-humidity climates [26].

³ <https://creativecommons.org/licenses/by/4.0/>

⁴ Source: <https://www.nrel.gov/pv/cell-efficiency.html>

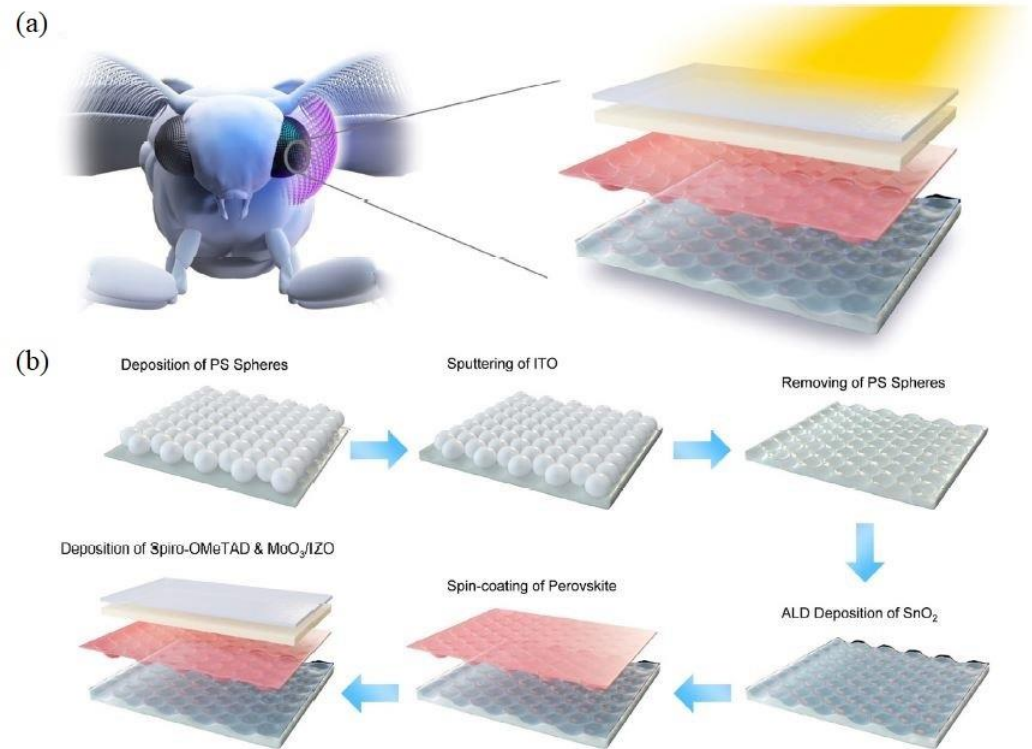


Figure 5. (a) Moth compound eye and schematic of the moth-eye inspired structure. (b) Illustration of the fabrication process of the sTPV device. Image reprinted from Zhu et al. [25] under license CC BY 4.0⁵.

3.2. Super-hydrophobic Surface Structuring for Stability

When considering large-scale commercial implementation of PVs, the three key factors to consider (or the “golden triangle” as termed by Meng et al.) are a low cost, a high PCE and a high stability, which translates to a long lifetime for the devices [27].

Both transparent and semi-transparent PVs are often required to operate outdoors, making their resistance to external factors such as humidity, dust, and staining agents an important characteristic for their successful implementation.

This is important in general for all types of photovoltaics: the presence of unwanted materials such as ice, snow, plant matter, and others that make the surface of a PV device dirty can lead to further reflection of light and loss in transparency, which in turn lowers the overall efficiency of the device [16, 28].

A promising way of addressing this problem is by utilising biomimetic super-hydrophobic coatings with self-cleaning capabilities [16, 29], especially since other technologies such as autonomous cleaning sensors are still at their infancy and have yet to reach commercial application.

A super-hydrophobic surface is commonly defined as one for which the contact angle of a drop of water on it is larger than 150° and its sliding angle (defined as the tilting angle of the surface at which the drop begins to slide on it) is lower than 5° [16], although a study conducted by Law suggests that 145° for the contact angle would be a better value for this definition [30]. When a drop of water is placed on such a surface, it rolls off very easily, generally carrying with it staining agents and cleaning the surface in the process, hence self-cleaning being a consequence of super-hydrophobicity.

It is worth pointing out, however, that super-hydrophobicity arises from a combination of chemical properties and high surface roughness, the latter being also a source of

⁵ <https://creativecommons.org/licenses/by/4.0/>

light-scattering: for this reason, super-hydrophobicity and anti-reflectance are competitive factors [31, 32], so a good balance between the two must be achieved for photovoltaic applications.

There are several examples of super-hydrophobic surfaces in nature: from the leaves of several species of plants [33], with the most well-known being the lotus leaf [34, 35], to insects' wings [36-39] and compound eyes [40, 41], including the already mentioned moth eyes [16, 33, 42].

An example of a biomimetic film with self-cleaning capabilities inspired by the latter can be found in the work of Ju et al. [43], in which a 170 nm high moth-eye pattern was fabricated on a 1.1 m wide PET film via roll-to-roll printing, making it suitable for large-scale photovoltaic applications (Figure 6). The resulting film was highly transparent, with an average transmittance in the visible of over 90 % and exhibited a contact angle of 140.3°; despite this value being lower than the one conventionally used to describe super-hydrophobic materials, the film still showed self-cleaning properties. The stability of these films was also tested in an oven at 60 °C and 80 % humidity: after 168 hours, the contact angle had only decreased to 139.8°, thereby demonstrating that the achieved super-hydrophobicity is stable even in relatively challenging environments. Furthermore, the implementation of the moth-eye pattern reduced the visible reflectance by 3.2 % and increased visible transmittance by 3.1 % on average compared to the bare PET film, thus improving performance for photovoltaic applications.

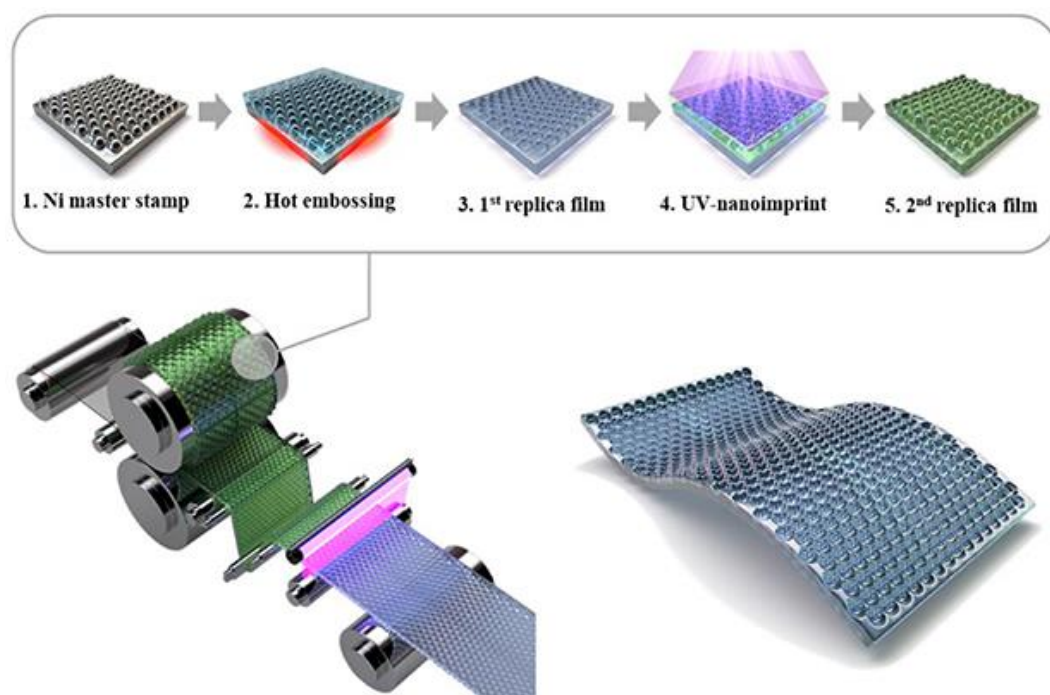


Figure 6. Schematic representation of the roll-to-roll printing process of the moth-eye film from Ju et al [43]. © IOP Publishing. Reproduced with permission. All rights reserved.

Another example of a transparent super-hydrophobic film can be found in the work of Bravo et al. [32], where the authors took inspiration from the lotus leaf. The super-hydrophobicity of this plant is a product of the presence of two levels of roughness (on the micrometric and on the nanometric scale); by applying this principle, a multi-layer film was fabricated utilising a mixture of 50 nm and 20 nm diameter SiO₂ nanospheres directly on a glass surface, with the aid of polymeric layers to promote adherence to the surface and homogeneity of the resulting film (Figure 7); the film was then treated with silane to change its surface chemistry and confer super-hydrophobicity. The fabrication method only required submerging the substrate various times in different aqueous

dispersions/solutions of nanospheres/polyelectrolytes, thus making it viable for large-scale applications. It is worth noting that different films were prepared with different numbers of nanosphere bilayers: the one achieving the highest AVT (around 90 %) was the one with 20 bilayers. This film also showed anti-reflecting capabilities, with a lowest reflectance of around 0.22 % at 562 nm and a highest value of 5.2 % at 710 nm, compared with a reflectance of around 8 % across all of the visible spectrum from the plain glass slide. If, however, an AVT value between 50-80 % is acceptable for the intended purpose, a larger number of bilayers can be applied, which in turn confers excellent super-hydrophobic features. Further studies are, however, required regarding the stability over time of these films. Furthermore, both the cited examples would benefit from a more extensive study regarding the permeability of the films to both oxygen and humidity, as these are detrimental factors to the performance of perovskite and organic photovoltaic cells. This kind of study would help in determining if they can also be used as encapsulant for such devices or if they should be added on top of more conventional encapsulation techniques.

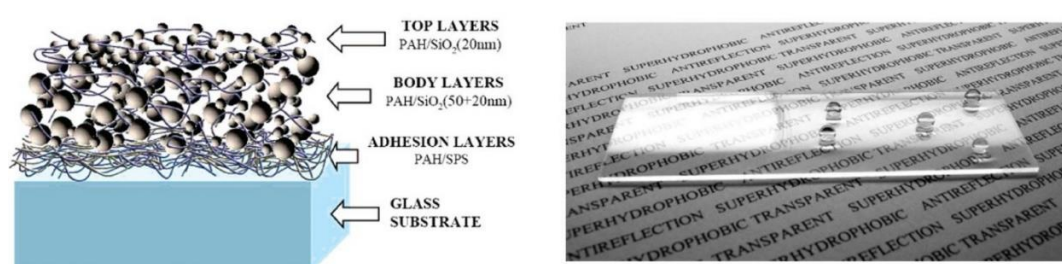


Figure 7. Schematic representation (left) of the transparent super-hydrophobic film and picture of a glass slide coated with it showing both its transparency and super-hydrophobicity. Adapted with permission from [32]. Copyright 2007 American Chemical Society.

4. Future Research and Applications

The natural world can be a source of inspiration for promising applications to (s)TPVs. There are numerous additional natural systems that could potentially open new lines of research in this field, one of them being silk fibroins.

Silks produced by spiders or silkworms are the strongest fibres found in nature [44], with mechanical properties comparable to those of steel or Kevlar [45]. Moreover, films made from silk fibroins extracted from the silkworm *Bombyx Mori* can exhibit an AVT of around 90 % [46], are highly bio-compatible [47], and are produced using only aqueous solution processing, usually at near room temperature and ambient pressure, making them a more eco-friendly alternative to other more conventional materials, often non-biodegradable and derived from non-renewable sources [48, 49].

Silk fibroin films have already been successfully used as a base for the fabrication of flexible, transparent substrates for OLEDs [49] and organic solar cells [50] by integrating a mesh of silver nanowires into the film (Figure 8). The resulting substrates exhibit an AVT of ~80 %, a sheet resistance of around 12 and 11 Ω/sq respectively, making them comparable with conventional ITO-coated PEN ones [49], and do not lose their conductivity after 200 bending cycles [50]. High bio-compatibility, high AVT, resistance to mechanical stress, and the possibility of conferring good conductivity to the film make silk fibroin-based materials an excellent candidate for the production of substrates for wearable devices, for which the direct contact with human skin makes bio-compatibility a fundamental requirement [50, 51], together with high transparency not detracting from the aesthetics of the final product. While on this topic, it is worth pointing out that silk fibroin-based materials can also be dyed by introducing selected dyes directly into the diet of the silkworms: this allows the production of intrinsically coloured or even fluorescent silk, making the dyeing process much more environmentally sustainable and reducing the amount of chemical waste produced [52-54], as well as making silk fibroin-based materials suitable for applications where a specific colour is required.

Despite possessing these attractive characteristics, to the best of our knowledge very little research has been done on the implementation of silk fibroin-based materials for transparent photovoltaics, making it a good candidate for future (s)TPV developments.

On the topic of future developments, we would like to point out how the peculiar features of (s)TPVs make them uniquely suited for several future applications.

Alongside the improvement on materials and fabrication techniques for cheaper production and viable large-scale applications for BIPVs, BAPVs, and VIPVs, there are other fields in which bio-inspired (s)TPVs could find future novel applications, like the aforementioned wearable devices, smart glasses, or even smart contact lenses with added functionalities like drug delivery and biosensing [55, 56].

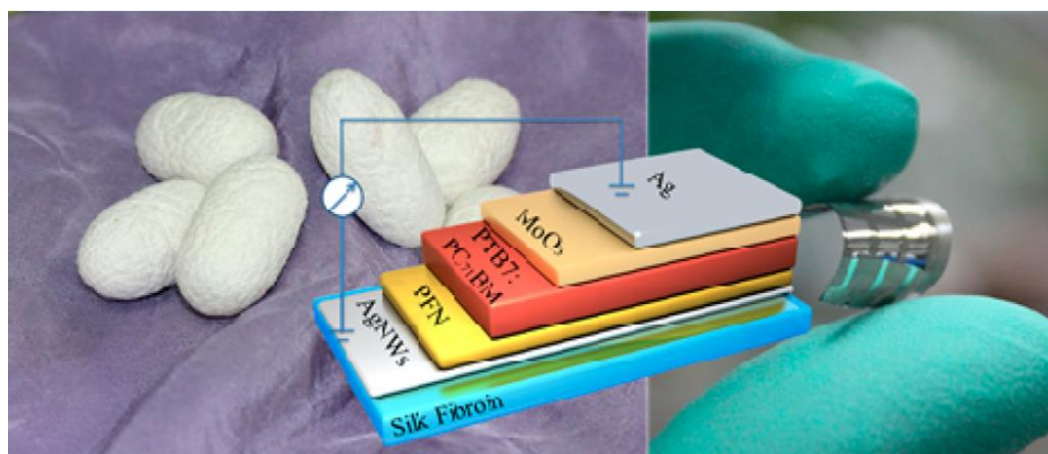


Figure 8. Bombyx Mori cocoons (left), schematic representation of the PVD (centre), and picture of the finished device (right). Reprinted with permission from [50]. Copyright 2014 American Chemical Society.

5. Conclusions

In this mini-review we have shown how a biomimetic approach to (s)TPVs can offer avenues to explore in the attempt to address the various key challenges in this field, by providing effective ways of improving the performance of devices without detracting from their aesthetics and making them more stable in non-controlled environments. New biomaterials can open new paradigms for research and applications in the field, such as fully bio-compatible (s)TPVs, while also providing a much greener approach to their fabrication.

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