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Design of an Architectural Element Generating Hydrogen Energy by Photosynthesis—Model Case of the Roof and Window

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Abstract: As is well known, the realization of a zero-waste society is strongly desired in a sustainable society. In particular, architectural elements that provide an energy-neutral living environment are attractive. This article presents the novel environmentally friendly architectural elements that generate hydrogen energy by the photosystem II (PSII) solution extracted from waste vegetables. In the present work, as an architectural element, the window (PSII window panel) and roof (PSII roof panel) were fabricated by injecting a PSII solution into a transparent double-layer panel, and the aging properties of the power generation and the appearance of these PSII panels are investigated. It was found that the PSII roof can generate energy for 18 days under the sun shining and can actually drive the electronic device. In addition, the PSII window, for which light intensity is weaker than that for the PSII roof, can maintain power generation for 40 days. These results indicate that the PSII roof and PSII window become the architectural elements generating energy, although the lifespan depends on the total light intensity. Furthermore, as an additional advantage, the roof and window panels composed of the semitransparent PSII panel yield an interior space with the natural color of the leaf, which gradually changes over time from green to yellow. Further, it was also found that the thermal fluctuation of the PSII window is smaller than that of the typical glass window. These results indicate that the roof and window panels composed of the PSII solution extracted from waste vegetables can be used as the actual architectural elements to produce not only the electrical energy but also the beautiful, transparent natural green/yellow spaces.

Keywords: architectural element; hydrogen energy; photosystem II

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1. Introduction

As a solution to global environmental problems, it is strongly desired to realize a "recycling-oriented society" by reconsidering "waste" as a "resource" and recycling it. As is well known, not only general garbage but also vegetables and the branches and leaves of trees that have been cut down are disposed of in large quantities, and the amount increases year by year [1,2]. For example, substandard vegetables are discarded in the agriculture and the food industries, and in the construction industry, trees are cut down for land development. Tree trunks are used as building materials in the forestry industry, but the leaves are discarded. Thus, although humans cannot live without trees, vegetables, and other plants, we throw away a lot of greenery in our daily life, including waste vegetables. A lot of this discarded greenery should be reused as a resource. In the energy field, environmentally friendly energy is required for next-generation energy [3–5], and research on renewable energy sources is conducted extensively. For example, there are many examples of the suse of renewable energy sources such as solar [6], wind [7], wave [8], tidal [9], hydroelectric [10], geothermal [11], and biomass for power generation [12]. However, many of these attempts to generate clean energy are simply placed inside buildings or function independently. For example, wind and tidal renewable energy facilities are built as structures that are completely separated from the living environment. In addition, photovoltaic panels are typically constructed independently on large parcels of land or are put on the roofs of buildings. In this way, there is no architecture that can generate energy directly from the windows and roofs themselves.

Recently, biomaterials have attracted attention as energy materials that can significantly reduce the environmental load. For example, there are several investigations such as biomass power generation [12], bioethanol fuel [13], bio-hydrogen production [14], and fuel cell electrolytes that use discarded biopolymers [15–20] and hydrogen fuel using the mechanism of photosynthesis [21,22]. Although there are examples of growing plants and algae on walls and rooftops, processing them in separate plants, reforming them into methane gas, and using them as energy [23], there are no examples of obtaining energy directly from plants integrated into architectures. In particular, there is no architecture that can not only directly produce energy from waste vegetables but also color the interior spaces of architecture with the natural colors of plants. If architectural components could beautify architectural spaces and directly produce energy, as we propose, we would be able to promote renewable energy in our daily lives further and create a disaster-resistant living environment. For example, as shown in the photograph in Figure 1, if these architectural components are applied to the roofs and windows of houses, it is possible to create energy and green spaces simultaneously as architecture without constructing large-scale facilities.

Figure 1. Photosynthetic architectural model [24].

Recently, we have developed a "photosynthetic screen" that functions as an indoor partition as a demonstration for use in interior elements [25]. Figure 2 shows a "photosynthetic partition" created by extracting photosystem II (PSII) from the chloroplasts of plants. This "photosynthetic partition" is composed of a silver ratio of 300 mm × 212 mm, a 150 mm × 106 mm transparent acrylic container (3 mm in thickness), and a PSII fuel cell integrated into this container, in which the PSII solution is injected. There is a hole at the top of the panel to release oxygen into the air. As shown in Figure 2, the three acrylic columns in the back allow for four sets of "photosynthetic panels" (PSII panels) to stand on their own, and each panel can be rotated. In addition, these panels can drive the clock, as shown in Figure 2. In this way, the "photosynthetic screen" is integrated with the photo-biofuel cell and becomes an interior element that creates a green space. The form of the screen evolved from a 100-year-old lacquered screen design by Irish architect and furniture designer Eileen Gray [26,27]. The natural green of the PSII-containing solution replaces the gloss produced by the Gray lacquer coating. The PSII panels rotate, and, by the angle of view, a three-dimensional space with complex gradations is produced. Thus, the light-transmitting PSII panels utilizing plant photosynthesis can be used as interior elements that produce energy and oxygen and further provide a living space that produces the original "color" and "light" of plants [25,28]. However, there are no experimental results on the use of PSII panels using vegetable waste as architectural elements. Since sunlight is an intense and unlimited source of energy, it is important to use sunlight.

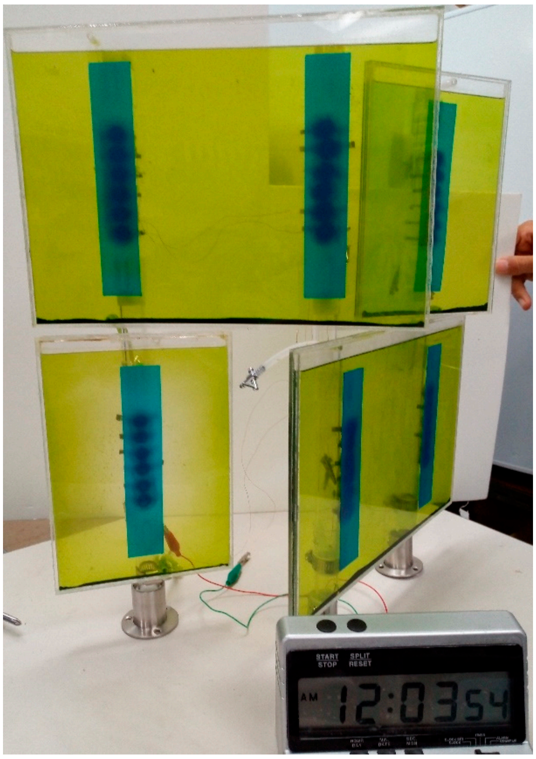

Figure 2. Photosynthetic partition.

More recently, by using the photosynthetic mechanism of waste vegetables, we have created architectural elements that simultaneously produce three elements—electrical energy, oxygen, and natural green beautiful space—and investigated the characteristics of the architectural elements. This paper reports on these results and demonstrates that roofs and windows utilizing the photosynthesis of waste vegetables can be used as new energy-generating architectural elements. This investigation will be helpful in the development of new energy-generating architectural elements for the next generation.

2. Materials and Methods

In this study, the roof (PSII roof) and window (PSII window), which possess the functions of energy generation by the PSII bio-fuel cell, were fabricated. In this section, we show the construction of the PSII panel, which becomes the base of the PSII roof and PSII window. Figure 3 shows a photograph of the PSII panel. As shown in Figure 3, the PSII panel consists of a collagen electrolyte fuel cell and a polycarbonate hollow plate with a thickness of 6 mm. The transparent sealant was used, and the collagen electrolyte fuel cell was attached to the polycarbonate hollow plate in order to prevent leakage of the PSII-containing solution. The hydrogen produced by the PSII-containing solution could be efficiently converted into energy. Fuel cells are known as a method to convert hydrogen into energy efficiently. Therefore, the PSII roof and PSII window panels are designed so that PSII-containing solutions are introduced into the hollow plate, and the hydrogen from the PSII-containing solutions can be used in a collagen electrolyte fuel cell installed directly on the polycarbonate hollow plate. The voltages generated by the PSII roof and PSII window panels were measured by a high-resolution electronic digital multimeter (DL-2060: TEXIO Technology Co., Ltd., Kanagawa, Japan) with a high-impedance input resistance.

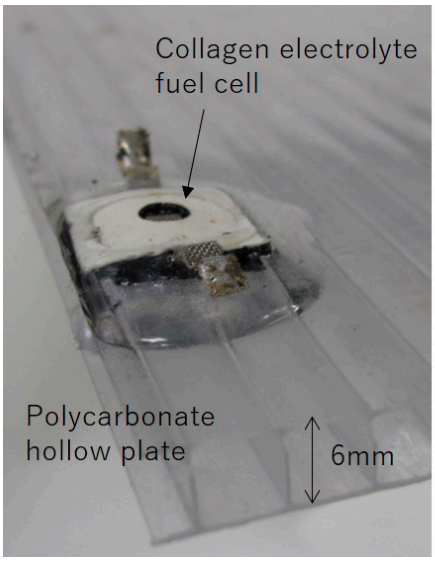

Figure 3. Shape of the photosynthetic panel.

2.1. PSII-Containing Solution

The PSII-containing solution provides the semitransparent green space and generates hydrogen fuel by light irradiation. Therefore, the PSII-containing solution is the most important material. As is well known, photosynthesis is a reaction that uses light energy to synthesize sugars from water and carbon dioxide. The thylakoid membrane in chloroplasts plays a central role in photosynthesis. In this membrane, there are membrane protein complexes such as photosystem I (PSI) and photosystem II (PSII) that are related to light absorption, electron and proton transfer, water splitting reaction, etc. Upon light irradiation, a water-splitting reaction occurs on the manganese cluster in PSII, and hydrogen ions, oxygen, and electrons are generated [29–31]. Therefore, we can obtain PSII-containing solutions that can generate hydrogen ions, electrons, and oxygen by separating PSII from the thylakoid membrane.

The PSII-containing solution was obtained from the waste spinach leaves in Figure 4a. The leaves were crushed in a pH7.0 phosphate buffer solution and filtered. The adjusting of the concentration of the PSII-containing solution was carried out by diluting the filtrated solution using a pH7.0 phosphate buffer solution.

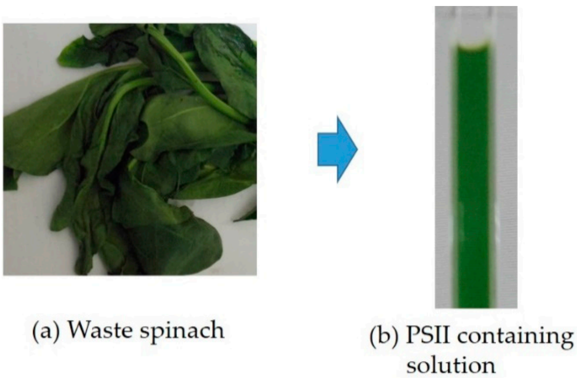

Figure 4. Extract of the PSII-containing solution.

The concentration was adjusted so that the chlorophyll concentration reached 15.6 μM. Then, the obtained PSII solution was mixed with the surfactant. The PSII solution can be obtained using the surfactant, as reported by Miyao, Shen, and Enami [32,33]. The present work used the 20 W/V% surfactants (Polysorbate 80: Nacalai tesque Inc., Kyoto, Japan) diluted with distilled water to obtain the PSII-containing solution. The obtained PSII-containing solution is shown in Figure 4b. As shown in Figure 4b, the PSII-containing solution has a beautiful semitransparent green color. The specific heat of the PSII-containing solution was estimated to be 3.97 J/g·K using the homemade adiabatic calorimeter. The obtained PSII-containing solution was injected into the anode of the PSII panels and used as fuel.

2.2. Collagen Electrolyte Fuel Cell

The fuel cell electrolyte used in this work is a collagen membrane obtained from the decalcified tilapia scales (Nitta Gelatin Inc., Osaka, Japan). The collagen membrane is recycled from the scales to be thrown away and is stable at temperatures up to 157 °C without softening [22]. The collagen membrane used as the electrolyte in the fuel cell is about 135 µm in thickness. Under the humidified condition, the collagen electrolyte exhibits proton conductivity by the transfer of protons (or H_3O^+) through the water bridges formed between the OH, CO, and NH groups of the side chains of the collagen peptide. Although the proton conductivity of the collagen is ~4×10^{-3} S/m and is smaller than that of ion-exchange membranes such as Nafion^{TM} [18,34], the hydrogen generation ratio per unit time in PSII is also not very high, and, therefore, the collagen electrolyte matches as electrolytes for PSII photo-biofuel cells.

Figure 5 shows a schematic diagram of the collagen electrolyte fuel cell. The collagen electrolyte fuel cell consists of a collagen electrolyte and electrodes made of stainless steel mesh plates and a Pt-C catalyst, as shown in Figure 5. In this work, hydrogen ions are directly introduced to the fuel electrode from the PSII-containing solution, and oxygen gas is filled from the air. For this purpose, a hole that was 4.5 mm in diameter was made in the polycarbonate hollow plate into which the PSII-containing solution was introduced, and a collagen electrolyte fuel cell was attached to the polycarbonate plate so that the PSII-containing solution contacted the collagen electrolyte and the anode of the fuel cell. When light is incident on the PSII-containing solution, hydrogen ions are generated in the PSII-containing solution, and the collagen electrolyte fuel cell operates. In this process, energy can be produced. In this way, the PSII roof and PSII window are new energy-generating architectural elements that can use hydrogen ions generated by the light irradiation to PSII-containing solutions as fuel without introducing hydrogen gas from the outside.

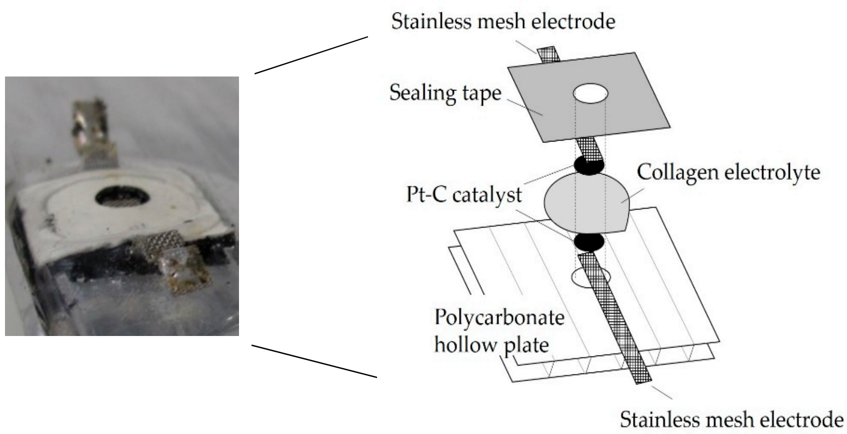

Figure 5. Collagen electrolyte fuel cell.

2.3. Measurement of Light Intensity and Temperature

The measurement of light intensity onto the PSII roof and PSII window was carried out using a photodiode (S2386-8K: Hamamatsu photonics K.K., Hamamatsu, Japan). The temperatures of the outside air and the internal space partitioned by the glass window, the PSII panel, and the slate roof, including the roof sheathing of the wood, were measured using the Cu-Constantan thermocouple. The values of light intensity and temperature were captured by the data acquisition system using the computer and an electronic digital multimeter (DL-2060: TEXIO Technology Co., Ltd., Kanagawa, Japan).

3. Results and Discussion

Figure 6 shows a photograph of the PSII roof and PSII window. The PSII window faces east and is set up perpendicular to the horizontal plane. On the other hand, the PSII roof is tilted at an angle of 30 degrees for the horizontal plane. Therefore, the amount of light irradiation remarkably differs between the PSII roofs and PSII windows. The collagen electrolyte fuel cell was installed near the top of the PSII roof and PSII window, as shown in Figure 6. The properties of the PSII roof and PSII window have been investigated based on the configuration in Figure 6. In addition, the panels are designed to allow oxygen to return to the air by opening air holes at the top of the panels.

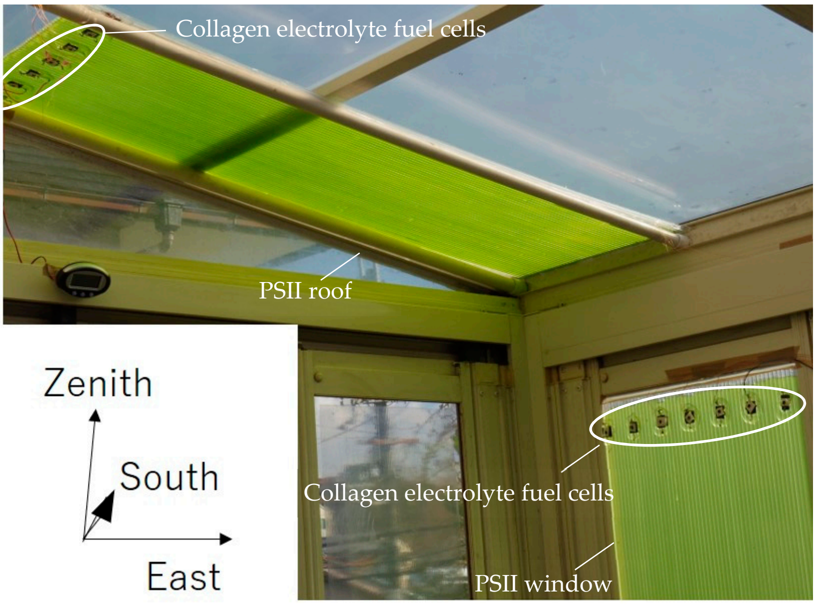

Figure 6. Photograph of the PSII roof and the PSII window.

As shown in Figure 6, the spaces created by the PSII roof and PSII window become beautiful, colored spaces formed by the transmitted light. Furthermore, the PSII roof and PSII window can produce energy. Figure 7a,b show the situations driving the digital clock by the PSII roof or PSII window, respectively.

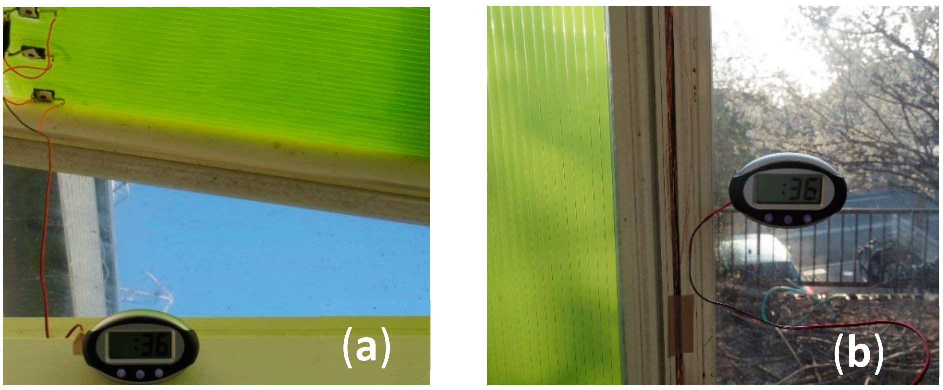

Figure 7. Photograph for the driving of the digital clock by the PSII roof (**a**) and PSII window (**b**).

As shown in Figure 7, both the PSII roof and PSII window can drive the digital clock by connecting three single cells in series. These results indicate that the PSII roof and PSII window can be actually used as the roof and windows to produce energy.

In order to investigate the voltage created by the PSII roof and PSII window, we measured the change in the open circuit voltages (OCVs) generated from the PSII roof and PSII window in one day. The open circuit voltages are obtained from the biofuel cell installed near the top of the PSII roof and PSII window. Figure 8 shows the time dependence of the OCVs in one day.

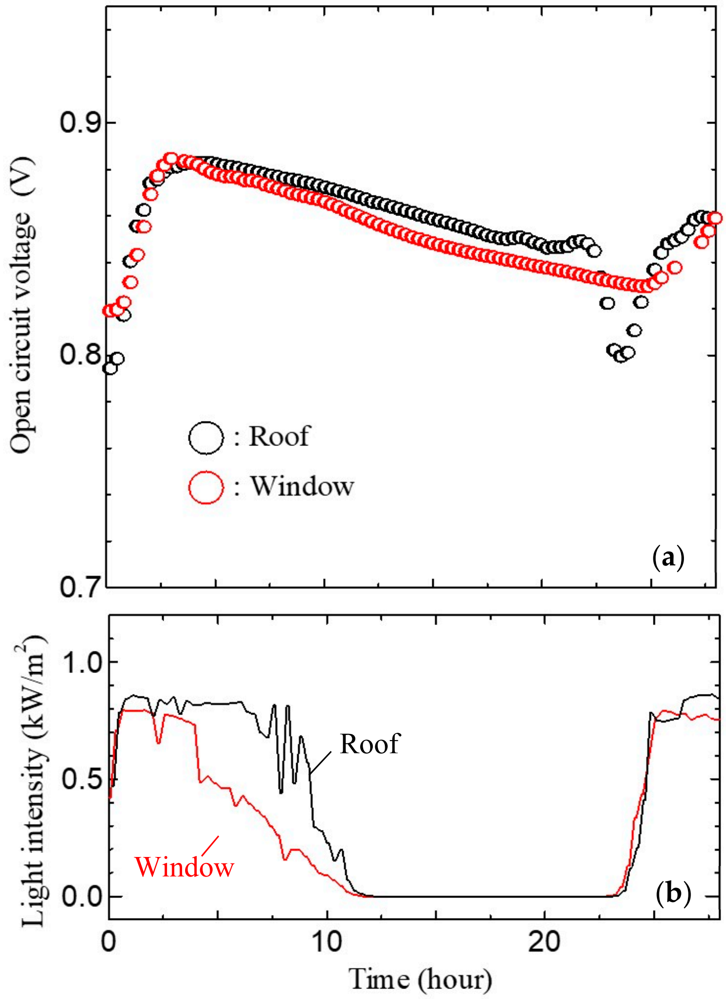

Figure 8. Typical time dependence of daily OCVs (**a**) and light intensity by sunshine (**b**).

The open circuit voltages of the PSII roof and PSII window begin to increase at sunrise and increase until ~0.88 V. These results indicate that the PSII roof and PSII window generate electricity by irradiating the sunshine. As shown in Figure 8, OCVs decrease at night due to the power generation from only the dissolved hydrogen ions remaining in the PSII-containing solution and begin to increase by the hydrogen generation due to the light irradiation at sunrise again.

Figure 9a shows the time dependence of the temperature of the outside air and the internal space partitioned by the glass window, PSII panel, and slate roof. Here, Figure 9b shows the time dependence of the light intensity. As shown in Figure 9a, the temperature of the internal space partitioned within the window glass increases rapidly with daylight irradiation and decreases rapidly with shade. On the other hand, in a typical Japanese roof (denoted as a "slate roof") composed of slate tiles and roof sheathing of wood, the temperature change in the daytime is small due to the shielding of daylight irradiation by the slate roof, and even in the shade, the temperature fluctuation is small. The temperature fluctuations in the internal space partitioned by the PSII panels are intermediate between those of the glass windows and the slate roof. It is speculated that the temperature increase due to the light irradiation in the internal space by the PSII panel is suppressed compared with that by the glass windows due to the light shielding of the PSII-containing solution and that the temperature decrease at night is reduced due to the specific heat (3.97 J/g·K) of the PSII solution, which is larger than that of the glass windows (~0.8 J/g·K [35]). Thus, the application of the PSII panel to the window can prevent indoor temperature fluctuations compared with the glass window. Further thermal analyses on the thermal shielding, insulation, and these influences on the living environment will appear in future issues.

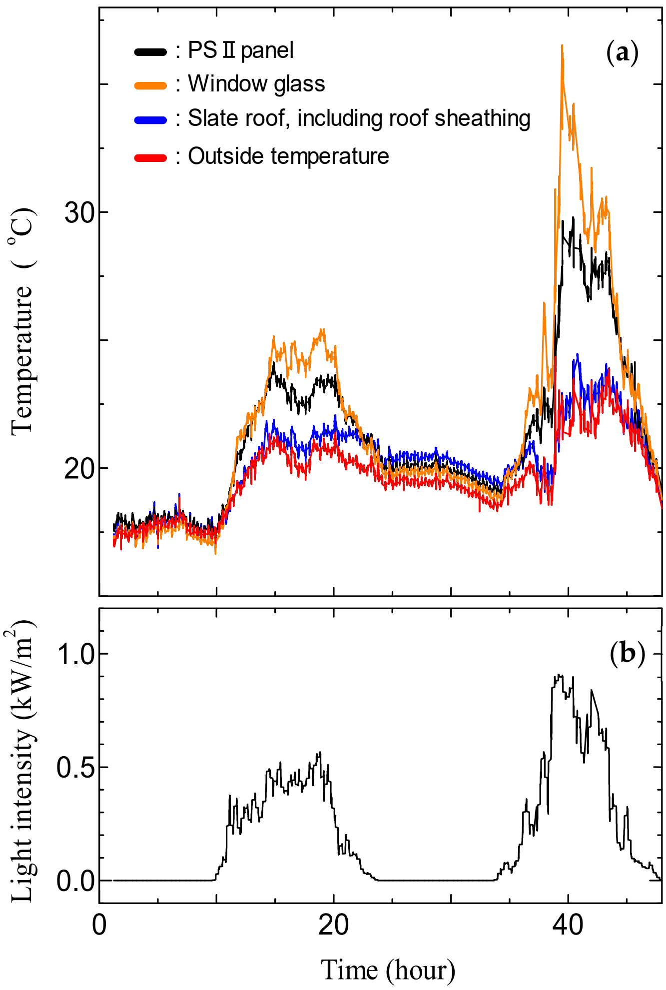

Figure 9. Typical daily temperature change of the front and back surfaces of the PSII roof (**a**) and light intensity by sunshine (**b**).

Figure 10 shows the time dependence of the color of the PSII window. As shown in Figure 10, the PSII window projects a green/yellow scene indoors. The green PSII solution changes to light green after 9 days. After 12 days, the light green color gradually changes to a light yellow-green, as shown in Figure 10f, allowing the viewer to sense the transition of nature over time. After 40 days, the color of the PSII window approaches transparency, but the clock is still driving, as shown in Figure 10h. Thus, using the PSII window makes it possible to create an architectural space where we can experience the original coloring of plants while generating energy for at least 40 days. In addition, by mixing green and yellow panels, it will be possible to create a space that resembles an autumn forest in color.

Figure 10. Time dependence of the color of the PSII window.

On the other hand, the color change of the PSII roof is different from that of the PSII window. Figure 11 shows the time dependence of the color of the PSII roof. As shown in Figure 11, the PSII roof also projects a green/yellow scene indoors. The PSII solution of green color changes to semitransparent light yellow after 18 days, and the clock is still working, as shown in Figure 11h, although the clock stops after 19 days.

Thus, the PSII roof can be used as an architectural space that generates the energy needed to drive the clock for at least 18 days and also produces the original colors of the plants—although, in the PSII roof, the time maintaining the green color becomes shorter compared with the time in the PSII window. It is also noted that the time dependence of the color in the PSII roof is remarkably different from that in the PSII window. It is important to note that the light intensity on the PSII roof is different from that of the PSII window. In order to investigate the difference in color between the PSII roof and PSII window, we have plotted the relationship between the sum of light intensity and the OCVs. Figure 12 shows this result. Here, the OCVs of the PSII roof and PSII window are the average daily value. As shown in Figure 12, the OCVs of both the PSII roof and PSII window are nearly constant up to a total light intensity of about 30 kWh/m^2 but decrease by further increasing light intensity. These results indicate that light irradiation above about 30 kWh/m^2 decreases the activity of hydrogen generation by the PSII-containing solution. The days corresponding to 30 kWh/m^2 of light intensity of the PSII roof are 4.4 days. On the other hand, the days of the PSII window are 8.9 days. Comparing the color of these days in the PSII roof and PSII window, this day corresponds to the day that the color starts to change from green to light yellow-green. From these results, regardless of the PSII roof and PSII window, it is suggested that the PSII-containing solution should be replaced at about 30 kWh/m^2. In addition, the driving of the digital clock can be realized until 40 days for the PSII window and 18 days for the PSII roof. The light irradiation of 40 days for the PSII window and 18 days for the PSII roof corresponds to the total light intensities of 120 kWh/m^2 and 135 kWh/m^2, respectively. These results indicate that we can use the energy to drive the digital clock up to the total light intensity of 120 kWh/m^2. It is expected from these results that the architecture element based on the waste plant can be a future-oriented building element that provides an energy-neutral living environment. In addition, the results demonstrate that both transparent green spaces and energy production can be achieved by the PSII roof and window, which can obtain new architectural products for unitized roofs and windows that yield energy, oxygen, and transparent natural green to yellow colors.

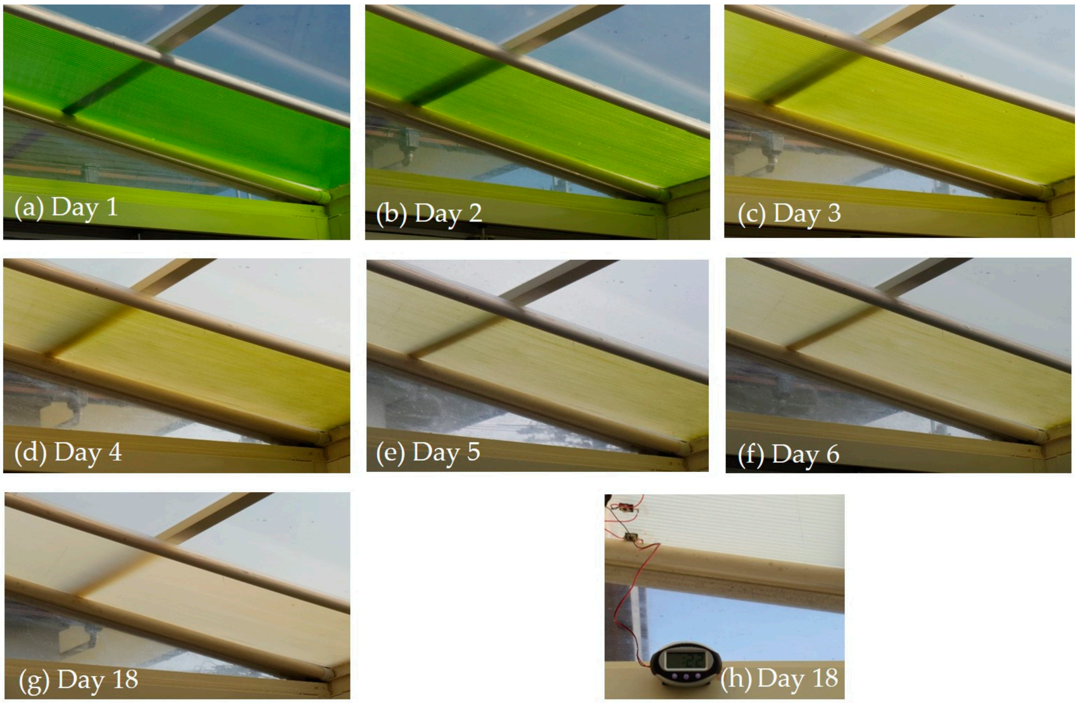

Figure 11. Time dependence of the color of the PSII roof.

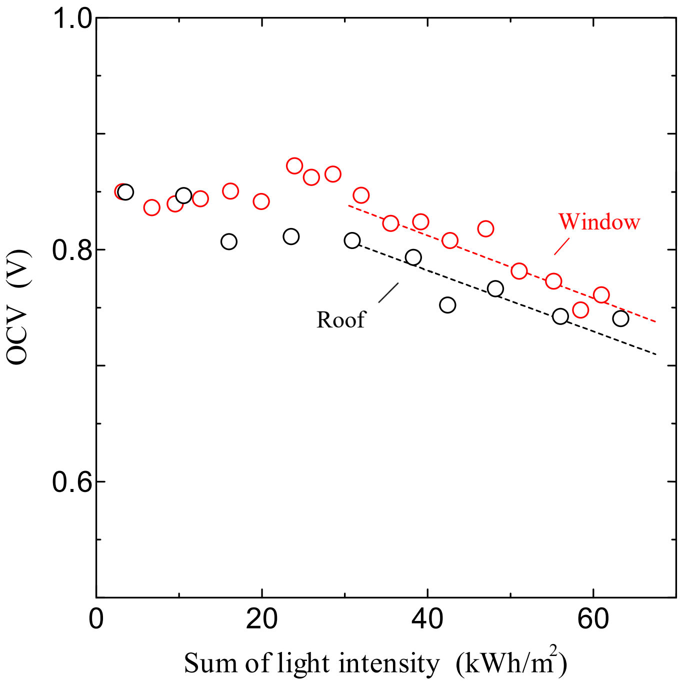

Figure 12. Relation between the OCVs and the sum of light intensity in the PSII window.

When we want to enjoy the green/yellow color of the photosynthetic panels for a long period, it is recommended to use photosynthetic panels on windows and walls with a low intensity of irradiation.

Finally, we roughly estimate the energy payback time (EPT) of the PSII panel. It is known that the hydrogen generated from the PSII-containing solution of 5 cm^3 generates about 7.64×10^{14} number/s by the light irradiation of the intensity of 0.5 mW/cm^2 [22]. Using this value and Faradays' second law, we can estimate the power density of the PSII panel at 1 m^2, assuming that the hydrogen generation number is proportional to the light intensity. The energy generated in the PSII panel at 1 m^2 (6 mm in thickness) per day is calculated to be 948 kJ/day under the condition of the light irradiation of the intensity of 0.8 kW/m^2 for 7 h. The embodied energy of the PSII panel can also be estimated. As shown in Figure 5, the PSII panel consists of a polycarbonate plate and a fuel cell. The cradle-to-grave non-renewable energy use of polycarbonate is known to be 111 MJ/kg [36]. Therefore, we can estimate the energy to be 1.39 MJ with a mass of 1.25 kg of the polycarbonate plate. The fuel cell is composed of platinum and graphite (Pt-C catalysis), stainless mesh, plastic adhesive, and collagen electrolytes of fish scale. The embodied energies of the platinum, graphite, and stainless plate are 212 MJ/g [37], 0.16 MJ/g [38], and 0.143 MJ/g [39], respectively. The embodied energy of the plastic adhesive is substituted with that of 0.086 MJ/g of plastic [39], and the embodied energy of the fish scale is assumed as zero because the fish scale is obtained as the rest of the fish dish. Considering the mass of these materials, we can estimate that the embodied energy of the fuel cell becomes 1223 MJ. In addition, the use energy per year of the PSII panel of 1 m^2 is estimated to be 33.9 MJ/year, considering the crush energy of 0.25 MJ of waste leaves and the exchange energy of 0.58 MJ of the PSII solution every 8.9 days. Furthermore, the energy in the disposal phase of a 10 W fuel cell can be estimated to be 44.7 MJ by substituting using the value of 1/10 of the disposal energy in a 100 W fuel cell [40]. Considering that the PSII solution can be disposed of in the sewage, the total EPT is roughly estimated to be 4.5 years using the above energies. The lifetime of the main body of the PSII panel will be determined by the polycarbonate and the fuel cell. It is known that the lifetimes of the polycarbonate and the fuel cell are about 15 years [41] and 4.6 years (40,000 h), respectively [42,43]. These values are longer than that of the estimated EPT. This result indicates that the PSII panel has the potential to be actually used as the energy-generating architecture element in various places. In addition, we can roughly compare the power generation between the typical photovoltaic panel (PV) panel and the PSII panel. As is well known, the power generation of a typical PV panel per 1 m^2 is approximately 200 W [44]. In contrast, the estimated power of the PSII panel per 1 m^2 is estimated at about 37.6 W, and this value is about 5.3 times lower than that of the typical PV panel per 1 m^2. On the contrary, the product cost of the PSII panel per 1 m^2 is approximately USD 50, assuming that the cost for the production of the PSII solution from waste vegetables can be negligible. This cost is five times lower than that of the PV panel (~USD 250) [45]. That is, the ratio of power per the cost of the PSII panel is almost the same compared with that of the PV panel. In this way, the PSII panel has benefits such as low cost, zero-emissions, transparent green space, the production of oxygen, and environmentally friendly energy, although the power density is low compared with that in the typical PV panel. The determination of the suitable conditions for the fuel cell configuration, such as the number of fuel cells and the area of the fuel cell electrodes, is necessary to obtain the precise calculations of EPT and cost. After determining these conditions, the investigation concerning EPT, with the cost, the oxidation condition, and the emissions of CO_2, will be carried out in the future.

In this way, photosynthetic architecture has the potential to be the next-generation energy for creating new architectural spaces in various places. We are currently adjusting the type and composition of surfactants to further improve the long-term driving of the PSII roof and PSII window. These results will also be revealed in a future issue.

4. Conclusions

In this study, architectural elements (PSII roof and PSII windows) fueled by a PSII-containing solution extracted from waste vegetables were fabricated. Their characteristics were investigated to realize an energy-neutral living environment. It was found that the PSII panels have been successfully produced using the PSII-containing solution extracted from waste vegetables, and these panels can produce energy. In particular, the energy generation in this study does not require complex processes such as extracting methane gas or ethanol from plants but simply uses the function of photosynthesis, and, therefore, energy can be obtained very cheaply and efficiently from waste vegetables. This result indicates that the PSII panels have advantages compared with other architectural elements such as “BIQ houses” [23] and “the bio-digital curtain,” [46] which consist of injected algae in windows or curtains and produce O_2 but cannot extract energy directly. It was also found that the PSII window and PSII roof panels are sufficiently usable, as the color of the PSII panel changes from yellowish-green to yellow, but the power generation capacity almost does not decrease at all during the total light intensity up to 30 kWh/m^2, and the color of the PSII panel keeps its green color. Moreover, although the color faded over time, it was found to generate electricity that can drive the digital clock up to a total light intensity of at least 120 kWh/m^2. These results suggest that the use of PSII panels on roofs and windows to generate energy through photosynthesis is feasible in waste vegetables. Furthermore, the application of the PSII panel to the window can reduce the temperature fluctuation indoors compared with the glass window. In addition, the EBT of the PSII panel was roughly estimated to be 4.5 years. In this way, the present method is expected not only to create beautiful interior spaces but also to be applied to distributed power generation in each house. Figure 13 shows an example of the architectural model with photosynthetic panels applied to the walls [47]. Thus, photosynthetic panels will apply not only to windows and roofs but also to walls.

Figure 13. Architectural model with photosynthetic panels applied to the walls.

In Figure 14, we show the future framework of this study. The PSII panels proposed in this work can be applied to architectural elements such as roofs, windows, walls, and so on. Therefore, as shown in Figure 14, PSII panels will lead to the architectures that generate energy and oxygen through photosynthesis. In addition, it is expected that, in the future, the apartment complex of photosynthetic architectures will be formed, and then cities that generate energy through photosynthesis will be created. In this way, the development of the present work will contribute to the realization of a sustainable society as a future energy source.

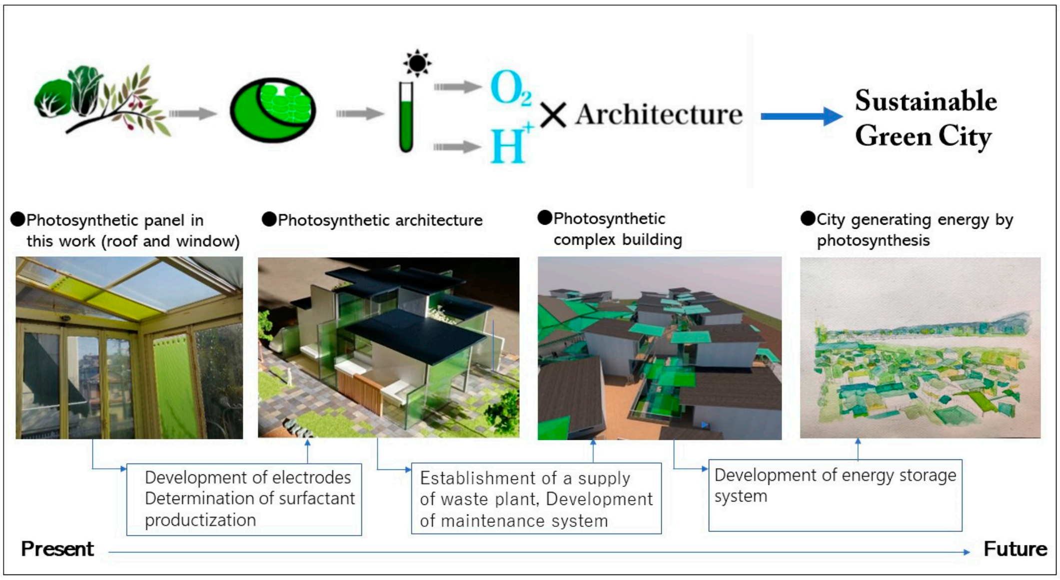

Figure 14. Framework of the benefits in the PSII panel.

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