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ORIGINAL PAPER

Biophotofuel cell (BPFC) generating electrical power directly from aqueous solutions of biomass and its related compounds while photodecomposing and cleaning

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Abstract A biophotofuel cell (BPFC) generating electrical power directly from aqueous solutions of biomass and its related compounds with simultaneous photodecomposition and cleaning was investigated. The BPFC had a nanoporous TiO_2 photoanode and an O_2-reducing cathode. As long as the compounds were either liquid or water-soluble they were photodecomposed and generated electrical power simultaneously. Various biomasses and related compounds such as glucose, amino acids, polysaccharides, proteins, lignin derivatives, cellulose derivatives and some polymers were investigated in the BPFC. Glucose was photodecomposed almost completely into CO_2 under O_2 within 20 h while generating electrical power. The incident photon-to-current conversion efficiency (IPCE) value of a 0.5 M glucose solution in the BPFC under O_2 was 29% based on the incident monochromatic light at 350 nm (intensity 3.6 mW cm^{-2}). A glycine aqueous solution could be decomposed photochemically into CO_2/N_2 in a nearly stoichiometric 4:1 (CO_2:N_2) molar ratio. The photodecomposition yield of 0.01 wt% lignosulfonic acid sodium salt was 86.5% in 24 h as estimated from the CO_2 evolved. The cellulose (sulfate) gave similar BPFC characteristics under air as under 1 atm O_2. Among the compounds the highest V_{oc} (open circuit voltage) value was 0.90 V for glutamic acid and phenylalanine.

Keywords Nanoporous titanium dioxide film · Biophotofuel cell (BPFC) · Biomass · Biomass related compound · Photoelectrochemical decomposition

1 Introduction

Biofuels that can be produced from biomass such as cornstarch, bagasse and lignocellulose derived from woods are attracting a great deal of attention as alternative fuels [1, 2]. However, the production of biofuels is an energy-consuming process so that the net energy acquired by the biofuels is not large enough to reduce CO_2 emission [3]. In addition to this, the environmental pollution by many biowastes such as livestock and human wastes, wastes from agriculture, industries, etc. is a big issue, which requires urgent solution. Since these biowastes are energy-rich (total biowastes in the world (ca. 130 EJ y^{-1}) corresponding to 1/3 of the world energy demand (400 EJ y^{-1}), the energy should be recovered and used simultaneously while decomposing and cleaning them. From these points of view, the present authors are interested in direct photoelectrochemical decomposition and energy conversion of biomass and its related compounds generating electrical energy, as one of the most feasible candidates for simultaneous environmental cleaning and energy conversion systems.

Photoelectrochemical reactions using semiconductor electrodes have been investigated since the work of Gerischer [4] and other groups. The photoelectrochemical reaction at a crystalline n-TiO_2 photoanode photodecomposed water by UV light under potential-controlled conditions [5]. Since then, crystalline n-TiO_2 photoanodes have been used to decompose many organic compounds [6–9]. At the TiO_2 surface, the holes produced by

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irradiation oxidize water or organic compounds, and simultaneously the photogenerated electrons reduce H^+ to produce H_2 at a counter electrode. A dye-sensitized solar cell (DSSC) was developed in the early 1990s. The cell is composed of a nanoporous TiO_2 film sensitized with ruthenium bipyridyl dyes and redox electrolytes (I^-/I_3^- solution). The TiO_2 film photoanode works not only as an acceptor for the photoexcited dye, but also as an electron conducting material [10–20]. We have proposed a biophotofuel cell (BPFC) that can generate electrical power by using a nanoporous TiO_2 photoanode and an O_2-reducing cathode [21]. Although the BPFC can utilize only UV light, which is a minor fraction of solar irradiation, the cell can be utilized to photodecompose and clean various biomasses while recovering electrical energy from such wastes. A photoelectrochemical biofuel cell composed of a porphyrin-sensitized nanoparticulate TiO_2 (or SnO_2) film on a conducting glass (photoanode), NADH/NAD redox pair, an enzyme, an ion-permeable membrane and a counter electrode soaked in a glucose (ethanol or methanol) aqueous solution (fuel), was reported previously [22, 23]. However, in these reports O_2 could not be used as electron acceptor at the cathode so that the system is not defined as a fuel cell.

In the present paper we investigated BPFC by using various biomass models and their related compounds derived from biomass resources such as polysaccharides, amino acids, polypeptides, cellulose paper, and synthetic polymers, and report cyclic voltammograms (CV) and BPFC characteristics of these compounds.

2 Experimental

2.1 Materials

Titanium dioxide (P-25, particle size, ca. 21 nm; specific surface area, 50 ± 15 $m^2 g^{-1}$) was received from Japan Aerosil Co. Ltd, and titanium dioxide (F-5, particle size 20 nm; specific surface area, 60–85 $m^2 g^{-1}$) from Showa Denko Co. Ltd. Sodium sulfate, phosphoric acid, glutamic acid, glucose and platinum black were purchased from Kanto Kagaku Co. Ltd and glycine from Junsei Chemical Co. Ltd. Tyrosine, cysteine and phenylalanine were purchased from Tokyo Chemical Industry Co. Ltd, agarose from Acros and gelatin from Sigma. Curdlan and polyethylenglycol (PEG) were from Wako Pure Chemical Co. Ltd, Triton X-100, polyacrylamide (PMA) and hexachloroplatinate from Kishida Chemical Co. Ltd and amylopectin from Fluka. Cellulose sulfate was purchased from Scientific Polymer Products, Inc, lignosulfonic acid sodium salt from Aldrich Co. Ltd, and collagen from Nitta Gelatin, Inc. Ar gas (purity > 99%) was obtained from Nippon Sanso Corp. These chemicals were of the purest grade available and used as received. F-doped SnO_2 conductive glass (FTO, surface resistance, 10 Ω/(sq) was received from Asahi Glass Co. Ltd.

2.2 Preparation of nanoparticulate TiO_2 films

A conventional TiO_2 film was prepared with P-25 or F-5 as follows: 12 g TiO_2 (P-25 or F-5) and acetylacetone (0.4 mL) were mixed well while adding 4 mL water slowly for 2 h. Triton X-100 detergent (0.2 mL) was added and further mixed well with the TiO_2 slurry followed by sonication. This mixture was spin-coated at 2,000 rpm on an FTO electrode (2 cm × 1 cm) for about 10 s to obtain 1 cm × 1 cm area of a nanoporous TiO_2 film, and the film was dried at 100 °C for 30 min. This procedure was repeated until the film thickness became 10 μm, and then the film was finally calcinated at 450 °C for 30 min.

2.3 Measurements

As an example glucose was used as the compound photodecomposed by a nanoporous TiO_2 film photoanode. The cyclic voltammogram (CV) was measured as follows. The TiO_2 film electrode (1 cm × 1 cm), a Pt-black coated Pt plate cathode (Pt-black/Pt) (1 cm × 1 cm), and a Ag-AgCl reference electrode were soaked in a 5 mL of glucose aqueous solution (from 1 mM to 0.63 M, pH 5 or 12) in a 10 mL cylindrical cell made of Pyrex glass containing 0.1 M Na_2SO_4 electrolyte. O_2 gas was bubbled into the solution for 30 min and the TiO_2 film was irradiated from the FTO side with a 500 W xenon lamp with a light intensity of 450 mW cm^{-2}. A solar simulator (Peccell Technologies Co. Ltd.) was also used under AM 1.5 and 100 mW cm^{-2} irradiation conditions. A cylindrical reactor (Pyrex glass cell) was sealed with a rubber septum, through which the gas phase was sampled by a syringe. A sample aliquot of 100 μL gas was taken for analysis. The N_2 gas evolved was analyzed by gas chromatography (Shimadzu, GC2014) with a 5A molecular sieve column at 40 °C under Ar carrier gas. CO_2 was analyzed with a silica gel column. All the photoelectrochemical measurements and reactions were performed at 25 °C.

The J–V characteristics of the photofuel cell (PFC) were measured by a two electrode system, i.e., with a nanoporous TiO_2 photoanode and a Pt plate cathode soaked in an aqueous solution of the fuel compound at 25 °C.

3 Results and discussion

The CV under 1 atm O_2 atmosphere at an FTO/nanoporous TiO_2 (P-25) film photoanode soaked in a 0.63 M glucose aqueous solution (pH 12) in the dark and under irradiation at 25 °C is shown in Fig. 1. After the CV curve under irradiation increased gradually with time, it tended to reach a constant value, showing that a steady state photoanodic current was generated. The CV under irradiation exhibited some hysteresis indicating that a slow electrochemical step is involved, most probably of a multi-electron nature either in glucose oxidation or O_2 reduction. Figures 2(a) and (b) show the typical characteristics of PFC in 0.5 M and 0.05 M glucose solutions at pH 5, respectively, with the FTO/TiO_2 (P-25) film photoanode and a Pt-black/Pt cathode under 1 atm O_2 atmosphere at 25 °C, and the results are summarized in Table 1 giving V_{oc} (open circuit voltage), J_{sc} (short circuit current density) and FF (fill factor). The FF means the ratio of a real maximum electrical power output per theoretical maximum output (= $V_{oc} \times J_{sc}$) estimated from the J–V curve (Figs. 2(a) and (b)) under irradiation. For the estimation of the V_{oc} and FF values, the average of the anodic and the cathodic scans was adopted. V_{oc} was little dependent on glucose concentration, but the J_{sc} was higher when the glucose concentration was lower. Since V_{oc} is determined by the conduction band energy level (E_{cb}) and the O_2 reduction potential, it is reasonable that V_{oc} is almost independent of the fuel concentration. That higher glucose concentration induced lower photocurrent may be ascribed to the higher viscosity of the solution and therefore slower diffusion of the fuel molecules in the nanopores of the TiO_2.

Table 1 Photofuel cell (PFC) characteristics of glucose solutions (pH 5.0) under O_2 atmosphere, irradiated by Xe lamp (450 mW cm^{-2})

Glucose (conc./M)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
0.50	0.64	0.50	0.32
0.05	0.60	0.80	0.20

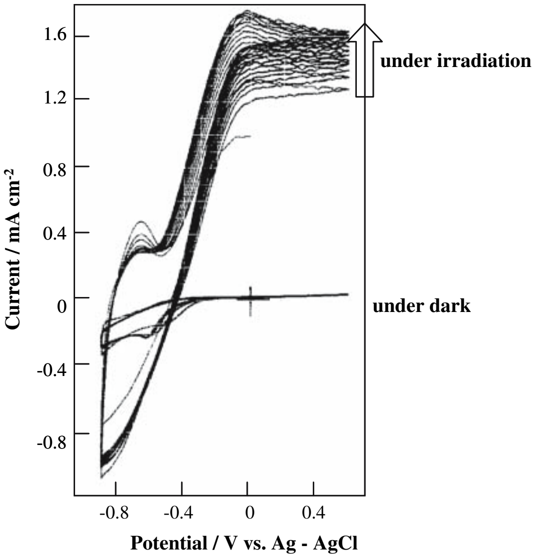
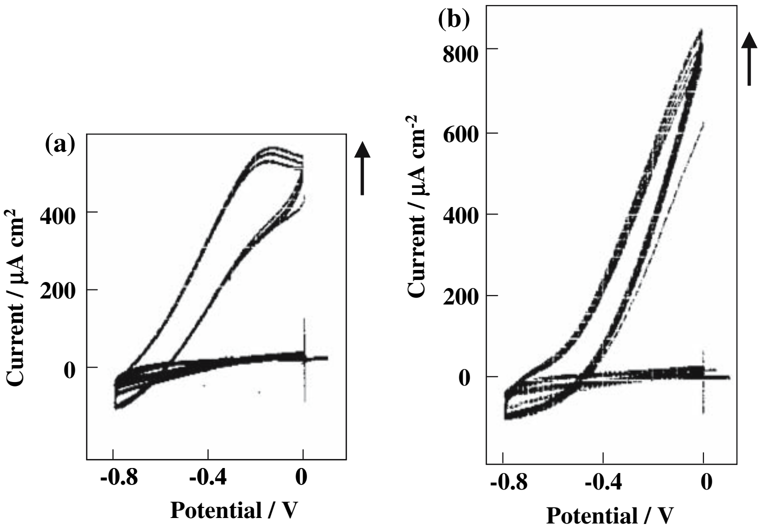


Fig. 1 Cyclic voltammograms of glucose (0.56 M) in an aqueous solution (pH12) containing Na_2SO_4 (0.1 M) under O_2 by using FTO/TiO_2(P-25) photoanode, Pt/Pt black cathode and Ag/AgCl reference electrode. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.9 → 0.6 → 0; scan rate, 10 mV s^{-1}

CO_2 gas was evolved during the photoelectrochemical process due to the decomposition of glucose with simultaneous consumption of O_2 in the glucose PFC. To compare the difference in the kind of TiO_2 particles, two TiO_2 particles, P-25 (particle size: ca. 21 nm; specific surface area: 50 ± 15 $m^2 g^{-1}$) and F-5 (particle size 20 nm; specific surface area: 60–85 $m^2 g^{-1}$), were used. The decomposition rates of a 1 mM glucose solution in the PFC using these two TiO_2 particles are shown in Fig. 3. The figure shows that both the TiO_2 exhibit a similar trend within the data scattering, suggesting that the specific surface area did not influence the photodecomposition rate at the 1 mM

Fig. 2 PFC characteristics of glucose in an aqueous solution containing Na_2SO_4 (0.1 M) by using FTO/TiO_2(P-25) photoanode, Pt/Pt black cathode under O_2: (**a**) Glucose, 0.5 M; (**b**) Glucose, 0.05 M. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.8 → 0; scan rate, 20 mV s^{-1}



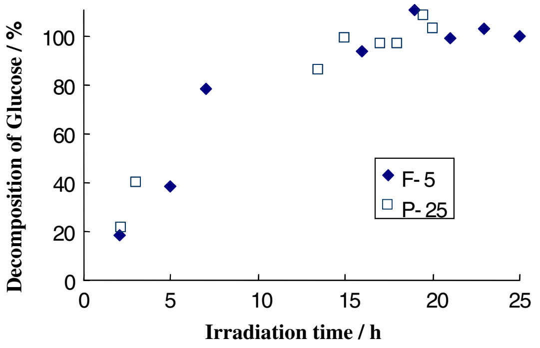


Fig. 3 Decomposition rate of a 1 mM glucose aqueous solution in PFC using FTO/TiO_2(P-25) photoanode, Pt/Pt black cathode under O_2, irradiated by Xe lamp (450 mW cm^{-2})

concentration level. Within 20 h irradiation the glucose was almost completely decomposed in both cases.

The incident photon (on the cell glass)-to-current conversion efficiency (IPCE) of a 0.5 M glucose solution in the PFC under O_2 was investigated and the result is shown in Fig. 4. The transmittance of the cell glass is also shown in Fig. 4. Unlike a quartz cell (transparent over 200 nm), the present Pyrex glass cell does not transmit the light below a wavelength of 300 nm as shown in Fig. 4. The IPCE curve showed a maximum around 350 nm. The decrease in the IPCE values below the wavelength of 350 nm is ascribable to the decrease in the photon number transmitted by the cell glass as shown in the transmittance curve. In contrast, the decrease in IPCE over the wavelength of 350 nm is due to the absorption of photons by the TiO_2 film since the band gap of TiO_2 is ca. 3.1 eV (about 400 nm) meaning that the absorption edge of the photon by the TiO_2 is at 400 nm so that absorption by the TiO_2 increases when the wavelength is below 400 nm. The IPCE value at the peak was corrected by the transmittance of the cell glass (76%), giving an IPCE (29%) based on the transmitted monochromatic light at 350 nm (intensity 3.6 mW cm^{-2}). The IPCE value for glucose was much higher than that (19%) for the ammonia PFC (APFC) reported previously [21].

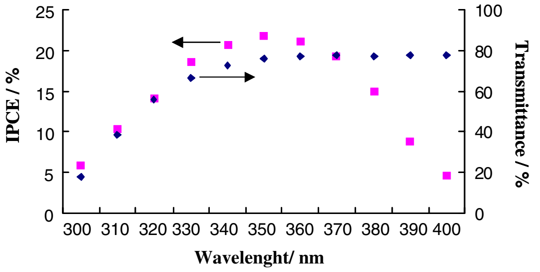


Fig. 4 IPCE of 0.5 M glucose in PFC using FTO/TiO_2(P-25) photoanode and Pt/Pt black cathode under O_2, and transmittance of the cell glass

The mechanism of glucose photodecomposition by irradiation on a TiO_2 photoanode and the energy diagram of the glucose PFC can be represented by Fig. 5. In the TiO_2 the photoinduced charge separation produces an electron (e^-) in the conduction band and a hole (h^+) in the valence band (Eq. (1)); the glucose molecule then reacts with h^+ on the TiO_2 to finally produce CO_2 and protons (H^+) (Eq. (2)). The electrons are transported to the Pt-black/Pt cathode via the outer circuit, and then O_2 is reduced there to produce H_2O (Eq. (3)). Thus the total reaction is represented by Eq. (4).

$$TiO_2 + 24\ \text{UV photons} \rightarrow 24\ h^+ + 24\ e^- \tag{1}$$

$$C_6H_{12}O_6 + 24\ h^+ + 6\ H_2O \rightarrow 6\ CO_2 + 24\ H^+ \tag{2}$$

$$6\ O_2 + 24\ e^- + 24\ H^+ \rightarrow 12\ H_2O \tag{3}$$

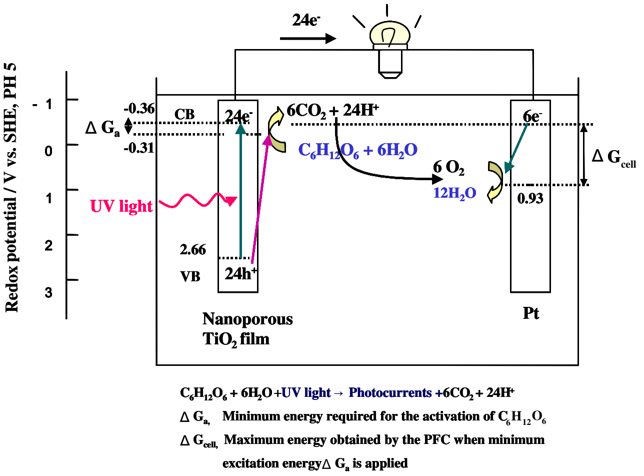
$$\begin{aligned} &C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O + 24\ \text{UV photons} \\ &\quad \rightarrow 6\ CO_2 + 12\ H_2O \end{aligned} \tag{4}$$

$$\begin{aligned} &6\ CO_2 + 12\ H_2O + 48\ \text{Vis phtons (2 steps)} \\ &\quad \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O \end{aligned} \tag{5}$$

The photosynthesis reaction is represented by Eq. (5), demonstrating that the present PFC reaction is the reverse of the photosynthesis. Under O_2 atmosphere the theoretical maximum cell voltage of the present glucose PFC is 1.29 V according to the calculated value based on the conduction band edge (E_{cb}) of TiO_2 (–0.36 V vs. SHE at pH 5, estimated from the value of $E° = –0.06$ V vs. SHE at pH 0 [11] and the redox potential for O_2/H_2O (0.93 V vs. SHE at pH 5, estimated from the value of $E° = 1.23$ V vs. SHE at pH 0). Since the redox potential of glucose is low ($E° = –0.014$ V vs. SHE at pH 0, calculated from thermodynamic data), which is close to the E_{cb} of TiO_2 ($E° = –0.06$ V vs. SHE), the minimum energy required for photoactivation is actually very small (0.05 eV). In the future an appropriate photoanode material capable of utilizing at least visible light with a high photon flux number should be investigated in order that a more efficient glucose PFC is realized.

According to whether the compounds are either liquid or water-soluble, they can be photodecomposed by the PFC while generating electrical power. Various biomasses and their related compounds such as amino acids, polysaccharides, proteins, lignin derivatives, cellulose derivatives and some polymers were investigated in the PFC. The PFC characteristics under 1 atm O_2 in a 0.5 M glycine and a 0.5 M glutamic acid aqueous solution (pH 5) in the dark

Fig. 5 Energy diagram of glucose PFC (at pH 5.0) using nanoporous TiO_2 film photoanode and Pt/Pt black cathode soaked in a glucose aqueous solution under O_2



and under irradiation at 25 °C is shown in Figs. 6(a) and (b), respectively. Both compounds gave clear PFC characteristics. CO_2 and N_2 gas evolution rate and the decomposition rate of a 0.5 M glylcine aqueous solution in the PFC are shown in Figs. 7(a) and (b), respectively. The volume of CO_2 and N_2 gas measured by a gas chromatograph was corrected based on the solubility of both gases in water. The glycine aqueous solution can be converted photochemically into CO_2/N_2 in a nearly stoichiometric 4:1 (CO_2:N_2) molar ratio as shown in Fig. 7(a). Over 48 h, the values for the decomposition rate based on N_2 and CO_2 evolved were 62.1% and 62.2%, respectively (Fig. 7(b)). These results indicate that glycine can be photodecomposed almost completely into CO_2 and N_2 while generating electrical power. The PFC characteristics of various kinds of amino acid are summarized in Table 2. Various kinds of amino acids can be photodecomposed and at the same time utilized as fuels for the PFC. The difference in the values is ascribable to the ability as donors as well as their binding ability onto the TiO_2.

As examples of naturally occurring polymers, the PFC characteristics of amylopectin and gelatin were investigated and the results are shown in Figs. 8 (a) and (b). The PFC characteristics of various kinds of polysaccharides and

Fig. 6 PFC characteristics of amino acid in an aqueous solution containing Na_2SO_4 (0.1 M) by using FTO/TiO_2(P-25) photoanode and Pt/Pt black cathode under O_2: (**a**) Glycine, 0.5 M; (**b**) Glutamic acid, 0. 5 M. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.8 → 0; scan rate, 20 mV s^{-1}

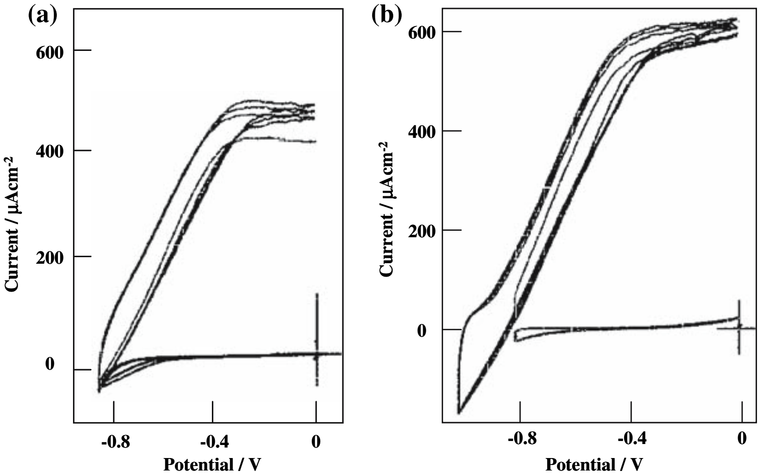


Fig. 7 (**a**) Gas evolution and (**b**) decomposition rate calculated based on the evolved N_2 and CO_2 of 1 mM glycine in PFC using FTO/TiO_2(F-5) photoanode and Pt/Pt black cathode under O_2, irradiated by Xe lamp (450 mW cm^{-2})

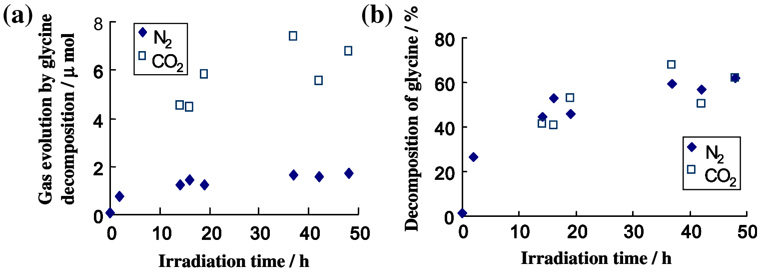


Table 2 Photofuel cell (PFC) characteristics of various amino acids aqueous solutions, irradiated by Xe lamp (450 mW cm^{-2})

Fuel (conc./M)	pH	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
Glycine (0.5)	5	0.76	0.45	0.51
Glutamic acid (0.5)	1	0.90	0.64	0.42
Tyrosine (0.5)	13	0.86	0.43	0.36
Phenyalanine (0.5)	13	0.90	0.61	0.53

Table 3 Photofuel cell (PFC) characteristics of various polysaccharides and polypeptides aqueous solutions, irradiated by Xe lamp (450 mW cm^{-2})

Fuel (wt%)	pH	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
Agarose (2)	5	0.60	0.14	0.51
Amylopectin (2)	5	0.60	0.22	0.30
Curdlan (2)	5	0.56	0.19	0.28
Gellan Gum (2)	5	0.60	0.42	0.31
Gelatin (2)	5	0.60	0.28	0.27
Collagen (3 mg/L)	1	0.60	0.23	0.24

polypeptides are summarized in Table 3. In both cases the V_{oc} values are almost similar (0.6 V) and the J_{sc} values are between 0.19 and 0.42 mA cm^{-2}. It is of importance that not only low molecular compounds such as amino acids and glucose, but also naturally occurring polymers can be photodecomposed and at the same time generate electrical power.

Recently, the decomposition of biomasses including lignocellulose and lignin has attracted a great deal of attention in order to clean them [1, 24]. As for the derivatives of cellulose and lignin, the PFC characteristics of cellulose sulfate and lignosulfonic acid sodium salt were investigated and the results are shown in Figs. 9 (a) and (b), respectively. It should be noted that even a lignin derivative is capable of being photodecomposed simultaneously generating electrical power; it is usually difficult to decompose lignin derivatives except by burning [25]. The V_{oc} values for both compounds were almost similar as the naturally occurring polymers mentioned above, but the J_{sc} value for lignosulfonic acid sodium salt was lower than that of the other compounds. Since the solution of the compound is brown colored, the lower value of J_{sc} might be partly ascribed to a filter effect. In other experiments the decomposition rate of 0.01 wt% lignosulfonic acid sodium salt reached 86.5% in 24 h based on the CO_2 evolved; this value was corrected based on the solubility of CO_2 gas in water (Fig. 10).

Synthetic polymers in addition to the naturally occurring polymers mentioned above can also be photodecomposed to generate electrical power. As an example of typical water-soluble polymers, the PFC characteristics of polyethyleneglycol (PEG) was investigated as shown in Fig. 11 and the results are summarized in Table 4, including the results of polyacrylamide (PAAm) as another example of synthetic polymers. Both V_{oc} and J_{sc} values of these synthetic polymers are similar to those of the naturally occurring polymers mentioned above. The lower J_{sc} values are ascribed to the difficult penetration of the polymers into the nanopores of TiO_2.

Irradiation by a solar simulator at airmass (AM) 1.5 and 100 mW cm^{-2} is also effective for generating electrical power. A 0.5 M glucose and a 0.5 M glycine aqueous solution was investigated for the PFC and the results are shown in Table 5. These also exhibit the effectiveness of solar irradiation for generating electrical power. In the case of glucose the values for both V_{oc} and FF were similar (Table 1), but the J_{sc} value under solar simulator was depressed by 50% due to the lower light intensity than that of the xenon lamp. On the other hand, for a glycine aqueous solution, all values under the solar simulator were smaller than those by xenon lamp (compare Tables 2 and 5).

To investigate the effect of O_2 partial pressure (1 atm O_2 or air), the PFC characteristics of glucose and cellulose sulfate were studied and the results are shown in Table 6. The difference in the J_{sc} values between under O_2 and air are clearly observed for glucose. In the case of cellulose sulfate the J_{sc} and V_{oc} values are almost similar under O_2 and air. Although the PFC characteristics are in general worse under air than under O_2, it is of importance that the present PFC can, in principle, also work under air.

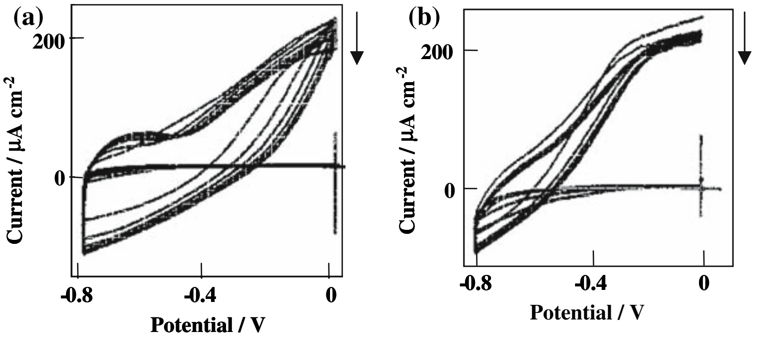


Fig. 8 PFC characteristics of naturally occurring polymer in an aqueous solution containing Na_2SO_4 (0.1 M) by using FTO/TiO_2(P-25) photoanode and Pt/Pt black cathode under O_2: (**a**) amylopectin, 2 wt%; (**b**) gelatin, 2 wt%. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.8 → 0; scan rate, 20 mV s^{-1}

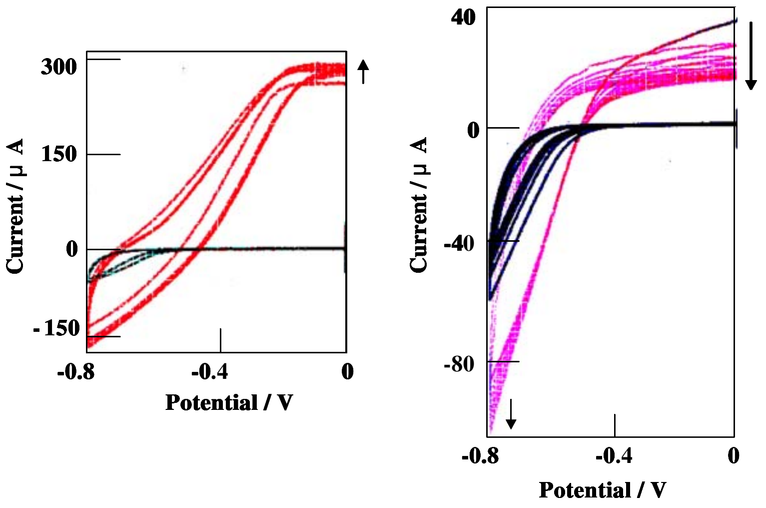


Fig. 9 PFC characteristics of derivatives of cellulose and lignin in an aqueous solution containing Na_2SO_4 (0.1 M) by using FTO/TiO_2(F-5) photoanode and Pt/Pt black cathode under O_2: (**a**) cellulose sulfate, 2 wt%; (**b**) lignosulfonic acid sodium salt, 0.5 wt%. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.8 → 0; scan rate, 20 mV s^{-1}

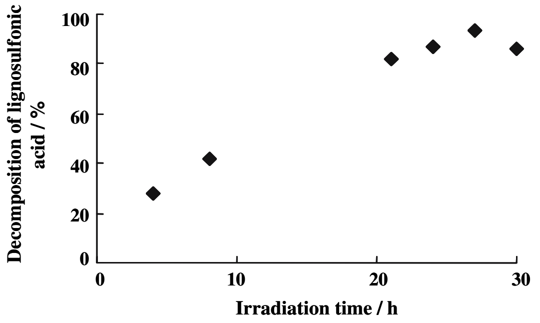


Fig. 10 Decomposition rate of 0.01 wt% lignosulfonic acid sodium salt in PFC using FTO/TiO_2(F-5) photoanode and Pt/Pt black cathode under O_2, irradiated by Xe lamp (450 mW cm^{-2})

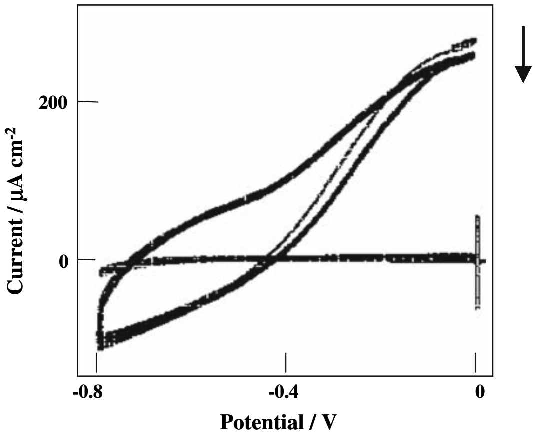


Fig. 11 PFC characteristics of 2 wt% polyethylenglycol in an aqueous solution containing Na_2SO_4 (0.1 M) by using FTO/TiO_2(P-25) photoanode and Pt/Pt black cathode under O_2. Light source, Xe lamp (450 mW cm^{-2}); sweep direction, 0 → –0.8 → 0; scan rate, 20 mV s^{-1}

Table 4 Photofuel cell (PFC) characteristics of polyethylene glycol (PEG) and polyacryamide (PAAm) aqueous solutions (pH 5), irradiated by Xe lamp (450 mW cm^{-2})

Fuel (wt%)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
PEG (2)	0.60	0.28	0.27
PMA (2)	0.60	0.23	0.24

Table 5 Photofuel cell (PFC) characteristics of glucose and glycine aqueous solutions (pH 5) under O_2 atmosphere, irradiated by solar simulator (100 mW cm^{-2})

Fuel (conc./M)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
Glucose (0.5)	0.62	0.28	0.26
Glycine (0.5)	0.60	0.10	0.32

Table 6 Photofuel cell (PFC) characteristics of glucose and glycine aqueous solutions (pH 5) under O_2 and air, irradiated by Xe lamp (450 mW cm^{-2})

Fuel	Atmosphere	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF
Glucose (0.5 M)	O_2	0.64	0.50	0.32
	Air	0.32	0.24	0.26
Cellulose sulfate (2 wt%)	O_2	0.56	0.29	0.34
	Air	0.56	0.26	0.21

In the PFC system, V_{oc} is determined by the potential difference between the level of the E_{cb} and the redox potential of O_2 reduction at the cathode. In Table 6 V_{oc} under O_2 or air is about 1/2 or 1/4 of the theoretical V_{oc} (1.29 V). It is most probable that the reaction involves a different mechanism in the first step of O_2 reduction. The first step of the reduction is either a 4-electron reduction of O_2 ($E°$ = 1.23 V vs. SHE) or a two-electron reduction of O_2

($E° = 0.68$ V vs. SHE). In the former case, the theoretical V_{oc} should be 1.29 V but in the latter case, V_{oc} should be 0.74 V, so that two-electron O_2 reduction would be involved at the cathode.

4 Conclusion

Various biomass resources and their related compounds including other synthetic polymers were successfully photodecomposed at a nanoporous TiO_2 film photoanode with an O_2-reducing cathode while generating electrical power. Their BPFC characteristics were demonstrated. The results show that the BPFC can be fabricated using aqueous solutions of the compounds derived from biomass and biowastes. The present BPFC could utilize visible light instead of UV light in the near future by using appropriate small bandgap photoanode materials to generate electrical power from biomass and biowastes with solar irradiation.

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