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Aqueous Biphasic Dye-Sensitized Photosynthesis Cells for TEMPO-Based Oxidation of Glycerol

Didjay F. Bruggeman, Annechien A. H. Laporte, Remko J. Detz, Simon Mathew, and Joost N. H. Reek*

Abstract: This work reports an aqueous dye-sensitized photoelectrochemical cell (DSPEC) capable of oxidizing glycerol (an archetypical biobased compound) coupled with H₂ production. We employed a mesoporous TiO₂ photoanode sensitized with the high potential thienopyrroledione-based dye AP11, encased in an acetonitrile-based redox-gel that protects the photoanode from degradation by aqueous electrolytes. The use of the gel creates a biphasic system with an interface at the organic (gel) electrode and aqueous anolyte. Embedded in the acetonitrile gel is 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), acting as both a redox-mediator and a catalyst for oxidative transformations. Upon oxidation of TEMPO by the photoexcited dye, the in situ generated TEMPO⁺ shuttles through the gel to the acetonitrile–aqueous interface, where it acts as an oxidant for the selective conversion of glycerol to glyceraldehyde. The introduction of the redox-gel layer affords a 10-fold increase in the conversion of glycerol compared to the purely aqueous system. Our redox-gel protected photoanode yielded a stable photocurrent over 48 hours of continuous operation, demonstrating that this DSPEC is compatible with alkaline aqueous reactions and used for energy-intensive applications, including transport and metal refining.[1,2] Dye-sensitized photoelectrochemical cells (DSPECs) are an extension of dye-sensitized solar cells (DSSCs) and produce fuel instead of electricity by introducing catalytic redox reactions at the respective electrodes within the device.[3] DSSCs use molecular dyes, wide-band gap semiconductors, and redox-mediators to absorb the light that facilitates a solar-to-electrical energy conversion.[4-6] Redox-mediators, responsible for dye regeneration in DSSCs, can be substituted for catalysts in DSPECs to realize catalytic chemical conversions.[7] The majority of DSPECs involve water-splitting and generate hydrogen gas (H₂) as a potential valuable combustible fuel and chemical feedstock, and oxygen gas (O₂) as a byproduct. Currently, the efficiencies of such water-splitting devices are still low (≈1%).[9] Partly, this is because the oxygen evolution reaction (OER) exhibits a high kinetic barrier, as water oxidation is a four-electron process. Therefore, there is an interest in exploring alternative oxidative reactions in DSPECs that preferably involve two-electron processes, e.g., alcohol oxidation at photoanodes.[10] Other potential advantages of novel reactions include the wider scope of reaction conditions that become accessible, e.g., the solvent and additives used, which have been demonstrated to improve photovoltaic properties in DSSCs.[17] The anodic co-valorization means that we can couple the production of commercially valuable compounds to H₂ as fuel, instead of producing O₂. Although the demand for such fine chemicals (and therefore the coupled H₂ production) is significantly smaller than that global consumption of fuels, the innate utility of both anodic and cathodic products might facilitate an earlier uptake of this technology. The sustainability of DSPEC-facilitated photosynthetic production is enhanced further if biomass-derived feedstocks are valorized by oxidative transformation. In this process, biomass is photochemically reformed to biofuels or fine chemicals through oxidation.[19] A promising candidate for biomass valorization is glycerol, as the oxidized products find application in, for instance, cosmetics and the preparation of polyesters and adhesives.[19-20] Current DSPEC designs are incompatible for glycerol conversion as the substrate is water-soluble and its oxidation requires alkaline (pH≈8.5) conditions.[21-23] The prerequisites for glycerol conversion causes stability issues at the photoanode as the ubiquitously employed carboxylic acid—the best performing anchoring group for dyes to metal oxides—is prone to cleavage under aqueous alkaline conditions leading to dye desorption.[24-25] More importantly, the photovoltaic properties in aqueous dye-sensitized systems
typically compare poorly with systems using an organic solvent like acetonitrile,[25] incurring losses in power conversion efficiency, lower injection efficiency and shifts of conduction band levels.[24]

To make the DSPEC compatible with alkaline aqueous phase conditions required for glycerol oxidation, we envision a biphasic DSPEC system in which the photoanode is protected by an organic phase gel layer. As such, the oxidation reaction takes place in the aqueous phase while an efficient solvent environment for the photoanode (e.g., acetonitrile) is maintained.

The biphasic DSPEC (Scheme 1) reported in this communication consists of a mesoporous TiO₂ photoanode on FTO (fluorine-doped tin oxide), sensitized with the high oxidation potential thienopyrroliodine-based dye APII,[26] 2,2,6,6-tetramethyl-piperidine-1-oxyl (TEMPO) is a clear choice for the redox-mediating catalyst because 1) its redox-mediating ability in quasi-solid DSSCs using acetonitrile-poly (vinylidene fluoride-hexafluoropropylene) (PVDF-HFP) gel electrolytes,[27] 2) it can act as a redox-mediating catalyst in acetonitrile-based DSPECs,[15,28] and 3) TEMPO⁺ has been utilized for the selective aqueous (pH ~ 8.5) chemical oxidation of glycerol to glyceraldehyde.[16,22,29] We created a biphasic system device by applying the acetonitrile-based PVDF-HFP gel[27] over the dye-sensitized photoanode, protecting it from aqueous reaction conditions that lead to device deactivation. Gel-embedded TEMPO can regenerate photooxidized APII at the dye–semiconductor interface, generating TEMPO⁺ that can diffuse through the gel to reach the gel–aqueous interface to facilitate glycerol oxidation. As shown by our previous work, it is crucial that in situ photogenerated TEMPO⁺ must migrate away from the semiconductor surface to prevent recombination.[30] Thus, our envisioned biphasic DSPEC design will only function if the TEMPO redox-mediating catalyst resides in the organic-gel layer. The photogenerated TEMPO⁺ should diffuse sufficiently fast to the interface to perform the chemical oxidation reaction. Lastly, the gel must not degrade under the employed reaction conditions.

Control experiments were performed to assess the ability of a TEMPO(BF₄)₃[31] loaded gel to oxidize glycerol in a biphasic system with glycerol residing in the aqueous layer. The TEMPO⁺ in this experiment was used to emulate photogenerated TEMPO⁺ in the envisioned DSPEC. At the same time, the gel stability and the substrate/product distribution over the different layers were probed after 16 hours of reaction time. All acquired experimental samples containing substrates and/or products in respective aqueous/organic solutions were TMS-derivatized prior to analysis by GC.[32,33] We found that the TEMPO⁺ strongly preferred (Table 1, Entry 1, 97 %) to remain in the gel phase. This behavior was independent of the gel layer thicknesses (Table S3, S4). The glycerol substrate and glyceraldehyde product (Table 1, Entries 2 and 3) demonstrated complementary solubility, with 85 % and 87 % residing in the aqueous phase, respectively. The orthogonal solubility of components in this system—redox-mediator in acetonitrile, substrate/product in aqueous—also simplifies product retrieval. Importantly, while these components are mainly in separate phases, efficient selective chemical oxidation of glycerol in the gel–aqueous system was confirmed, with only a ≈ 50 % decrease in conversion (16.2 %) compared to a fully homogeneous mixed reaction mixture (29.8 %). We found that the gel stayed intact, and the system remained biphasic over several days, easily accommodating the 23 to 48-hour time-course of DSPEC experiments (see below). As such, the PVDF-HFP gel system displays the desired properties to construct the biphasic DSPEC (for more details, see Supporting Information, Table S2–S5). Notably, substrates that show a preference for organic layers are proven to be not suitable for such a system (Table S7 and S8).

Preliminary experiments revealed that a minimum redox-gel thickness of 3 mm over the photoanode is needed in the DSPECs to obtain an even, reproducible and stable gel layer coverage over the entire surface of the photoanode. Therefore, the impact of gel layer thickness on the photovoltaic properties was assessed in sandwich-cell quasi solid-

### Table 1: Overview of the relative distribution over a 1:1 biphasic system of glycerol (1 eq.) and TEMPO(BF₄) (1.5 eq.) and conversion of glycerol to glyceraldehyde by TEMPO(BF₄) at t = 16 hours. Biphasic systems consist of TEMPO(BF₄) in the acetonitrile-based gel and glyceraldehyde in the aqueous layer. Conversion and distribution over various gel thickness are shown in Table S3. Data is analyzed with GC after TMS-derivatization.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Compound</th>
<th>Gel phase [%]</th>
<th>Aquous phase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TEMPO⁺⁻⁰</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Glycerol</td>
<td>15</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>Glyceraldehyde</td>
<td>13</td>
<td>87</td>
</tr>
</tbody>
</table>
state DSSCs using redox-gels to confirm sufficient (re)generation of the photooxidized dye and TEMPO+.

These quasi solid-state DSSCs were compared to a typical DSSC based on acetonitrile-based TEMPO4+ electrolyte. The construction of the sandwich DSSC is detailed in the Supporting Information and Figure S5, and the photovoltaic parameters under irradiation with the 100 mW cm−2 LED white light source (Figure S6) are presented in Table 2. A typical AP11-sensitized DSSCs (Table 2, Entry 1) featuring an acetonitrile liquid electrolyte exhibits a short-circuit photocurrent (Jsc) of 3.8 mA cm−2 and an open-circuit voltage (Voc) of 0.62 V. Electrolyte substitution with the TEMPO-gel (Table 2, Entry 2) yielded a ≈10% reduction in Jsc, and minimal impact to Voc. Increasing the gel thickness from 60 μm to 1, 2 or 3 mm resulted in an approximately similar reduction of photovoltaic performance (Table 2, Entries 3–5). The DSSC with the redox-gel thickness of 3 mm experienced a reduction in Jsc to 2.6 mA cm−2 (from 3.8 mA cm−2) while the Voc reduced to 0.41 V (from 0.61 V). The lower performance is a result of increased distance between the electrodes leading to diffusion limitations and, as a result, increased recombination at the semiconductor–gel interface due to the accumulation of oxidized species at the photoanode, in line with what was previously reported.[34,36] Furthermore, the gel increases cell resistance due to low ion diffusion that leads to a lower Fill Factor (FF). The combined effects contribute to a decrease in η for the 3 mm gel DSSC compared to the liquid 0.060 mm analog (by 70%).[30] However, it still produces sufficient Jsc to generate TEMPO+ for glycerol oxidation in DSPECs. Importantly, future optimization may focus on the generation of devices with smaller gel layers.

Next, we explored the light-driven oxidation of glycerol to glyceraldehyde in a DSPEC. DSPECs were assembled with enlarged WEs (FTO | TiO2 | AP11, masked size 0.64 cm2) and CEs (FTO | Pt), which were prepared similar to the (photo)electrodes used in DSSCs (see above). The electrodes were placed in a DSPEC photoreactor (Figure 1A) composed of two Teflon compartments (photoanodic for glycerol oxidation and cathodic for H2 production) separated by a Nafion-117 membrane. The redox-gel containing the TEMPO (1.0 M) was (hot) drop-casted on the photoanode yielding a protective gel layer with a thickness of 3 mm. After the gelation was complete (∼0.5 hours), the anolyte containing 0.1 M glycerol was introduced (sat. NaCl, NaHCO3, pH 8.3, 3 mL; see Figure 1B). Chronoamperometric experiments were performed by illuminating the photoanode with a 100 mW cm−2 white LED (Figure S6) for 23 hours, using a small bias potential of 0.1 V vs. Ag/AgCl (Figure S7A). Aliquots of the anodic reaction mixture were TMS derivatized and analyzed by GC to probe the conversion, and the results are shown in Figure 2B and summarized in Table 3. Control experiments were performed using the redox-gel DSPEC without illumination, using a redox-gel DSPEC without TEMPO as a redox-mediating catalyst, and by using the DSPEC without gel.

The experiment where the biphase redox-gel DSPEC system was irradiated for 23 hours (Table 3, Entry 1) yielded

Table 2: Photovoltaic parameters of the n-type quasi solid-state FTO | TiO2 | AP11 (active area 0.19 cm2) sandwich DSSCs with a standard deviation of N=3 in brackets. CE = FTO Pt electrodeposited, electrolyte: 1.2 M LiTFSI, 1.0 M TEMPO and 0.1 M TEMPO(BF4) with 10%wt PVDF-HFP in acetonitrile. Data was obtained from J–V measurements performed using a 100 mW cm−2 LED white light source with a 0.07 cm2 mask. a) Surlyn or b) Teflon spacer.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Redox-gel [mm]</th>
<th>Voc [V]</th>
<th>Jsc [mA cm−2]</th>
<th>FF</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.060 (liquid)</td>
<td>0.62</td>
<td>3.8</td>
<td>0.68</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(±0.003)</td>
<td>(±0.11)</td>
<td>(±0.01)</td>
<td>(±0.07)</td>
</tr>
<tr>
<td>2</td>
<td>0.060</td>
<td>0.61</td>
<td>3.4</td>
<td>0.60</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(±0.007)</td>
<td>(±0.14)</td>
<td>(±0.08)</td>
<td>(±0.02)</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.46</td>
<td>2.8</td>
<td>0.44</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(±0.019)</td>
<td>(±0.36)</td>
<td>(±0.01)</td>
<td>(±0.06)</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>0.43</td>
<td>2.6</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(±0.020)</td>
<td>(±0.41)</td>
<td>(±0.05)</td>
<td>(±0.05)</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>0.41</td>
<td>2.6</td>
<td>0.45</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(±0.059)</td>
<td>(±0.32)</td>
<td>(±0.02)</td>
<td>(±0.02)</td>
</tr>
</tbody>
</table>

Table 3: Light-driven glycerol oxidation reactions using redox-gel biphase DSPEC performed for t=23 hours and control experiments.

The biphase gel DSPEC: WE electrode compartment consisted of a FTO | TiO2 | AP11 WE (active area 0.74 cm2) with a 1.0 M TEMPO 3 mm redox-gel layer (10%wt PVDF-HFP, 1.2 M LiTFSI in acetonitrile) and filled with 0.1 M glycerol aqueous solution (sat. NaCl, NaHCO3, pH 8.3, 3 mL). An Ag/AgCl RE which was placed close to the WE. The CE compartment was separated by a Nafion-117 membrane and consisted of a FTO | Pt CE and was filled with 1.0 M AcOH in acetonitrile (3 mL). An bias potential on the WE of 0.1 vs. Ag/AgCl was employed and the system was illuminated with a 100 mW cm−2 white LED light source (masked size 0.64 cm2). Differences in control experiments are indicated. Product analysis was measured by GC after TMS-derivatization. * Faradaic efficiency was not obtained for system with photocurrent near 0 μmol. Images of photoanodes are shown in Table S10.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Glyceraldehyde produced [μmol]</th>
<th>Conversion based on photocurrent [μmol]</th>
<th>Faradaic efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biphase gel</td>
<td>68.3</td>
<td>66.2</td>
<td>≈100</td>
</tr>
<tr>
<td>2</td>
<td>w/o light</td>
<td>0</td>
<td>&lt;0</td>
<td>~</td>
</tr>
<tr>
<td>3</td>
<td>w/o TEMPO</td>
<td>0</td>
<td>1.00</td>
<td>~</td>
</tr>
<tr>
<td>4</td>
<td>w/o gel (aqueous)</td>
<td>7.60</td>
<td>7.40</td>
<td>≈100</td>
</tr>
</tbody>
</table>
The DSPEC photoanodes and redox-gels were investigated after the experiments to gain insight into the stability of the device. The redox-gel preserved its bright orange color after 48 hours of chronoamperometric illumination (Figure 1C), consistent with the control experiments described in Table 1 that reveal only a small fraction (6%) of all TEMPO was found in the aqueous layer samples (Figure S8). The water present in the gel layer only increased by 1% (Table S6) after a 48-hour experiment. Quantitative and qualitative colorimetric analysis of FTO|TiO$_2$|AP11 photoanodes (Figure 2A and Table S10) is performed, as the disappearance of the yellow color indicates detachment or decomposition of the AP11 dye due to the lingering of the dye in the oxidized state. Soaking studies were performed in the dark to avoid dye decomposition by over-illumination, to study the impact of alkaline aqueous conditions, and confirmed the leaching of AP11 of TiO$_2$ in such an environment (Table S9). Interestingly, the yellow color was retained in the photoanode protected with the redox-gel, indicating that the gel prevents cleavage of the dye, and there is sufficient redox-mediator in the gel system present to avoid the photodecomposition of the dye. Furthermore, the redox-gel based DSPEC still performs after 24 hours, whereas the fully aqueous-based DSPEC no longer generates photocurrent after ≈15 hours (Figure S7B).

Interestingly, the system needs several hours before the reaction proceeds with 100% Faradaic efficiency. We surmise that the DSPEC builds up the TEMPO$^+$ concentration in the gel based on the diffusion through the redox-gel layer to a steady-state required to allow oxidation reactions to occur at the gel-electrolyte interface. Therefore, we performed 48-hour experiments to confirm the steady-state in TEMPO$^+$ and further probe the system's stability. These experiments show (Figure S11–S13) that the DSPEC with a gel layer tends to stabilize after approximately 20 hours of irradiation, after which a stable photocurrent density of ≈0.18 mA cm$^{-2}$ is observed, producing glyceraldehyde with a near 100% Faradaic efficiency. In a separate experiment, the redox-gel based DSPEC was illuminated for 7 hours to quantify the amount of H$_2$ formed during the experiment, and this experiment shows (Figures S9 and S10) a high Faradaic efficiency in H$_2$ formation (of ≈90%). This experiment ultimately shows that the gel-protected biphasic DSPEC allows simultaneous fuel formation and glycerol oxidation.

In conclusion, we have demonstrated the selective light-driven TEMPO-mediated oxidation of glycerol to glyceraldehyde coupled to the production of H$_2$ in a biphasic DSPEC utilizing a gel-protected photoanode. The TEMPO redox-mediating catalyst is photooxidized to TEMPO$^+$ in the acetonitrile-based gel and oxidizes glycerol at the gel–aqueous interface. The presence of the gel layer on the photoanode increases the photocurrent density and product formation by 10-fold compared to the aqueous DSPEC system. In the

68.3 μmol of glyceraldehyde. This translates to a 100% Faradaic efficiency based on the photocurrent produced. Negligible photocurrent is produced in control experiments that exclude light or TEMPO (Figure S7B), and no glyceraldehyde was formed in these experiments as judged by GC analysis. As expected, both light and TEMPO are necessary to create an operational cell capable of the glycerol oxidation reaction (Table 3, Entries 2 and 3). The redox-gel DSPEC is compared to a fully aqueous DSPEC (Table 3, Entry 4 and Figure 2D), which contains a saturated solution of TEMPO (≈0.5 M). Although the TEMPO concentration is lower in the fully aqueous DSPEC, our previous studies have shown that DSPECs with TEMPO concentrations as low as 0.01 M in acetonitrile still work well and outperform the DSPEC based on the aqueous anolyte. Furthermore, it is known that wettability issues for TEMPO-based aqueous electrolytes leading to poor pore infiltration are not an issue. While both DSPECs—the TEMPO redox-gel and the completely aqueous redox system—demonstrate a Faradaic efficiency for glyceraldehyde production of ≈100%, the photocurrent produced by the TEMPO redox-gel based DSPEC is ≈10-fold higher than that of the aqueous system. In line with this, the improved photocurrent results in a 10-fold increase in glyceraldehyde production.

Figure 2. A) Images of used photoanodes in 23 hours DSPEC experiments, and B) GC quantification of light-driven glyceraldehyde production in a DSPEC with 3 mm TEMPO redox-gel layer (orange) and a full aqueous TEMPO-based system (blue) with the anticipated amount of glyceraldehyde based on photocurrent (redox-gel: brown, aqueous dark blue). The integration of half the photocurrent determines the number of electrons to account for two electrons needed per oxidation reaction. A bias potential of 0.1 V vs Ag/AgCl was applied on the WE and the system was illuminated with a 100 mW cm$^{-2}$ white LED light source.

The DSPEC photoanodes after DSPEC treatment shows (Figures S11–S13) a high Faradaic efficiency in the photoanode protected with the redox-gel, indicating that the gel prevents cleavage of the dye, and there is sufficient redox-mediator in the gel system present to avoid the photodecomposition of the dye. Furthermore, the redox-gel based DSPEC still performs after 24 hours, whereas the fully aqueous-based DSPEC no longer generates photocurrent after ≈15 hours (Figure S7B).
absence of the gel layer, the photoanode decolorizes due to dye detachment under these conditions. The improved efficiency and high stability of the redox-gel-based DSPEC opens up the possibility for the photoconversion of other solely water-soluble including biomass-derived substrates such as cellulose, which also require relatively harsh conditions.[7] Furthermore, product collection from the aqueous solution is improved thanks to the embedding of the active redox-mediating catalyst in the redox-gel. Most excitingly, the concept of employing a redox-gel to enhance the stability of aqueous DSPECs can be considered in the context of water-splitting DSPECs. On top of that, we are currently investigating if the redox-gel can prevent recombination in such cells by physically separating the water oxidation complex from the photoanode surface.

Acknowledgements

We kindly acknowledge Merck and the Netherlands Organization for Scientific Research (NWO) for financial support. Tijmen Bakker, Hans Ellermeijer and Daan van Giesen are kindly thanked for their contribution to the development of the cell.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: Biphasic Dye Sensitized Photovoltaic Cell · Hydrogen · Solar Fuel · Supramolecular Gel · TEMPO-Catalyzed Glycerol Oxidation

[34] M. M. Abdel-Galeil, R. Kumar, A. Matsuda, R. E. El-Shater, Optik 2021, 227, 166108.

In our previous study, enlarging the spacer distance of liquid DSSCs (60 μm) to the format of DSPECs (6 cm) showed an η loss of 20 %, see ref [28].

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