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## REVIEW ARTICLE

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## Aqueous dye-sensitized solar cells

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Nowadays, dye-sensitized solar cells (DSSCs) are the most extensively investigated systems for the conversion of solar energy into electricity, particularly for implementation in devices where low cost and good performance are required. Nevertheless, a key aspect is still to be addressed, being considered strongly harmful for a long time, which is the presence of water in the cell, either in the electrolyte or at the electrode/electrolyte interface. Here comes the present review, in the course of which we try our best to address the highly topical role of water in DSSCs, trying to figure out if it is a poisoner or the keyword to success, by means of a thoroughly detailed analysis of all the established phenomena in an aqueous environment. Actually, in the last few years the scientific community has suddenly turned its efforts in the direction of using water as a solvent, as demonstrated by the amount of research articles being published in the literature. Indeed, by means of DSSCs fabricated with water-based electrolytes, reduced costs, non-flammability, reduced volatility and improved environmental compatibility could be easily achieved. As a result, an increasing number of novel electrodes, dyes and electrolyte components are continuously proposed, being highly challenging from the materials science viewpoint and with the golden thread of producing truly water-based DSSCs. If the initial purpose of DSSCs was the construction of an artificial photosynthetic system able to convert solar light into electricity, the use of water as the key component may represent a great step forward towards their widespread diffusion in the market.

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### 1. Introduction

Due to the gradual, but constant and inescapable depletion of fossil fuels and the increasing energy demand to support the current model of economic growth, mankind is facing a global energy problem.<sup>1,2</sup> Amongst the number of alternative resources, renewable energies are rapidly becoming the leading solution to fulfil the growing needs of power sources.<sup>3,4</sup> In this respect, wind power, solar energy, hydropower, geothermal energy, biomass and biofuel are extensively investigated for a few decades both from the scientific/academic and industrial viewpoints.<sup>5</sup>

At present, solar energy is considered the most promising renewable resource: every day, the Sun shines on the Earth, thus providing around  $3 \times 10^{24}$  J of green energy per year, which exceeds by a factor of  $10^4$  the present global population consumption.<sup>6–8</sup> A simple calculation leads self-evidently to the conclusion that covering only around 0.1% of the Earth's surface

by means of energy conversion devices having an efficiency of about 10% would satisfy the present global energy needs. These encouraging numbers are inducing the scientific community to make even greater efforts towards the direction of improving solar energy conversion technologies as well as proposing new intriguing solutions.<sup>9,10</sup> To have an idea of the magnitude of this effort, a rapid search on a scientific database (e.g., Scopus), using the simple keyword “solar energy”, provides more than 10 000 publications for each of the recent years.

The creation of a potential difference, or electric current, in a material upon exposure to light is possible because of the photovoltaic (PV) effect, and – depending on the materials used – three generations of solar energy devices have been developed to date.<sup>11–13</sup> Among all, the mostly studied device of the last generation is the dye-sensitized solar cell (DSSC), being a low-cost and high efficiency solar energy-to-electricity converter. Firstly assembled and demonstrated by O'Regan and Grätzel in 1991,<sup>14</sup> they are composed of only five components (Fig. 1): a transparent conductive oxide (TCO) substrate,<sup>15</sup> a nanostructured n-type semiconductor,<sup>16</sup> a visible-light absorber dye,<sup>17</sup> an electrolyte<sup>18</sup> and a counter electrode.<sup>19</sup> With the key idea of mimicking the natural photosynthesis, DSSCs are being pursued as eco-friendly devices, which could be easily fabricated.<sup>20,21</sup> In a dye-sensitized solar cell, upon absorption of light, dye molecules reach an excited state and, with an appropriate energy level alignment of all the

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components, charge separation occurs at the interface between the dye-sensitized semiconductor and the electrolyte. While electrons are injected into the conduction band (CB) of the semiconductor (usually titanium dioxide,  $\text{TiO}_2$ ) and transported to the conductive electrode, the regeneration of the oxidized dye takes place at the counter electrode by means of an electron-donor species (typically a liquid electrolyte based on the redox couple iodide/triiodide,  $\text{I}^-/\text{I}_3^-$ ).<sup>22</sup> Multidisciplinarity, academic and industrial interests have boosted the number of publications per year (Fig. 2), resulting in about 4000 international peer-reviewed papers in the 2013–2014 period of time. Some of these articles, which led to the identification of new materials

with concrete applications also in other research fields,<sup>23,24</sup> are highly cited: each of them counts even more than 1000 citations.<sup>25–28</sup>

The most performing DSSCs (efficiencies up to 13% have been recently demonstrated<sup>29</sup>) use organic solvent-based liquid electrolytes. These have the relevant drawback of high vapour pressure and a severe environmental impact. Moreover, several organic solvents are toxic and/or explosive, thus seriously limiting their practical applications in DSSCs because of safety issues. Although several alternatives to organic solvents have been proposed (*i.e.*, plastic crystals and solid-state conductors<sup>30,31</sup>), the biggest – sometimes ignored – issue still remaining unsolved



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*Faraday Medal and the Millennium Technology Grand Prize. He has published ~1100 papers, 50 reviews/book chapters and is the inventor/co-inventor of >50 patents. His studies have been cited over 140 000 times (h-index 170), making him one of the 10 most highly cited chemists in the world.*



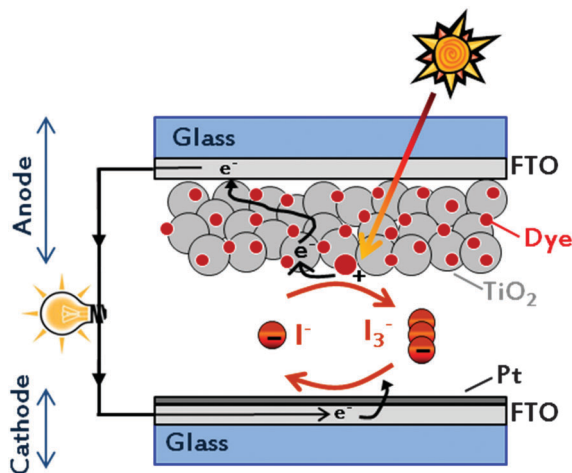


Fig. 1 Schematic representation of the components and of the basic operating principle of a DSSC.

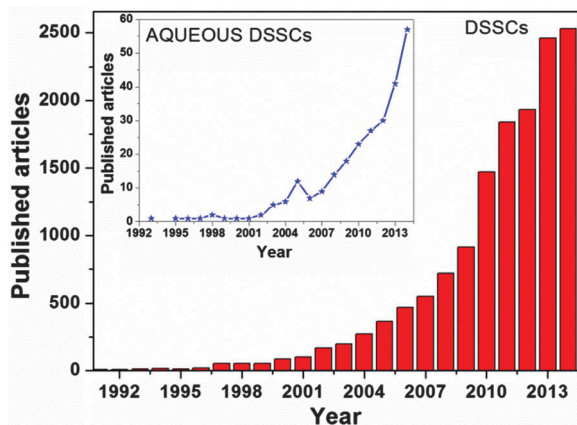


Fig. 2 Number of research articles published per year in the field of DSSCs. Inset: data for aqueous DSSCs. Source: SCOPUS Database.

in standard aprotic DSSC systems is the contamination of the cell by means of moisture/water. This often affects both the cell performance and the long-term stability, even if robust encapsulation systems and specifically conceived barrier materials are utilised. In fact, traces of water are always present in the electrolytic solution and in the pores/voids of the semiconductor electrode film, being eventually introduced during cell assembly or upon operation under ambient conditions (tiny defects in the encapsulation are often present). This phenomenon is even more accentuated when the production of flexible DSSCs is envisaged,<sup>32,33</sup> quite rapidly permeated by water molecules (*i.e.*,  $0.01 \text{ g m}^{-2} \text{ day}^{-1}$ ) even in the presence of rather expensive barrier layers; in fact, it has been calculated that the water content in the electrolyte may be  $>10\%$  after one year of real outdoor use.<sup>34</sup> These results have led to the general opinion that water is detrimental, in fact a poisoner, for DSSCs.

The aim of this review article is to thoroughly unravel the specific role of water as an electrolyte component in DSSCs. First of all, it is fundamental to understand how the presence of water can influence the device performance; many studies have

been proposed over the years in this respect. Crossing experimental data obtained by using very different techniques as well as theoretical simulations would help in identifying the interactions between water molecules and DSSC components. Then, we consider very much interesting and surprising to show how, in the last few years, the scientific community has turned its efforts in the direction of DSSCs fabricated with water-based electrolytes. Indeed, being less expensive, non-flammable and more environmentally friendly, these novel devices would also not suffer from water contamination issues, with the added value of easily solvating many potential redox mediators. Photoanode modifications, introduction of novel additives and surfactants, selection of specifically conceived redox couples, preparation of suitable cathodes and stabilization of electrolytes have progressively led to the fabrication of 100% aqueous DSSCs. Achieving high performance in a fully aqueous cell represents the *Holy Grail* for DSSCs, and brings back the attention to their initial purpose: the realisation of an artificial photosynthetic system able to convert solar visible light energy into electricity, by using a unique solvent, water, the solvent of life.

## 2. Electrolytes for DSSCs: state of the art

The electrolyte has been identified as one of the component which most significantly influences DSSC efficiency and stability, since it has a key role in the regulation of the electron transfer kinetics. According to their physical consistency, electrolytes may be classified into three main classes: liquid, quasi-solid and solid.

Traditional liquid electrolytes consist of a redox couple and a few additives dissolved into an organic solvent. As previously stated, the standard redox mediator is the  $\text{I}^-/\text{I}_3^-$  couple, but several valid alternatives have been proposed. In particular, cobalt complexes<sup>35</sup> have exceeded the performance of the standard redox pair, achieving efficiencies up to 13%.<sup>29</sup> Other redox mediators, such as  $\text{SCN}^-/(\text{SCN})_3^-$ ,<sup>36</sup>  $\text{SeCN}^-/(\text{SeCN})_3^-$ ,<sup>37</sup>  $\text{Br}^-/\text{Br}_3^-$ ,<sup>38</sup> sulphur-based systems,<sup>39</sup> copper complexes,<sup>40</sup> ferrocene derivatives<sup>41</sup> and stable nitroxide radicals,<sup>42</sup> have also been proposed. Each of these systems is characterized by peculiar thermodynamic and kinetic properties, which must be well matched with the other cell components. Moreover, also counterions of redox mediators must be properly selected, since it has been reported that the photocurrent decreases and the photovoltage increases while increasing the cation radius, due to the variation of the  $\text{TiO}_2$  CB energy ( $E_c$ ) and the associated influence on the electron injection efficiency.<sup>43</sup>

Additives are often introduced in appropriate amounts to increase the PV parameters; among them, nitrogen-containing heterocyclic compounds and guanidinium thiocyanate (GuSCN) are the most frequently used. While the former improve cell photovoltage by shifting the band edge of  $\text{TiO}_2$  and increasing the electron lifetime,<sup>44</sup> the latter enhances the photocurrent by positively moving the flatband potential of the photoelectrode, thus increasing the electron injection yield.<sup>45</sup>



As regards organic solvents, acetonitrile (ACN), valeronitrile (VAN), 3-methoxypropionitrile (MPN), methoxyacetonitrile (MAN), ethylene carbonate (EC), propylene carbonate (PC),  $\gamma$ -butyrolactone (GBL) and *N*-methylpyrrolidone (NMP) are the most commonly used, due to their high dielectric constant and low viscosity. Since all these solvents can be considered as electron acceptors, a classification of their donor number (*i.e.*, the enthalpy of reaction of the solvent with a strong electron acceptor) was proposed,<sup>46</sup> and it was proved that an increase in the electron-donor (or basic) character led to higher cell potentials and lower photocurrents.<sup>47</sup> The worst drawback of organic solvents is their high volatility, thus room temperature ionic liquids (RTILs), being non-flammable and non-volatile organic compounds, are widely used as additives or solvents in order to guarantee good chemical and thermal stabilities.<sup>48</sup> However, RTILs often show high viscosity values, and specific improvements of their rheological characteristics are necessary to ensure an efficient ion transport. The enormous research efforts carried out in the field of liquid electrolytes have been already thoroughly discussed in several review articles.<sup>49–53</sup>

Limited long-term stability, difficulty in hermetic sealing and leakage of the liquid electrolyte have been identified as relevant drawbacks in view of real indoor and outdoor applications of DSSCs.<sup>54–56</sup> A possible solution is represented by the entrapment of the liquid electrolyte by means of a polymeric or inorganic network. Polymeric quasi-solid electrolytes can be prepared in the form of gels<sup>57</sup> or membranes,<sup>58,59</sup> where a huge amount of crosslinked matrices has been investigated.<sup>60–62</sup> As an alternative, inorganic nanoparticles (NPs) have been adopted to jell liquid electrolytes, creating a quasi-solid (paste-like) network containing self-assembled channels able to ensure sufficient ionic transport.<sup>63–65</sup> To date, quasi-solid electrolytes are considered the optimum compromise between efficiency and durability,<sup>66</sup> and the recent advances in this subject have been collected in some review articles.<sup>67–69</sup>

Solid electrolytes are based on a completely different working principle: holes transferred from the dye are transported *via* hopping between the electronic states of the solid electrolyte to the metallic or polymeric counter electrode. Crystalline p-type semiconductors,<sup>70</sup> organic hole-conducting molecules,<sup>71</sup> as well as conductive polymers<sup>72</sup> have been widely studied.<sup>73–75</sup> However, the poor intrinsic conductivity, the low electron transfer from the dye molecules, the poor penetration into the mesoporous TiO<sub>2</sub> and the faster recombination phenomena do not allow solid cells to be more efficient than their liquid and quasi-solid counterparts. Studies on solid DSSCs have recently led to the development of perovskite solar cells (PSCs), in which compounds like CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3-x</sub>Cl<sub>x</sub> act as the light harvester as well as the conductor of both electrons and holes.<sup>76–78</sup> PSCs have achieved efficiencies above 19%<sup>79</sup> (certified value: 17.9%,<sup>80</sup>) and, although very young, will surely be able to establish themselves as a leading device for solar energy conversion.

The introduction of water in liquid, quasi-solid and solid electrolytes causes a very complex set of effects on the PV performance of the resulting DSSCs. The initial section of this review will focus on their detailed investigation, while the rest

of the manuscript will deal with cells in which water is purposely added to the electrolyte with gradually increasing percentages, giving rise to so-called “aqueous DSSCs”.

### 3. Harmful effects due to water contamination

As anticipated in the Introduction, the presence of water was initially viewed as a strongly negative aspect for DSSCs. Where does water in cells come from? Unless DSSCs are assembled in a N<sub>2</sub>- or Ar-filled glove-box (procedure almost never encountered in the literature), water is present during all the manufacturing steps. Indeed, it can be adsorbed on the anodic semiconductor, be present in the solvents and in the solutions used to make the dye-uptake or the liquid electrolyte filling, permeate the polymer films used for device sealing. The effects of water on the PV performance, and the stability and the visual aspects of DSSCs have been extensively studied by adopting several experimental techniques and/or through computational studies, which are reported in the following Sections (3.1–3.5). For ease of understanding, we will report the water content as percentage by weight (wt%) or volume (vol%); however, in the case of very low quantities we will adopt the molar concentration (for H<sub>2</sub>O, 1.0 M corresponds to 1.8 wt%).

#### 3.1 Effects on photovoltaic parameters

A couple of years after inventing the DSSCs, Grätzel and coworkers proposed the first study on the stability of *cis*-X<sub>2</sub>bis(2,2'-bipyridyl-4,4'-dicarboxylate)-ruthenium(II) (X = Cl<sup>−</sup>, Br<sup>−</sup>, I<sup>−</sup>, CN<sup>−</sup> and SCN<sup>−</sup>) sensitizers.<sup>81</sup> All of the cells showed an initial 20–30% decay in short-circuit current density ( $J_{sc}$ ), which was attributed to the absorption of residual UV light as well as to the contamination by water molecules. Such detrimental effects were attributed to the electronic and chemical equilibration of the dye-loaded TiO<sub>2</sub> with the liquid electrolyte, the water uptake from ambient air being envisaged as their main cause. Indeed, when a water-tight cell sealant was used, the initial decay in the performance of the cell was suppressed.

The first analytical investigation of water contamination dates back to 1998, when Lindquist and coworkers showed that  $J_{sc}$  decreased (Fig. 3A) and open-circuit voltage ( $V_{oc}$ ) increased (Fig. 3B) when the water content in the electrolytic solution (LiI 0.10 M and I<sub>2</sub> 10 mM in MAN) increased from 0 to 2.2 M.<sup>43</sup> It was proposed that water molecules, being strongly adsorbed onto the TiO<sub>2</sub> surface, coordinated with the surface Ti atoms<sup>82</sup> and blocked the reaction of I<sub>3</sub><sup>−</sup> with the electrons in the TiO<sub>2</sub> CB. As a result,  $V_{oc}$  increased proportionally to the amount of water introduced in the cell. Such a phenomenon was so strong as to balance and quantitatively overcome the negative shift of the CB which was caused by the addition of water to the aprotic electrolytic solution.<sup>83</sup> Anyway, despite the improvement in  $V_{oc}$ , cell performance decreased due to the neat reduction of  $J_{sc}$  values. In their preliminary studies, Lindquist and coworkers motivated this effect by arguing the following hypotheses: desorption of the N3 dye from the TiO<sub>2</sub> surface, weakening of





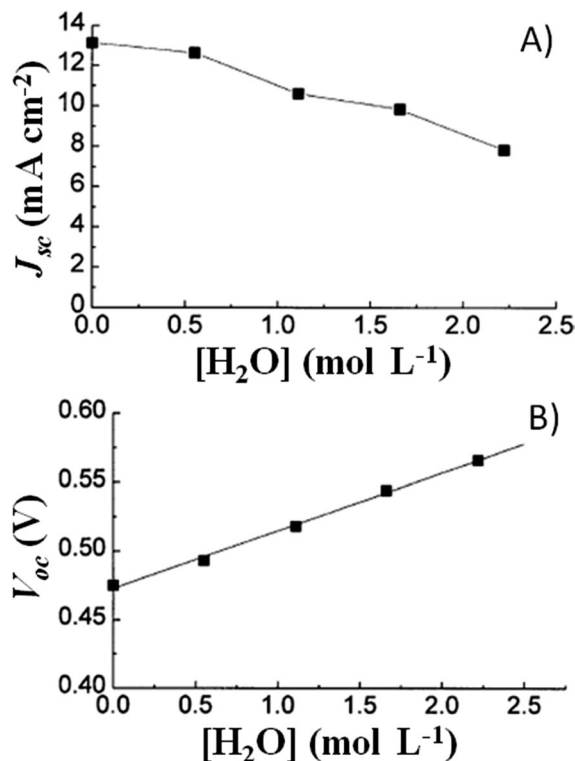


Fig. 3 Variation of  $J_{sc}$  (A) and  $V_{oc}$  (B) values, measured at 0.82 sun, due to water addition in the liquid electrolyte. Electrolytes: LiI 0.10 M and I<sub>2</sub> 10 mM in MAN/H<sub>2</sub>O. Dye: N3. Adapted and reprinted from ref. 43.

the TiO<sub>2</sub>-dye interaction, photoinduced substitution of the -NCS ligand of the dye and change in the absorption properties of the sensitizer molecules due to the variation in the solvent polarity. For sure, the most intriguing phenomenon was observed when the contaminated electrolyte was replaced by a freshly prepared water-free one:  $J_{sc}$  was fully restored (from 1.93 to 2.62 mA cm<sup>-2</sup>), while  $V_{oc}$  retained a higher value (0.535 V vs. the initial 0.453 V). As a result, the overall cell efficiency ( $\eta$ ) increased (from 5.2% to 6.4% at an irradiation intensity  $P_{in}$  of 0.15 sun), and Lindquist's group compared the effect observed in the water-contaminated systems to that provided by the traditionally used pyridine derivative additives.<sup>84</sup>

### 3.2 Spectroscopic investigation of water-promoted effects

Fourier transform infrared (FTIR) studies reported in Fig. 4A–C showed that when the working electrodes were immersed in an electrolyte (LiI 0.50 M and I<sub>2</sub> 50 mM in MPN) containing 5 vol% H<sub>2</sub>O, the broadening as well as decreased intensity of the -NCS ligand absorption band (2100 cm<sup>-1</sup>) was observed. In the same study, Hagfeldt and coworkers found a small absorption peak at 1575 cm<sup>-1</sup>, which was assigned to the symmetric bending of the water molecules, either bonded to the N719 dye or adsorbed onto the nanostructured TiO<sub>2</sub> film.<sup>85</sup> UV-Vis spectra (Fig. 4D–F) showed blue-shifted absorption maxima with respect to the reference ( $\lambda_{max}$  = 551 nm), both under dark ( $\lambda_{max}$  = 529 nm) and under normal illumination conditions ( $\lambda_{max}$  = 500 nm); these shifts were probably caused by the exchange of the -NCS

ligands of the dye with water molecules and/or OH<sup>-</sup> anions in the contaminated electrolyte.

To ascertain the eventual influence of hydrogen bonds and hydrophobic interactions on the water-contaminated cell components, the use of water isotopes (*i.e.*, H<sub>2</sub>O, D<sub>2</sub>O and H<sub>2</sub><sup>18</sup>O) has been proposed by Yang and coworkers,<sup>86</sup> who exploited the potential prospects of this procedure usually applied in geology, biology and medicine.<sup>87,88</sup> By monitoring the time-dependent surface reaction occurring on the photoelectrodes in the presence of water isotopes, the diffuse-reflectance infrared Fourier transform (DRIFT, Fig. 5) technique showed that the intensity of the SCN<sup>-</sup> ligand remarkably decreased when the water content in the electrolyte (LiI 0.50 M, I<sub>2</sub> 50 mM and TBP 0.50 M in ACN; TBP = 4-*tert*-butylpyridine) increased (from 0 to 5 wt%). Additionally, the peak intensity of SCN<sup>-</sup> decreased with prolonged soaking time, due to the progressive replacement of the -SCN ligand with water molecules or OH<sup>-</sup> ions.<sup>89</sup> This was confirmed by the appearance of a strong band at 3000–3600 cm<sup>-1</sup>, due to water adsorption on the nanostructured TiO<sub>2</sub> lattice.<sup>90</sup> Moreover, the interaction of Li<sup>+</sup> cations (from LiI) with the free SCN<sup>-</sup> anions led to the formation of LiNCS, as indicated by the peak at 2079 cm<sup>-1</sup>.<sup>91</sup> Considering the sensitizer structure as a whole, it resulted that only the bipyridine ligands of the sensitizer did not take part in the degradation process. When water isotopes were used, Yang and coworkers measured that the degradation rate increased in the order of H<sub>2</sub>O > D<sub>2</sub>O > H<sub>2</sub><sup>18</sup>O, fully consistent with the diffusion rate of these isotopes in the electrolyte, which is inversely proportional to the square root of their molecular masses.<sup>92</sup> As regards the PV performance, the bonding between Li<sup>+</sup> and SCN<sup>-</sup> ions gave rise to negative shifts in the TiO<sub>2</sub> Fermi level, which resulted in lower  $V_{oc}$  values for aqueous DSSCs, in contrast to the previously discussed results by Lindquist and coworkers.<sup>43</sup>

### 3.3 Imaging techniques and visual aspects: how cells change over time

Photocurrent imaging techniques represent a valuable investigation method to provide information on problems related to DSSC efficiency as well as long-term stability.<sup>93,94</sup> Cell mapping is usually carried out by means of a He-Ne laser (632 nm), inducing a photocurrent point by point, which is registered through a lock-in amplifier. Using such a technique, Tributsch and coworkers observed the bleaching of the electrolyte, as a result of the disappearance of I<sub>3</sub><sup>-</sup> ions.<sup>95</sup> This resulted in the increase of the internal resistance, because the I<sub>3</sub><sup>-</sup> reduction reaction at the counter electrode stopped. Interestingly, this was the first work to go in contrast to the others: the effect of water was not geared solely to the dye stability, but also the electrolyte underwent major changes. Even if the formation of iodate (IO<sub>3</sub><sup>-</sup>) from I<sub>3</sub><sup>-</sup> was expected by Tributsch and coworkers, FTIR analysis revealed the absence of iodate in the electrolyte. Nevertheless, the FTIR spectrum of the electrolyte in the region of the OH-stretching mode showed increased water concentration values in the solvent (ACN). Moreover, the water content increased with time, and aging studies showed that the corresponding OH-stretching mode became the main signal in the spectrum after 84 days. Thus, it was proposed that water could



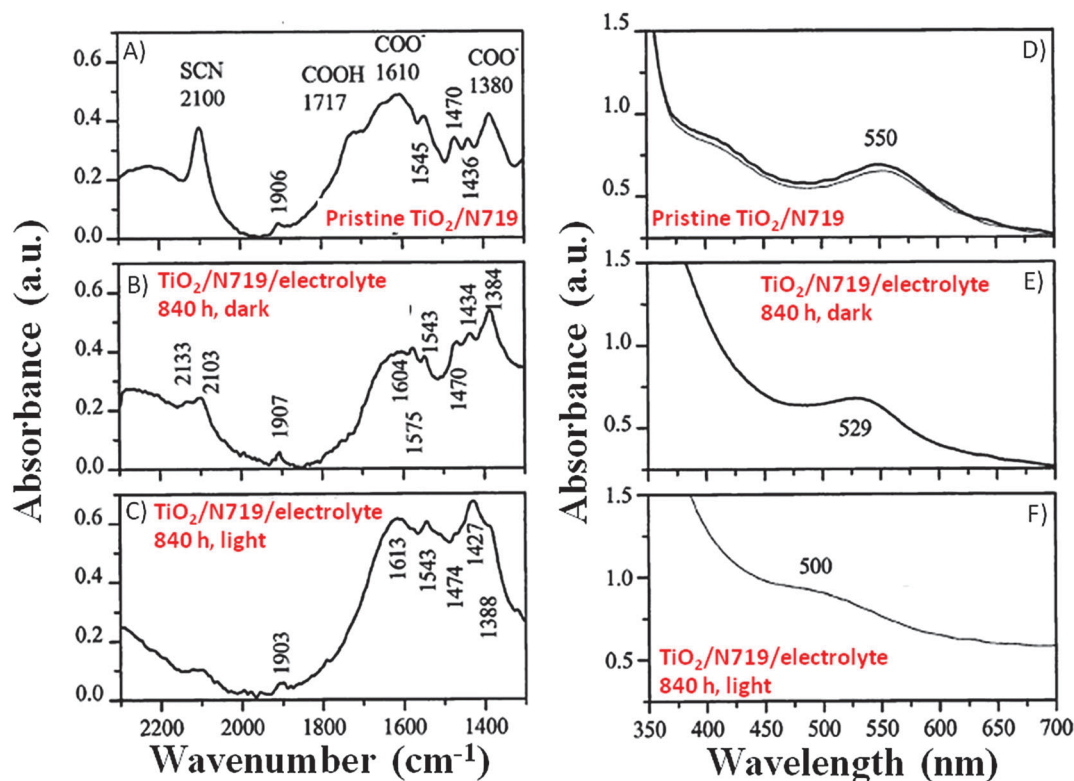


Fig. 4 FTIR (left side) and UV-Vis (right side) spectra of: (A, D) non-treated working electrodes in an Ar atmosphere; (B, E) working electrodes being soaked in a liquid electrolyte (LiI 0.50 M and I<sub>2</sub> 50 mM in MPN) with 5 vol% H<sub>2</sub>O under dark for 840 h; (C, F) working electrodes being soaked in the same liquid electrolyte under visible light illumination for 840 h. FTIR spectra of the treated samples were normalized based on the TiO<sub>2</sub> absorption maximum of the reference sample at 832 cm<sup>-1</sup>. Adapted and reprinted from ref. 85.

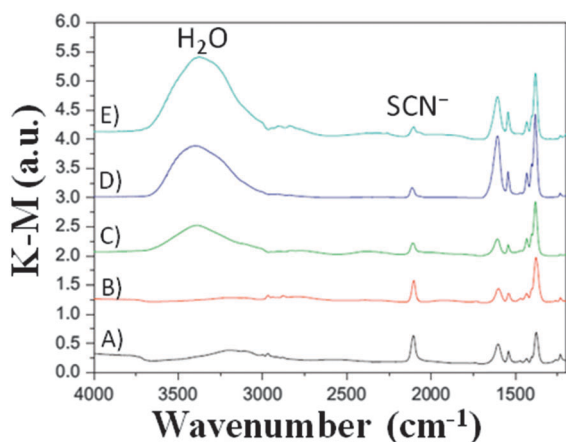


Fig. 5 DRIFT spectra of N719/TiO<sub>2</sub> films immersed in liquid electrolytes (LiI 0.50 M, I<sub>2</sub> 50 mM and TBP 0.50 M in ACN) having different water contents for 192 h: (B) 0 vol% H<sub>2</sub>O; (C) 1 vol% H<sub>2</sub>O; (D) 2 vol% H<sub>2</sub>O; (E) 5 vol% H<sub>2</sub>O. The response of the photoelectrode before immersion is also shown (A) for comparison purposes. Adapted and reprinted from ref. 86.

activate as a weak base TBP, commonly used as a  $V_{oc}$  improver.<sup>44</sup> This would have caused the instability of the  $I_3^-$  anions: as well-known from basic ion chemistry,  $I_3^-$  ions become unstable and  $IO_3^-$  is formed when the pH increases up to 8–10.<sup>96</sup> However, the expected absorption of  $IO_3^-$  at 800 cm<sup>-1</sup> was not detected,<sup>97</sup> thus its adsorption on the TiO<sub>2</sub> electrode was proposed.

Spatially resolved photocurrent mapping<sup>98</sup> has also been proposed by Cameron and coworkers, who coupled Z907 dye-sensitized photoelectrodes with ACN- as well as water-based electrolytes.<sup>99</sup> When vacuum-filled, the ACN-containing cells showed a homogeneous performance all over their volume (Fig. 6A), with the exception of an area of high photocurrent at the top of the device, where dye coverage was higher. As regards aqueous cells, the map showed an area with high photocurrent spreading out from the filling hole (Fig. 6B), where maybe electrolyte filling was relatively poor. To overcome such a defect, aqueous cells were vacuum treated at 80 °C: homogeneous current densities were obtained across the whole area of the cell (Fig. 6C), due to an improved electrolyte penetration. Anyway, all of the aqueous cells underwent a loss of photocurrent (and dye as well) nearby the filling holes; Cameron and coworkers hypothesized that TBP-based alkali solutions could desorb dye from TiO<sub>2</sub>, especially around the filling holes. After the previous study by Tributsch and coworkers,<sup>95</sup> this was the second research article where a synergistic effect between water and TBP was observed to have detrimental effects on the device stability.

### 3.4 Modelling interactions between water and cell components

After being experimentally consolidated that water interacts with the molecules of dye adsorbed onto the semiconductor

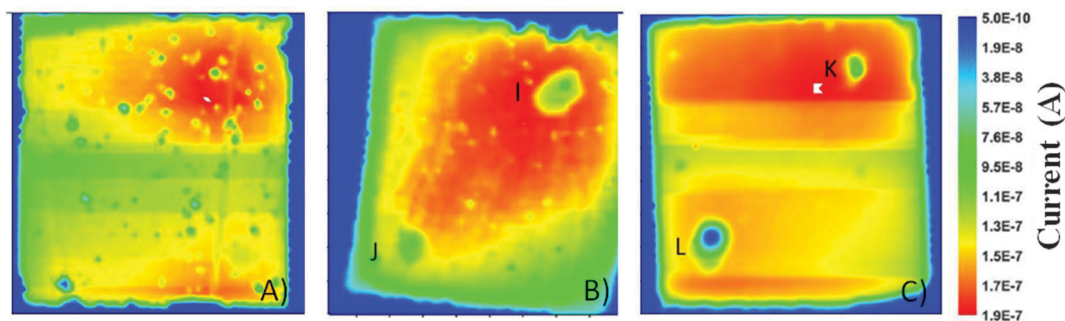


Fig. 6 Photocurrent maps for: (A) vacuum-filled ACN-based cell; (B) vacuum-filled aqueous cell; (C) high temperature vacuum-filled aqueous cell. The positions of the filling holes and the corresponding cold spots are indicated by the letters I–L. The side of each image is 1 cm. Adapted and reprinted from ref. 99.

active material particles, several mechanistic studies have been proposed to investigate this phenomenon. De Angelis and coworkers performed an *ab initio* molecular dynamics simulation and an extensive time-dependent density functional theory (TDDFT) excited state calculation of a squaraine dye<sup>100,101</sup> anchored to an anatase slab exposing the (101) surface,<sup>102</sup> surrounded by 90 water molecules.<sup>103</sup> Water was observed to adsorb, also in overlayer configuration,<sup>104</sup> at the TiO<sub>2</sub> surface. As a result, the blocking function toward recombination of injected electrons with oxidized species in the electrolyte proposed by Lindquist and coworkers<sup>43</sup> was confirmed. As regards the squaraine dye, the TDDFT study demonstrated that an intensive solvent reorganization around the TiO<sub>2</sub>-bonded carboxylic group led to a transition from the starting bridged-bidentate to the monodentate adsorption configuration. The latter was stable for ~6 ps; then, the proton anchored at the surface was transferred to the anionic carboxylic group, resulting in the desorption of the dye, which is illustrated in Fig. 7.

Apart from the dye to water interaction, the concurrent presence of TiO<sub>2</sub> to water as well as organic solvent to water interactions should also be considered in DSSC modelling. It is important to recall that aprotic solvents (e.g., ACN and MPN) are responsible for the high DSSC efficiency,<sup>105</sup> due to their high dielectric constant and solubilisation ability *versus* many inorganic and organic salts and additives.<sup>106,107</sup> Furthermore, transient adsorption spectroscopy (TAS) demonstrated that, when photoanodes were immersed in ACN, a 50% increase in the signal intensity occurred, indicating that aprotic solvents increased the electron injection efficiency. In this respect, Tateyama and coworkers modelled the effect of ubiquitous water contamination in an ACN-based electrolyte solution<sup>108</sup> by means of DFT methods implemented in Car–Parrinello molecular dynamics (CPMD).<sup>109,110</sup> Surprisingly, considering the solvation shell (ACN)<sub>46</sub>(H<sub>2</sub>O)<sub>1</sub> ([H<sub>2</sub>O] = ~0.50 M), it was illustrated that ACN molecules prevented water from coming in contact with the (101) TiO<sub>2</sub> surface by means of a network of hydrogen bonds. However, CPMD also indicated that water molecules that were already adsorbed onto the photoanode before cell assembly were hardly removed because of their strong interaction with the anatase (101) surface. This strong water to TiO<sub>2</sub> interaction (Fig. 8) was observed to be stable up to

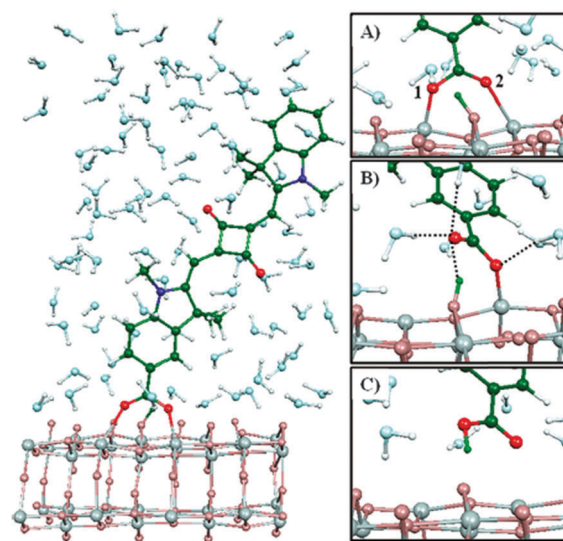


Fig. 7 Squaraine dye adsorbed onto an anatase slab, surrounded by 90 water molecules. In the right hand-sided images, relevant configurations sampled during the TDDFT study are shown: (A) initial bridged-bidentate configuration with labeled oxygen atoms; (B) monodentate configuration; (C) dissociated dye. Note the different proton positions (green). Dashed lines in (B) represent hydrogen bonds to the carboxylic group. Reprinted from ref. 103.

400 K, and could be detrimental for DSSC performance. In fact, photogenerated holes could migrate to water molecules (due to the oxygen atoms charges), thus producing water cation radicals able to interact with the dye molecules onto the TiO<sub>2</sub> surface. Therefore, the common procedure to operate in an anhydrous environment during DSSC fabrication was strongly recommended by the authors.

### 3.5 Effects of sealing conditions and device area

The experimental conditions of DSSC manufacture have been studied by Dittrich and coworkers,<sup>111</sup> who focused their attention on oxygen- and water-related surface defects on the photoanode, such as oxygen vacancies (or Ti<sup>3+</sup> donor states) and hydroxy surface complexes. Cells were assembled either with or without pre-treatment under vacuum. It was observed that  $J_{sc}$  values decreased when the TiO<sub>2</sub> surface was pre-treated under vacuum, due to the





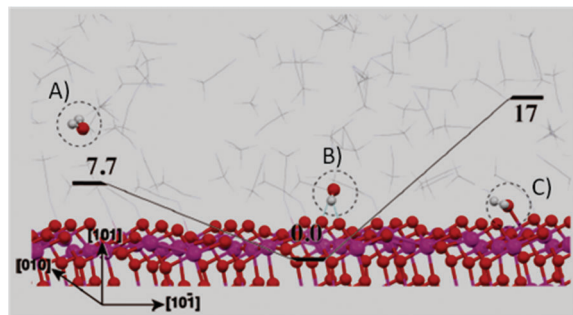


Fig. 8 Structures (with energy values in kcal mol<sup>-1</sup>) of the TiO<sub>2</sub>/bulk-ACN interfaces contaminated with water. (A) Water molecules exist in bulk ACN; (B) the most stable structure of water molecule in bulk ACN and water adsorbed on the TiO<sub>2</sub> surface via a hydrogen bond through the H atom in water; (C) water adsorbed onto the TiO<sub>2</sub> surface via a hydrogen bond through the O atom in water. Adapted and reprinted from ref. 108.

formation of recombination paths for injected electrons.<sup>112,113</sup> The decrease of  $J_{sc}$  was observed to be more pronounced when the cells were pre-treated under a mixed vacuum/water environment, the interaction of -OH groups with TiO<sub>2</sub> being very intense on defective sites.<sup>114</sup> In contrast, chemisorption of water improved  $V_{oc}$  values in both vacuum and oxygen pre-treated cells, as a result of the increase of the barrier height between the TiO<sub>2</sub> CB and the redox mediator potential ( $E$ ).

All of the studies so far reported focusing on water contamination highlighted several detrimental phenomena occurring in different DSSC components: negative shift of the TiO<sub>2</sub> CB, weakening of the TiO<sub>2</sub>-dye interaction up to dye desorption, photoinduced substitution of the -NCS ligand and the related change in the absorption properties of the sensitizer, disappearance of I<sub>3</sub><sup>-</sup> ions, unwelcome interaction of water with both additives (TBP) and salts (LiI). Moreover, thinking about DSSCs large-scale applications it is important to consider that all of these drawbacks are exponentially emphasized with the increase in the overall volumetric dimension of the device. Considering 5 cm × 5 cm cells assembled under an ambient atmosphere (50–60% RH), Kitamura and coworkers observed the progressive decolouration of the photoelectrodes, accompanied by a 40% decrease in  $J_{sc}$  after 800 h at ambient temperature and under dark conditions.<sup>115</sup> This effect was prevented by assembling the cells in the inert atmosphere of an Ar-filled dry glove box (0.1% RH).

At present, two options are available. Specific technologies that may 100% avoid water contamination during the whole manufacturing process of DSSCs as well as during their entire operational life have to be adopted. Alternatively, scientists have to propose dyes, electrodes and electrolytes which can properly operate under a partial or fully aqueous environment, taking advantage of the amount of positive aspects that water would guarantee to third generation PV devices, as stated in the introductory section of this review. We believe that the first option is hardly feasible in terms of cost as well as manufacturing issues (especially because DSSCs are considered promising also for their ease of manufacture), while the development of water-based or fully aqueous DSSCs is certainly the most exciting and

promising prospect as will be detailed and analysed in the following sections.

## 4. Back to 1988: aqueous photoelectrochemical cells

Before discussing the recent findings concerning aqueous DSSCs, it is important to move a step back to a few years before their invention (1991). Indeed, it must be enlightened that the photoelectrochemical cells developed in the 1980–1990 decade were intended to operate with fully aqueous electrolytes.<sup>116,117</sup>

In 1988, Grätzel and coworkers reported on the surprisingly broad band sensitization of TiO<sub>2</sub> to visible light by means of *cis*-Ru(II)L<sub>2</sub>(H<sub>2</sub>O)<sub>2</sub><sup>2-</sup> (L = 2,2'-bipyridyl-4,4'-dicarboxylate).<sup>118</sup> A high surface area fractal anatase film deposited onto a Ti sheet acquired an intense violet coloration due to adsorption of the dye from an acidic aqueous solution. The regenerative photoelectrochemical cell containing a KI 0.10 M and I<sub>3</sub><sup>-</sup> 1.0 mM aqueous electrolyte provided an efficiency of 2% ( $J_{sc}$  = 0.38 mA cm<sup>-2</sup>,  $V_{oc}$  = 0.520 V, fill factor FF = 0.70;  $P_{in}$  = 0.7 sun). Interestingly, the photocurrent remained stable after 4 days of illumination, thus confirming the remarkable stability of the sensitizer; moreover, a maximum incident photon to current efficiency (IPCE) value of 62% was observed. In this study, water was present in the sensitizer molecule, in the dye-uptake solution and in the electrolyte as well.

In 1988, RuL<sub>3</sub><sup>4-</sup> (L = 2,2'-bipyridyl-4,4'-dicarboxylate) was proposed by Grätzel and coworkers as another promising sensitizer for aqueous photoelectrochemical cells;<sup>119</sup> it was also coupled with a new Br-based redox couple (LiBr 1.0 M, Br<sub>2</sub> 1.0 mM and HClO<sub>4</sub> 1.0 mM). Upon irradiation with a 1.58 W m<sup>-2</sup> monochromatic light (470 nm), the cell demonstrated a remarkable efficiency of 12% (short-circuit current  $I_{sc}$  = 135 μA,  $V_{oc}$  = 0.720 V, FF = 0.74; IPCE = 56%); at that time, this was the highest monochromatic conversion yield achieved using a dye-sensitized regenerative photoelectrochemical cell.

With the advent of DSSCs in 1991,<sup>14</sup> aprotic organic solvents replaced water, and cells operating in an aqueous environment were no longer investigated for the following 10–15 years.

## 5. The trend is being reversed: aqueous electrolytes

In the twenty-first century, scientists started again to focus their research efforts on more deeply investigating the effects of water in DSSCs, the final challenging goal being the full replacement of the traditionally used organic solvents. The seminal paper published in 2010 by O'Regan and coworkers may be undoubtedly considered the fundamental contribution for the scientific community in this context.<sup>120</sup> The authors varied the relative fractions of MPN and water to prepare electrolytes (PMII 2.0 M, I<sub>2</sub> 50 mM, GuSCN 0.10 M and TBP 0.5 M; PMII = 1-propyl-3-methylimidazolium iodide) having 0, 20, 40, 60, 80 and 100 vol% H<sub>2</sub>O with respect to MPN. Three noticeable insights were proposed in this work: the use of a



hydrophobic dye (TG6), the introduction of 1% Triton X-100 (see Section 7) to avoid phase separation in the aqueous electrolyte and the selection of a high PMII concentration, which concurrently acted as an iodide source and a surfactant. As shown in Table 1, being iodide more soluble in water than tri-iodide, the addition of water shifted  $E$  towards positive values. Moreover, no detrimental effect on cell performance was observed up to 40 vol% H<sub>2</sub>O. The basic functions of DSSCs (injection, regeneration and transport) worked properly even when using electrolytes having high water contents. Furthermore, the 80 vol%-based cell showed only 7% and 8% losses in  $J_{sc}$  and  $V_{oc}$ , respectively, after 1000 h under 1 sun (35 °C with UV-filter). The desorption of the hydrophobic dye TG6<sup>121,122</sup> was not detected.

Interestingly, it was observed that, by reducing the irradiation intensity, the performance mismatch between aqueous and non-aqueous electrolytes decreased. As shown in Fig. 9, O'Regan and coworkers observed that the fraction of photocurrent lost at low  $P_{in}$  and the saturation photocurrent at higher  $P_{in}$  values were correlated, and an increase in performance variation between identical cells at high water content was present. This represented a key issue: if in Section 3 we reported that the presence of water affected the PV parameters, the stability over time and the visual appearance of DSSCs, now also the worsened reproducibility emerges. Such a scenario opened the debate in the scientific community, and the following arguments were proposed:

- A reduction in the dye excited-state lifetime occurred due to the increase in the dielectric constant when moving from organic solvents towards water.<sup>123</sup> However, even if losses at the injection step could be independent of  $P_{in}$ , they were not expected to strongly vary when identical cells were considered.

- Electrons could be lost by increased recombination with the oxidized dye molecules, due to the increase of  $E$  (see Table 1), which reduced both the driving force and the rate constant for dye regeneration. However, even if losses from this route are usually strongly dependent upon  $P_{in}$ , O'Regan and coworkers performed photovoltage transient experiments which demonstrated that the variation in the electron recombination lifetime was reduced by a factor of two over all the different water contents.

- The real explanation of the behaviour showed in Fig. 9 involved phase segregation inside the pores of TiO<sub>2</sub>, due to non-homogeneity in the pore sizes as well as in the dye coverage. In fact, the concurrent presence of (i) pores having high I<sub>2</sub>/TBP

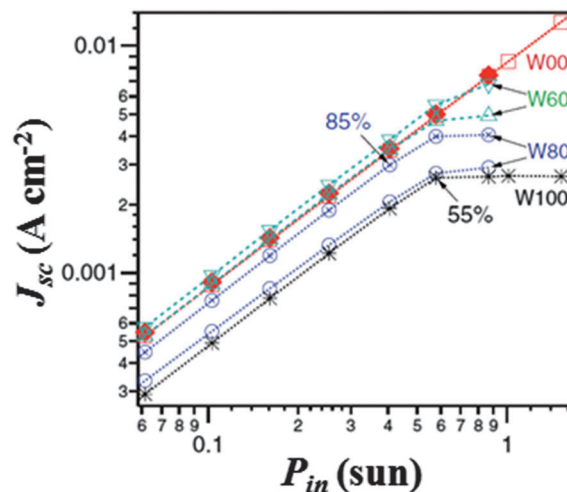


Fig. 9  $J_{sc}$  vs.  $P_{in}$  for selected water-free and water-based DSSCs (see Table 1). Percentages are  $J_{sc}$  relative to the water-free cell at the same  $P_{in}$  value. Adapted and reprinted from ref. 120.

phases, (ii) high H<sub>2</sub>O/I<sup>−</sup> phases and (iii) empty pores resulted in a reduced redox couple diffusion throughout the photoanode. Since phase segregation was sensitive to the exact pore structure, the variation in performance within identical cells at high water content was explained.

Following the insights proposed in the work by O'Regan's group, it is reasonable to assume that the above reported segregation phenomena occurring in water electrolytes should not occur when non-mesoporous films are considered. Nevertheless, to the best of our knowledge and the present literature reports, no scientific group has undertaken this research path so far.

Other literature reports showed as well that the presence of a specifically selected amount of water in the electrolyte can increase the PV conversion efficiency. Weng and coworkers observed that, by increasing the water concentration up to 2.2 M,  $V_{oc}$  and FF values increased monotonically, while  $J_{sc}$  showed a continuous decrease, as reported in Table 2.<sup>124</sup> Efficiency increased from 3.8% to 4.5% in the presence of a 1.7 M H<sub>2</sub>O solution in a standard liquid electrolyte (LiI 0.50 M and I<sub>2</sub> 50 mM in MPN/H<sub>2</sub>O). The authors made the following hypotheses regarding the reasons for the  $V_{oc}$  improvement: an increased electron injection efficiency, a decreased electron density and a retardation of decay rate. Time-resolved infrared absorption spectroscopy, a useful technique to directly detect the CB as well as the trapped electrons,<sup>125–127</sup> showed that – in the presence of water – the optical phonon scattering, which indicates surface trapped states, was observed. It revealed that hydroxide group interaction with TiO<sub>2</sub> gave rise to an increase in the surface-trap states.<sup>114</sup> The interfacial back electron transfer process was retarded in an aqueous environment, and the electron injection efficiency increased up to 1.7 M of water.

Mixtures of water and organic solvents have been recently investigated by Frank and coworkers.<sup>128</sup> Regardless the water content, Table 3 shows that  $V_{oc}$ , FF and  $\eta$  values were higher for the ACN:VAN-based DSSCs than for the MPN-based counterparts,

Table 1  $E$  values for aqueous electrolytes and PV parameters ( $P_{in} = 1$  sun) of the corresponding DSSCs. Electrolytes: PMII 2.0 M, I<sub>2</sub> 50 mM, GuSCN 0.1 M and TBP 0.5 M in H<sub>2</sub>O/MPN. Dye: TG6. Adapted and reprinted from ref. 120

H <sub>2</sub> O (vol%)	$E$ (V)	$J_{sc}$ (mA cm <sup>−2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
0	0.058	11.3	0.73	0.67	5.5
20	0.077	11.8	0.73	0.67	5.7
40	0.103	11.1	0.73	0.68	5.5
60	0.117	8.9	0.75	0.67	4.5
80	0.129	6.5	0.75	0.68	3.3
100	0.136	4.7	0.74	0.69	2.4

**Table 2** PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with electrolytes prepared at various concentrations of water. Electrolytes: LiI 0.50 M and  $\text{I}_2$  50 mM in MPN/ $\text{H}_2\text{O}$ . Dye: N3. Adapted and reprinted from ref. 124

$\text{H}_2\text{O}$ (M)	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
0	16.5	0.47	0.49	3.8
0.6	15.8	0.49	0.53	4.1
1.2	15.1	0.52	0.55	4.3
1.7	14.1	0.54	0.59	4.5
2.2	12.1	0.55	0.62	4.1

**Table 3** PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with electrolytes containing different amounts of water and organic solvents. Electrolyte: PMII 1.0 M,  $\text{I}_2$  0.15 M, GuSCN 0.10 M and NBBI 0.50 M. Dye: Z907. Adapted and reprinted from ref. 128

Organic solvent	$\text{H}_2\text{O}$ (vol%)	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
MPN	0	15.77	0.647	0.658	6.72
MPN	10	16.15	0.662	0.643	6.87
ACN:VAN	0	14.63	0.661	0.725	7.01
ACN:VAN	10	15.67	0.680	0.706	7.52

while  $J_{\text{sc}}$  followed the opposite trend. As regards water addition in the liquid electrolyte (PMII 1.0 M,  $\text{I}_2$  0.15 M, GuSCN 0.10 M and NBBI 0.50 M; NBBI = *N*-butylbenzimidazole), it enhanced both  $J_{\text{sc}}$  and  $V_{\text{oc}}$  for any of the organic solvents used, but lowered FF values. Such a behaviour was quite different with respect to what reported by Weng and coworkers,<sup>124</sup> who used N3 dye instead of Z907. Further investigation was carried out by means of electrochemical impedance spectroscopy (EIS) under bias light at 680 nm. It showed that the addition of water decreased the difference in the potential values between  $E_{\text{c}}$  and  $E$  of about 28 mV: this resulted from a downward shift of 10 mV for  $E$  toward positive electrode potentials, along with a 38 mV downward shift of the  $\text{TiO}_2$  CB. All of these changes in the potential values of the different energy levels were attributed to an increased proton concentration at the photoanode surface.<sup>129,130</sup> By combining transport and recombination measurements, it was evidenced that the addition of water increased the charge-collection efficiency.<sup>131,132</sup> This effect, together with the higher charge-injection efficiency derived from the downshift of the  $\text{TiO}_2$  CB upon water addition,<sup>133</sup> led to improved  $J_{\text{sc}}$  values. Frank and coworkers also expected a reduced  $V_{\text{oc}}$  due to the lower gap in the potential between  $E_{\text{c}}$  and  $E$ ; however, the addition of water increased the photovoltage of about 15–19 mV (Table 3). Such a behaviour was justified by considering the decreased recombination in aqueous cells by a factor of 4–5.<sup>86,134</sup> As regards the decreased FF values, an increase in the dark exchange current was detected, which was attributed to a larger dark electron concentration in the presence of water.<sup>84</sup> Outstandingly, the  $J$ - $V$  characteristics of the DSSCs assembled using electrolytes prepared both with and without the addition of water showed essentially the same aging behaviours upon 1000 h of continuous light soaking. This represents a key issue, quite in contrast with what reported in Section 3: does the presence of water have an influence on the cell stability or not? Dye nature, electrolyte composition or dye-electrolyte combination: what the preponderant factor is? From Frank and coworkers study,

**Table 4** PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with electrolytes based on water and/or ethanol–water mixtures recovered from industrial effluents. Electrolyte: KI 0.50 M and  $\text{I}_2$  25 mM. Adapted and reprinted from ref. 138

Solvent	Dye	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
$\text{H}_2\text{O}$	N3	2.70	0.37	0.60	0.6
$\text{H}_2\text{O}$	N719	2.00	0.40	0.63	0.5
$\text{H}_2\text{O} : \text{EtOH}$ 65 : 35	N3	4.68	0.47	0.59	1.3
$\text{H}_2\text{O} : \text{EtOH}$ 65 : 35	N719	4.04	0.48	0.57	1.1

it seems that the adoption of a thermally stable electrolyte solvent (MPN/ $\text{H}_2\text{O}$ ) and a hydrophobic dye (Z907) can lead to equally stable water-free and water-based DSSCs.

The remarkable advantage in terms of safety as well as eco-compatibility of replacing organic solvents by water has been already detailed in the introductory section. However, it should be also considered that some industrial processes (*i.e.*, biotechnology and food industry) produce water–ethanol mixtures as effluents, the separation of which is not economically advantageous. The recovery of these wastewaters surged as a hot research topic only recently,<sup>135–137</sup> after the pioneering work of Miyasaka and coworkers, who proposed their reuse in aqueous DSSCs.<sup>138</sup> Table 4 shows the enhancement of  $J_{\text{sc}}$  values when using EtOH– $\text{H}_2\text{O}$  solutions, which was attributed to the activation of the mesoporous  $\text{TiO}_2$ /electrolyte (KI 0.50 M and  $\text{I}_2$  25 mM) interface. Pristine photoanodes were found not to be hydrophilic enough to absorb water into their interior pores, thus the addition of alcohols improved their wettability because of the higher affinity with the surface functionalities present at the inner surface of the mesopores. Moreover, the addition of ethanol reduced both the surface tension and the viscosity of the aqueous electrolyte, thus increasing the effective area of the electrochemically active  $\text{TiO}_2$ –electrolyte interface with respect to the pure aqueous system, in which a hydrogen-bonded large cluster of water molecules could not effectively penetrate the whole mesoporous structure. As a result, efficiency values were doubled.

The brief analysis of the recent scientific reports has evidenced a real turnaround in the DSSC research community: water is no longer intended to be a poisoner to be utterly avoided, in fact it started to be gradually introduced in progressively larger amounts. This novel trend is accompanied by electrochemical and spectroscopic investigation of the new phenomena and new interfaces, to guarantee the useful insights towards the improvement of the device characteristics. As will be explained in the following sections, each cell component is currently the subject of thorough investigation from the physical as well as engineering viewpoint in order to ensure its highest possible efficiency in an aqueous environment.

## 6. Additives for aqueous electrolytes

Nowadays, it is widely known that the introduction of specifically selected additives in the electrolyte may guarantee remarkable improvements in the PV performance of a DSSC.<sup>139–141</sup> Indeed, for the same dye, while  $J_{\text{sc}}$  is closely related to the type





and concentration of the redox mediator under use,  $V_{oc}$  can be ameliorated by introducing nitrogen-containing heterocyclic compounds, such as pyridines, aminotriazole, pyrimidine, aminothiazole, pyrazole and quinoline. Above all, in 1993 Grätzel and coworkers introduced TBP.<sup>81</sup> Being adsorbed onto the surface of the  $TiO_2$  photoelectrode, it prevented the leakage of the injected electrons in the electrolyte and also prevented  $I_3^-$  from contacting the surface of the photoanode. As reported in the course of this review, TBP has been already introduced in some aqueous electrolytes; however, it showed rather low solubility in water. Thus, alternative additives have been proposed for aqueous DSSCs (in this section) or their solubilisation has been achieved through the introduction of surfactants (see Section 7).

*N*-Alkylbenzimidazole derivatives represent another category of organic additives which were found to behave similarly to TBP. Indeed, *N*-methylbenzimidazole (NMBI) is often added in liquid electrolytes both for  $TiO_2$ <sup>142</sup> and ZnO-sensitized DSSCs.<sup>143,144</sup> Yang and coworkers proposed several bis-benzimidazole derivatives containing an ethylene glycol repeating unit (BBEG<sub>n</sub>, see Fig. 10) for aqueous DSSCs (DMPII 0.50 M, LiI 0.10 M,  $I_2$  50 mM and TBP/BBEG<sub>n</sub> 0.50 M in ACN/ $H_2O$ ; DMPII = 1,2-dimethyl-3-propylimidazolium iodide) and evaluated the cell durability.<sup>145</sup> As listed in Table 5,  $V_{oc}$  and FF values were found to be higher in all the water-based cells. This was ascribed to the strong adsorption of water onto the  $TiO_2$  surface, which blocked the reaction between  $I_3^-$  ions and injected electrons; moreover, as previously stated by O'Regan's group,<sup>120</sup> the electrochemical potential of the iodine-based redox mediator in water-based cells was positively shifted. As a drawback, the addition of water led to the detachment of the adsorbed N719 dye molecules, thus limiting the flux of the injected electrons from the excited states of the dye which adversely influenced  $J_{sc}$  values.

As shown in Table 5, the novel BBEG<sub>n</sub> additives proposed by Yang and coworkers did not guarantee improved performances if compared to TBP. Nevertheless, the resulting devices demonstrated enhanced stability upon the aging test, while TBP-based cell efficiency dropped significantly (62% in 135 h). Indeed, the chemical structure of BBEG<sub>n</sub> additives incorporated ethylene glycol linkages between two benzimidazoles, which produced H-bond bonding sites for the water molecules. In this way, ethylene glycol linkages sequestered the water molecules, thus preventing their interaction with the  $TiO_2$ -dye linkage as well as the dye -SCN functional group. Moreover, the BBEG<sub>n</sub>/ $H_2O$  phase solvated  $I_3^-$  ions, thus decreasing their concentration in the dyed  $TiO_2$  surface and avoiding back electron transfer phenomena. Summarising, by the proper use of specifically selected and optimised additives, aqueous DSSCs may become

**Table 5** PV parameters ( $P_{in}$  = 1 sun) of DSSCs assembled with electrolytes based on pure ACN or ACN- $H_2O$  mixtures. Electrolytes: DMPII 0.50 M, LiI 0.10 M,  $I_2$  50 mM and TBP/BBEG<sub>n</sub> 0.50 M. Dye: N719. Adapted and reprinted from ref. 145

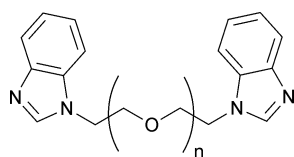
Additive	$H_2O$ (vol%)	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
TBP	0	14.99	0.73	0.65	7.14
TBP	10	5.05	0.80	0.70	2.82
BBEG <sub>n</sub> , $n = 1$	0	11.31	0.78	0.60	5.27
BBEG <sub>n</sub> , $n = 1$	10	4.19	0.80	0.69	2.31
BBEG <sub>n</sub> , $n = 3$	0	13.04	0.78	0.62	6.29
BBEG <sub>n</sub> , $n = 3$	10	5.75	0.80	0.64	2.96

as much stable as (or eventually even more stable than) their standard aprotic counterparts. In this respect, the search for new additives for water-based liquid electrolytes is currently under intensive investigation in many research laboratories.

## 7. Surfactants: key ingredients for aqueous DSSCs

An electrolyte of a DSSC is a fairly complex chemical system: the solvent should be able to solubilise both inorganic salts and non-polar species (*i.e.*, iodine and additives such as TBP and NMBI). When the aqueous electrolyte contains a mixture of water and organic solvents, homogeneity and stability of all the components in solution are fairly easy to be obtained (once optimized their concentrations), as described so far. On the other hand, if a fully aqueous DSSC has to be fabricated, a way to solubilise all of the aforementioned electrolyte components has to be found. This is a particularly complex work, which requires the modification or the functionalization of the traditionally used chemical compounds, or the introduction of a new class of additives: surfactants. The ability of surfactants in lowering the surface (or interfacial) tension between two liquids or between a liquid and a solid is well-established;<sup>146</sup> their application as detergents, wetting agents, emulsifiers, foaming agents and dispersants are vitally important in our daily life.<sup>147,148</sup> The scientific community considers surfactants as key ingredients for drug delivery systems<sup>149</sup> as well as environmental decontamination and rehabilitation procedures.<sup>150</sup> Several applications are also envisaged in the field of energy conversion and storage<sup>151</sup> due to the unique properties of surfactants particularly in the synthesis and functionalization of porous anodic<sup>152,153</sup> and cathodic<sup>154,155</sup> nanostructures.

For what concerns aqueous DSSCs, surfactants have initially been used to segregate water molecules within the micellar phase, thus promoting its solubility in the organic liquid electrolyte. The use of Triton X-100,  $C_{14}H_{22}O(C_2H_4O)_n$ , a non-ionic surfactant having a hydrophilic polyethylene oxide chain and an aromatic hydrocarbon lipophilic or hydrophobic group, was proposed by Kim and coworkers.<sup>156</sup> They introduced Triton X-100 in the 20 mM concentration into an aqueous liquid electrolyte (LiI 0.10 M, HDMII 0.60 M,  $I_2$  50 mM and TBP 0.50 M in MPN/ $H_2O$ , HDMII = 1-hexyl-2,3-dimethylimidazolium iodide), and observed increased  $V_{oc}$  and FF values while increasing the amount of water (0.0–4.4 M); conversely,  $J_{sc}$



**Fig. 10** Chemical structure of benzimidazole-based additives (BBEG<sub>n</sub>) used in aqueous DSSCs, ref. 145.



monotonically decreased. A peak efficiency value of 5.9% when  $[H_2O] = 2.2\text{ M}$  was obtained (Table 6).

Three hypotheses may be elaborated to justify the increased  $V_{oc}$  values observed in surfactant-laden liquid electrolytes:

- The reduction in the back electron transfer from the  $TiO_2$  CB to the  $I_3^-$  ions in the electrolyte: in fact,  $I_3^-$  ions have higher solubility in the hydrophilic Triton X-100/ $H_2O$  phase than at the interface with the photoanode.

- The negative shift of the flat band potential of  $TiO_2$ : some of the protons transferred by the sensitizer (which contains  $-COOH$  groups) to the  $TiO_2$  surface are removed by the hydrophilic Triton X-100/ $H_2O$  phase, thus leading to a shift of the flat band potential which becomes less positive than that occurring in the absence of the surfactant-added aqueous phase.<sup>157,158</sup>

- The positive shift of  $E$ .

$J_{sc}$  decreased because of the reduced number of injected electrons, due to the improved  $V_{oc}$  caused by the increase of the barrier height for their injection.<sup>159</sup> Interestingly, the trend observed for the photocurrent differed from that expected by Kim and coworkers by means of chronoamperometry and EIS measurements. Indeed, an increase of the limiting current for the oxidation of  $I^-$  was detected. This accounted for the enhancement in the diffusion of  $I^-$  ions in the presence of Triton X-100 and water, as also indicated by the decrease in the series ( $R_s$ ) as well as charge transfer resistance at the counter electrode ( $R_{CE}$ ) measured for aqueous DSSCs (Table 6). Along with the observed decrease in viscosity, this should have resulted in improved  $J_{sc}$  and FF values.

The long-term stability of Triton X-100-added DSSCs was surprisingly high (–19% after 7 days under dark), even higher than the corresponding aprotic cell (–67%), thanks to the increased stability of  $J_{sc}$ . In fact, Triton X-100 was able to strongly retain the molecules of solvent, thus suppressing their evaporation; its aqueous phase could even extract the water traces which were inevitably introduced during cell fabrication.<sup>160</sup> The harmful effects caused by the presence of water during irradiation (*i.e.*, hydrogen evolution and photocatalytic processes) were avoided, thus demonstrating that a surfactant-added aqueous DSSC can perform better than a standard cell. However, for the sake of the reader we must point out that the cells of this article were not sealed with a rigorous procedure; indeed, a 67% efficiency decrease in a week only is not a data comparable with the state of the art of sealed liquid DSSCs.<sup>161,162</sup>

Data reported in Section 5 show that the performance of 100% water-based DSSCs is still low compared with those of

traditional DSSCs, and one of the reasons is surely the incomplete wetting of the dye-coated  $TiO_2$  interface by the aqueous electrolyte. In this context, it is well known that the addition of a surfactant increases the wettability and minimizes the separation between materials in two different phases. Yan and coworkers investigated a series of surfactants in organic solvent-free DSSCs (NaI 2.0 M,  $I_2$  0.20 M and GuSCN 0.10 M): hexadecyltrimethylammonium bromide (CTAB),  $N,N,N$ -trimethyl-3-(perfluorooctyl sulfonamido)-propan-1-aminium iodide (FC-134), bis(2-ethylhexyl) sulfosuccinate sodium salt (AOT) and triethylammonium perfluorooctane sulphonate (FK-1).<sup>163</sup> As can be seen in Table 7, both anionic (AOT, FK-1) and cationic (CTAB, FC-134) surfactants dramatically improved the PV performances of N719-sensitized DSSCs. At the same time, higher charge-transfer resistance values were measured at the  $TiO_2$ /electrolyte interface, and the resulting reduced charge recombination and increased electron lifetime were attributed to the enhanced interfacial compatibility due to the addition of the surfactants.<sup>164,165</sup> On the other hand, Mott-Schottky experiments and capacitance measurements suggested that the surfactant addition did not shift the  $TiO_2$  CB edge, thus contradicting what previously reported by Kim and coworkers.<sup>156</sup> In the presence of surfactant-added aqueous electrolytes, photoanodes showed reduced contact angle (CA) values compared to the corresponding surfactant-free ones (Fig. 11), thus further demonstrating the improved wettability of the photoanode/electrolyte interface.<sup>166,167</sup>

Sunlight-to-electricity conversion of surfactant-added DSSCs was improved under low  $P_{in}$ ; as an example, the efficiency of the FC-134 (0.2 wt%)-laden cell increased from 3.96 to 4.66% when  $P_{in}$  decreased from 1.0 to 0.5 sun. The lower efficiency yielded under full sunlight irradiation intensity, maybe due to the inefficient charge screening of the electron transport in the mesoporous  $TiO_2$ ,<sup>168,169</sup> paved the way to the use of aqueous cells in a relatively dark environment, where DSSCs are increasingly establishing themselves as the leading device.<sup>170,171</sup> As regards the long-term stability, the surfactant-free cell provided only 17% of the initial efficiency after 50 days under constant 1.0 sun illumination (at room temperature, RT, with UV-filter), where the CTAB-laden one was able to retain the 48%. Such an improvement was assigned to the surfactant molecules adsorbed at the surface of the photoanode. The resulting coating layer prevented  $I_3^-$  ions from contacting the dye-coated  $TiO_2$  active material particles, reduced the recombination rate and avoided the sensitizer degradation by enhancing the dye-regeneration rate.

**Table 6** PV ( $P_{in} = 1$  sun) and electrochemical parameters of DSSCs assembled with electrolytes containing different amounts of water. Electrolytes: LiI 0.10 M, HDMII 0.60 M,  $I_2$  50 mM, TBP 0.50 M in MPN/ $H_2O$ . Dye: N719. Adapted and reprinted from ref. 156

$H_2O$ (M)	$J_{sc}$ ( $mA\ cm^{-2}$ )	$V_{oc}$ (V)	FF	$\eta$ (%)	$R_s$ ( $\Omega$ )	$R_{CE}$ ( $\Omega\ cm^{-2}$ )
0.0	13.44	0.74	0.53	5.3	20.97	2.74
1.1	12.10	0.79	0.57	5.4	20.90	2.18
2.2	11.77	0.81	0.62	5.9	20.79	2.12
3.3	11.65	0.82	0.59	5.7	20.83	1.64
4.4	10.38	0.81	0.61	5.1	20.74	1.36

**Table 7** PV parameters ( $P_{in} = 1$  sun) of DSSCs assembled with electrolytes encompassing different kinds of surfactants. Electrolyte: NaI 2.0 M,  $I_2$  0.20 M and GuSCN 0.10 M in  $H_2O$ . Dye: N719. Adapted and reprinted from ref. 163

Surfactant	$J_{sc}$ ( $mA\ cm^{-2}$ )	$V_{oc}$ (V)	FF	$\eta$ (%)
None	7.50	0.51	0.66	2.51
CTAB (0.1 wt%)	8.94	0.51	0.69	3.14
AOT (0.1 wt%)	8.44	0.50	0.71	2.98
FK-1 (0.1 wt%)	9.99	0.51	0.69	3.55
FC-134 (0.1 wt%)	9.69	0.51	0.70	3.56
FC-134 (0.2 wt%)	10.97	0.53	0.68	3.96



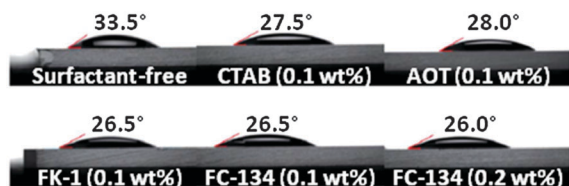


Fig. 11 CA measurements of different aqueous electrolytes at the surface of dye-coated  $\text{TiO}_2$  films. Adapted and reprinted from ref. 163.

Due to its positive effect, AOT was recently employed by Jang and coworkers with the aim of controlling both the total and the local concentration of the redox couple (BMII 0.70 M,  $\text{I}_2$  30 mM, GuSCN 0.10 M and TBP 0.50 M in ACN/VAN; BMII = 1-butyl-3-methylimidazolium iodide).<sup>172</sup> By means of its  $-\text{SO}_3^-$  group,<sup>173</sup> AOT can be chemisorbed onto the  $\text{TiO}_2$  nanoparticles, thus hindering the access of  $\text{I}_3^-$  anions and facilitating the access of  $\text{I}^-$  ones to enhance the dye regeneration rate. Upon concurrent addition of water, the absorbance of  $\text{I}_3^-$  at 363 nm decreased due to the triiodide hydrolysis reaction: one of the resulting products was  $\text{I}^-$ , which further assisted the dye regeneration efficiency (from 71% to 78%). Table 8 shows that such a combined effect of water and AOT led to the improvement in both  $J_{\text{sc}}$  and  $V_{\text{oc}}$  values; the  $R_{\text{CE}}$  was improved as well, thus demonstrating that the triiodide reduction reaction at the counter electrode/electrolyte interface occurred much more efficiently in the AOT/water-laden devices. At present, the 10.8% efficiency value obtained by Jang and coworkers (see the insight outlined in Fig. 12) is the highest

Table 8 PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with electrolytes laden with water and/or AOT. Electrolyte: BMII 0.70 M,  $\text{I}_2$  30 mM, GuSCN 0.10 M, TBP 0.50 M in ACN/VAN. Dye: N719. Adapted and reprinted from ref. 172

Additives	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)	$R_{\text{CE}}$ ( $\Omega$ )
None	15.3	0.832	0.73	9.3	6.93
AOT (1.0 mM)	16.5	0.829	0.74	10.1	4.93
$\text{H}_2\text{O}$ (10 mM)	16.9	0.850	0.71	10.2	6.89
AOT + $\text{H}_2\text{O}$	17.5	0.850	0.73	10.8	4.83

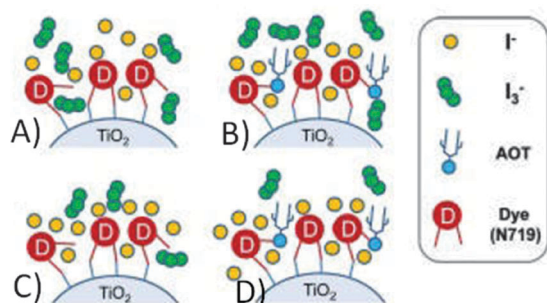


Fig. 12 Local concentration control of the  $\text{I}_3^-/\text{I}^-$  redox couple by the hydrogen bonding interaction between the AOT and the carboxyl group of the N719 dye. (A) AOT- and water-free system; (B) in the presence of AOT,  $\text{I}_3^-$  is hindered from approaching the  $\text{TiO}_2$ /dye surface; (C) accelerated hydrolysis of  $\text{I}_3^-$  by water; (D) AOT and water are simultaneously added to reduce the recombination rate and to enhance the dye regeneration yield. Adapted and reprinted from ref. 172.

value ever measured for a DSSC containing water. However, we cannot call it “aqueous DSSC”, as the amount of water added to the electrolyte was minimal (10 mM).

## 8. Exploiting water to introduce new redox couples

As stated in Section 2, several redox mediators have been proposed during the past decades;<sup>50</sup> among others, the iodide/triiodide couple<sup>51</sup> and cobalt complexes<sup>29</sup> have proven to be the most stable and the best performing, respectively. Nevertheless, due to their ability in solubilising compounds which are insoluble in conventional aprotic organic solvents, the use of water as a solvent opened up new possibilities in the preparation and selection of the redox mediator.

The first exotic redox couple for aqueous DSSCs was a cerium-based compound. It was proposed by Teoh and coworkers in 2008.<sup>174</sup>  $\text{Ce}(\text{NO}_3)_3$  0.10 M and  $\text{Ce}(\text{NO}_3)_4$  50 mM were dissolved in a 35:65 EtOH: $\text{H}_2\text{O}$  mixture. This electrolyte was coupled with a variety of commercial and natural sensitizers, such as crystal violet, mercurochrome, chlorophyll, extracts of *Bongainvillea brasiliensis*, *Garcinia suubelliptica*, *Ficus Reusa* and *Rhoeo spathacea*. Indeed, due to their simple preparation techniques, wide availability and low cost, natural dyes could be the best option for an aqueous, thus truly eco-friendly solar energy conversion device. As a further insight, Teoh and coworkers used their electrolyte with a 38 nm-thick Schottky barrier<sup>175</sup> composed of Au NPs deposited onto the photoanode, in order to improve the efficiency of the electron injection.<sup>176,177</sup> As a result, electrons in the LUMO of the dye passed through the Au thin layer by tunnelling the  $\text{TiO}_2$  CB, thus avoiding the electron recombination reaction.  $J_{\text{sc}}$  and  $V_{\text{oc}}$  values measured in the presence of commercial dyes were found to be lower than those of natural dyes; the highest efficiency ( $\eta = 1.49\%$ ,  $J_{\text{sc}} = 10.9 \text{ mA cm}^{-2}$ ,  $V_{\text{oc}} = 0.496 \text{ V}$ , FF = 0.27) was obtained in the presence of *Rhoeo spathacea* (RhS).

A cerium-based aqueous electrolyte (30:70 in EtOH: $\text{H}_2\text{O}$ ) was also coupled with natural pigments, such as the green and the red parts of *Codiaeum variegatum* and *Aglaonema*. Moreover, with the aim of improving the photovoltage, Su and coworkers<sup>178</sup> coupled this system with a  $\text{ZrO}_2$  photoanode characterised by a wide band gap energy (5.8 eV) and a CB higher than that of  $\text{TiO}_2$ .<sup>179,180</sup> When the green part of *Codiaeum variegatum* (CV-G) was used, a  $V_{\text{oc}}$  of 0.624 V was achieved, definitely higher than those usually measured for natural pigment-sensitized  $\text{TiO}_2$ -based DSSCs.<sup>181</sup> Furthermore, the effective dielectric constant and refractive index of the  $\text{ZrO}_2$  layer were experimentally tuned, and the light transmission of the photoanode was improved, resulting in a cell efficiency of 0.69% ( $J_{\text{sc}} = 0.52 \text{ mA cm}^{-2}$ , FF = 0.53).

Working in aqueous media allows the application of redox couples such as  $\text{Fe}(\text{CN})_6^{4-/3-}$ , which can overcome iodate formation, light absorption and corrosiveness typical of standard iodine-based mediators. In 2012, Spiccia and coworkers introduced the ferrocyanide/ferricyanide redox couple in a truly water-based electrolyte: 0.40 M  $\text{K}_4\text{Fe}(\text{CN})_6$ , 40 mM  $\text{K}_3\text{Fe}(\text{CN})_6$ , 0.10 M KCl and 0.1 vol% Tween 20, dissolved in  $\text{H}_2\text{O}$  at pH 8.<sup>182</sup> The redox



**Table 9** PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with  $\text{Fe}(\text{CN})_6^{4-/3-}$  and  $\text{I}^-/\text{I}_3^-$ -based electrolytes, in the presence of different solvents. Dye: MK-2. Adapted and reprinted from ref. 182

Redox couple	Solvent	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
$\text{Fe}(\text{CN})_6^{4-/3-}$	$\text{H}_2\text{O}$	7.21	0.761	0.75	4.10
$\text{I}^-/\text{I}_3^-$	ACN	11.86	0.769	0.66	6.05

potentials of  $\text{Fe}(\text{CN})_6^{4-/3-}$  and  $\text{I}^-/\text{I}_3^-$  being similar,<sup>183</sup> a typical hydrophobic carbazole dye (MK-2) was used; besides showing an high molar extinction coefficients,<sup>184</sup> it allowed the use of relatively thin  $\text{TiO}_2$  films, thus resulting in reduced interfacial area for recombination as well as improved charge extraction. Moreover, it showed only faint signs of desorption when stored under water for 30 days (conversely, the complete desorption of Z907 dye was observed in the same conditions).  $\text{Fe}(\text{CN})_6^{4-/3-}$ -based DSSC showed an efficiency equal to 4.1% (Table 9);  $J_{\text{sc}}$  was the only value which decreased with respect to the corresponding  $\text{I}^-/\text{I}_3^-/\text{ACN}$ -based cell (MPII 0.60 M, LiI 0.10 M,  $\text{I}_2$  0.20 M and TBP 0.50 M; MPII = 1-methyl-3-propylimidazolium iodide). It was supposed that ferrocyanide, being able to sensitize  $\text{TiO}_2$ ,<sup>185</sup> contributed as a co-sensitizer, but its performance was obviously lower than that of MK-2. By means of intensity modulated photovoltage and photocurrent spectroscopies, also combined with charge extraction analysis,<sup>186</sup> it was demonstrated that the  $\text{Fe}(\text{CN})_6^{4-/3-}$ -based electrolyte guaranteed a three orders of magnitude faster rate of recombination if compared to the reference couple. Besides, no difference in  $V_{\text{oc}}$  values was observed, which was related to the negative CB shift of 150 mV induced by  $\text{Fe}(\text{CN})_6^{4-/3-}$ . The only drawback of this new redox couple was the performance decay measured under unfiltered white light illumination, which was caused by the well-known photolysis and photocatalytic decomposition of the ferrocyanide/ferricyanide redox couple.<sup>187,188</sup> By introducing a 480 nm long-pass filter, no performance decay was observed. Anyway, modification of the  $\text{TiO}_2$  surface or its replacement with an alternative wide band-gap semiconductor should be considered for the fabrication of cells stable under full solar irradiation; otherwise, also the replacement of the cyanide ligands with stronger binding units may be taken into account.

Experimental investigation showed that the poor solubility of  $\text{I}_2$  in water is the major limiting factor affecting aqueous DSSC performance. Even if this drawback can be solved by adopting suitable surfactants (see Section 7), the challenge of finding non-corrosive redox couples, which may also guarantee weak light absorption in the visible light region, has encouraged researchers to test sulphur-based systems, such as thiolate/disulphide.<sup>189–192</sup> Despite most of these species demonstrating rather low water solubility, Sun and coworkers identified a water-soluble thiolate/disulphide redox couple. It consisted of 1-ethyl-3-methylimidazolium 4-methyl-1,2,4-triazole-3-thiolate ( $\text{TT}^-\text{EMI}^+$ ) and 3,3'-dithiobis[4-methyl-(1,2,4)-triazole] (DTT) (Fig. 13,<sup>193</sup>). The resulting truly aqueous electrolyte ( $\text{TT}^-\text{EMI}^+$  0.20 M, DTT 0.20 M, TBP 0.50 M and Triton X-100 1 vol%) was coupled with a hydrophobic dye having a short methoxyl chain in the donor unit (D45, Table 14), which increased the probability of interaction with



**Fig. 13** Structures of the  $\text{TT}^-\text{EMI}^+/\text{DTT}$ -based redox couple. Adapted and reprinted from ref. 193.

**Table 10** PV parameters ( $P_{\text{in}} = 1$  sun) of DSSCs assembled with  $\text{TT}^-\text{EMI}^+/\text{DTT}$ - and  $\text{I}^-/\text{I}_3^-$ -based electrolytes, in the presence of different dyes and solvents. Adapted and reprinted from ref. 193

Redox couple	Solvent	Dye	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
$\text{TT}^-\text{EMI}^+/\text{DTT}$	$\text{H}_2\text{O}$	D45	7.2	0.650	0.55	2.6
$\text{TT}^-\text{EMI}^+/\text{DTT}$	$\text{H}_2\text{O}$	D51	9.5	0.610	0.59	3.5
$\text{TT}^-\text{EMI}^+/\text{DTT}$	ACN:VAN	D45	3.5	0.570	0.53	1.1
$\text{I}^-/\text{I}_3^-$	ACN:VAN	D45	11.7	0.790	0.61	5.6

the redox system. An efficiency equal to 2.6% was recorded (Table 10). Replacing water with ACN did not modify  $E$ , but led to the desorption of the dye from the  $\text{TiO}_2$  surface. When compared to a traditional  $\text{I}^-/\text{I}_3^-$ -based system (DMHII 0.60 M, LiI 60 mM,  $\text{I}_2$  40 mM and TBP 0.40 M in ACN/VAN; DMHII = 3-hexyl-1,2-dimethylimidazolium iodide), the aqueous electrolyte showed remarkably reduced diffusion coefficients, being  $D(\text{TT}^-)$  and  $D(\text{DTT})$  equal to  $4.01 \times 10^{-6}$  and  $1.87 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ , respectively, while  $D(\text{I}^-)$  and  $D(\text{I}_3^-)$  were equal to  $1.70 \times 10^{-5}$  and  $1.10 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ , respectively, thus almost one order of magnitude different. However, since PV measurements under different light intensities did not show any enhancement in the performance under weak light intensity, low electrolyte diffusion coefficients were not likely to be responsible for the low  $J_{\text{sc}}$  recorded; on the other hand, it was observed that D45 regeneration was slowed down by a factor of four in the presence of  $\text{TT}^-\text{EMI}^+/\text{DTT}$ . When D45 dye was replaced by D51 (Table 14), efficiency jumped up to 3.5% (Table 10), which was attributed to the higher extinction coefficient and broader absorption spectrum of the sensitizer. During the stability test, aqueous DSSCs were able to assure only 63% of their initial efficiency after 4 h of light soaking at RT. However, despite FF values decreasing due to the poor stability of DTT in solution, Sun and coworkers highlighted that the optimization of the electrolyte composition could be considered as an effective strategy to overcome stability issues in aqueous DSSCs.

As previously stated, the recent efficiency records of DSSCs have been obtained using cobalt complexes as redox mediators.<sup>29,35</sup> Being transition metal ion complexes, they are highly soluble in water which accounts for their suitable application in aqueous DSSCs. Indeed, Spiccia and coworkers easily dissolved 0.20 M of  $[\text{Co}(\text{bpy})_3]^{2+}$  and 40 mM of  $[\text{Co}(\text{bpy})_3]^{3+}$  in water, along with the addition of NMBI (0.70 M) as a  $V_{\text{oc}}$ -booster and various amounts of poly(ethylene glycol) (PEG 300) to minimize phase separation between the hydrophobic dye (MK-2) and the aqueous electrolyte.<sup>194</sup> A bell-shaped performance trend was observed as a function of the amount of PEG 300 added; the best energy conversion efficiency of 4.2% ( $J_{\text{sc}} = 8.3 \text{ mA cm}^{-2}$ ,  $V_{\text{oc}} = 0.685 \text{ V}$ ,



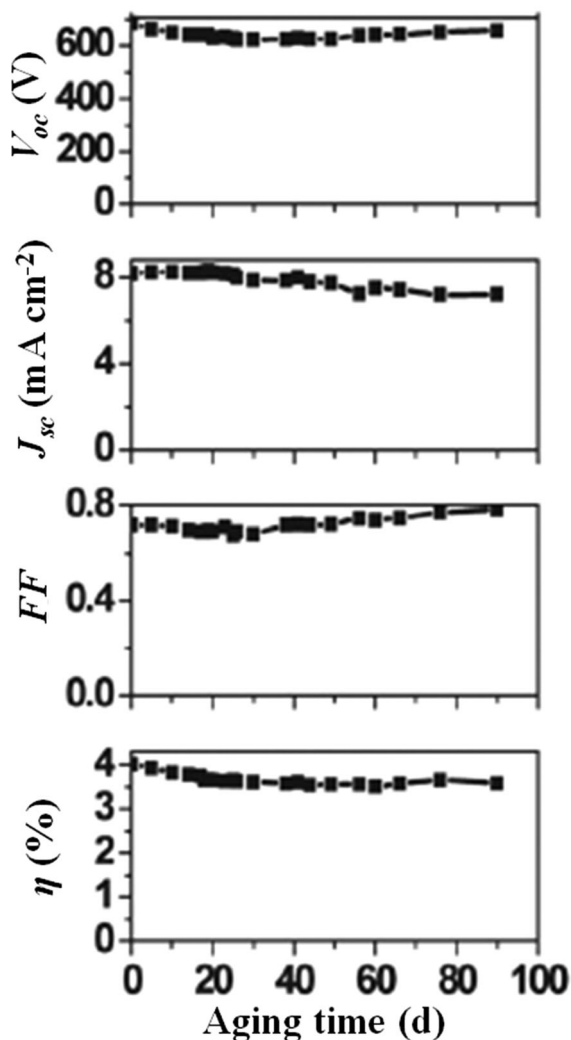


Fig. 14 Long-term stability under dark of a DSSC assembled with an aqueous electrolyte composed of [Co(bpy)<sub>3</sub>]<sup>2+</sup> 0.20 M, [Co(bpy)<sub>3</sub>]<sup>3+</sup> 40 mM, NMBI 0.70 M and PEG 300 1 vol%. Dye: MK-2. Adapted and reprinted from ref. 194.

FF = 0.72) was achieved upon addition of 1 wt% PEG 300. Noteworthy, such an additive was able to concurrently guarantee the highest possible electron recombination resistance and the lowest diffusion resistance of the redox species. The durability of cobalt-based electrolytes being a topic of great interest right now,<sup>195</sup> aqueous DSSCs were investigated for their stability under prolonged aging conditions by Spiccia and coworkers, demonstrating a limited 10% decrease of the initial efficiency after more than three months under dark (Fig. 14).

## 9. Photoanode activation: a way to improve the interfacial characteristics between electrodes and aqueous electrolytes

Nowadays, it is widely established that the interface between the photoanode and the aqueous electrolyte is a key point

remarkably affecting the efficiency of water-based DSSCs. This is in fact an important issue even for standard DSSCs, where the surface modification of the photoanode is usually carried out by means of barrier layers,<sup>196</sup> N-doping,<sup>197</sup> hybrid organic–inorganic linkers,<sup>198</sup> nanodecorations<sup>199</sup> and physical techniques.<sup>200</sup> Furthermore, for the first time, the solid electrolyte interphase formation (SEI layer, well known and investigated in the field of Li-ion batteries,<sup>201</sup>) has been recently evidenced even in DSSCs, which implies a novel series of challenging research goals for the scientific community.<sup>202</sup>

A simple interfacial activation for aqueous DSSCs was proposed by Miyasaka and coworkers, by means of treating the mesoporous layer with gaseous active oxygen prior to dye adsorption.<sup>203</sup> In particular, the TiO<sub>2</sub> layer was concurrently etched by air rich in O<sub>3</sub> (300 ppm) and exposed to UV light for 60 min. Water CA values decreased from 71 to 22°, which highlighted the improved hydrophilicity of the electrode. An efficient permeation of the aqueous redox electrolyte (KI 0.50 M and I<sub>2</sub> 25 mM in H<sub>2</sub>O:EtOH 65:35) through the mesoporous electrode structure was achieved; both  $J_{sc}$  and  $V_{oc}$  increased, from 4.94 to 5.80 mA cm<sup>-2</sup> and from 0.55 to 0.60 V, respectively. As a result, efficiency noticeably increased from 1.7% to 2.2%. Noteworthy, TBP (5 vol%), being insoluble in water, was introduced in the dye-uptake solution and not in the electrolyte. Authors hypothesized that TBP could be considered as a base and, when adsorbed onto the TiO<sub>2</sub> surface, could improve the rate of deprotonation of the carboxyl groups of the Ru complex to reinforce the bonding between dye and TiO<sub>2</sub>, thus leading to improved electron injection efficiencies. In other words, TBP provided itself as a ligand for the Ru complex, forming a mixed ligand complex with tetrabutylammonium (TBA).

An alternative way to modify the photoanode could be the introduction of a Schottky barrier, which can increase the electron injection efficiency.<sup>175</sup> To this purpose, Lai and coworkers prepared Au NPs modified by tetraoctylammonium bromide, which were then anchored at the TiO<sub>2</sub> surface by means of (3-mercaptopropyl)trimethoxysilane.<sup>204</sup> A self-assembly monolayer process was performed and, by successively repeating the preparation steps, a layer-by-layer Au NPs coating was formed on the conducting substrate (Fig. 15). Being the I<sup>-</sup>/I<sub>3</sub><sup>-</sup> couple corrosive towards Au, a Fe<sup>2+</sup>/Fe<sup>3+</sup> redox mediator was used, despite its high sensitivity to hydrolysis in aqueous solutions due to the formation of iron aquo complexes with water. To possibly avoid such a drawback, mixtures of H<sub>2</sub>O/EtOH in the 65:35 ratio were selected for the preparation of the electrolyte (FeCl<sub>2</sub> 0.10 M, FeCl<sub>3</sub> 50 mM and LiNO<sub>3</sub> 0.10 M).<sup>205</sup> In the presence of four Au NP layers,  $J_{sc}$  more than doubled (*i.e.*, from 2.76 to 5.96 mA cm<sup>-2</sup>); FF increased as well (*i.e.*, from 0.23 to 0.35). However, the efficiency of the aqueous DSSC remained rather low (*i.e.*, 0.95% against 0.26% for the Au-free cell), maybe because of the redox mediator instability and/or the selection of the dye (merbromin, MB, hardly known for its high efficiency).

In liquid DSSCs, the diffusive nature of the ion flow throughout the electrolyte creates an upper limit to the current (diffusion limited current,  $J_{dl}$ ) that can pass across the cell. It is controlled by the diffusion coefficient of the limiting species



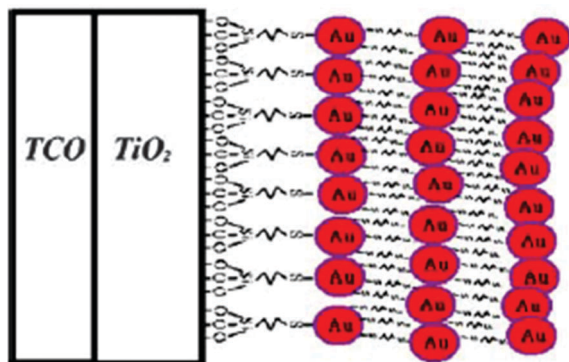


Fig. 15 Layer-by-layer Au NP assembly onto the  $\text{TiO}_2$  electrode to act as a Schottky barrier in aqueous DSSCs. Adapted and reprinted from ref. 204.

( $\text{I}_3^-$  ions), their concentration, the cell thickness as well as the thickness and morphology of the  $\text{TiO}_2$  photoanode. While in organic solvent-based liquid electrolytes the  $J_{\text{dl}}$  values ( $\sim 30$  and  $\sim 100 \text{ mA cm}^{-2}$  in MPN and ACN, respectively) are larger than  $J_{\text{sc}}$  values, under incomplete wetting conditions the reduced cross sectional area through which ions can diffuse causes lower  $J_{\text{dl}}$  values. Since the latter situation may occur in aqueous DSSCs, O'Regan and coworkers proposed several strategies to improve the rather critical wettability of Z907-dyed  $\text{TiO}_2$ .<sup>206,207</sup> Among the different surfactants being investigated, cheno-deoxycholic acid (CDCA) demonstrated the highest values of  $J_{\text{sc}}$  (3 fold increase) and  $J_{\text{dl}}$  (10 fold increase): this beneficial effect was attributed both to the hydrophobic centre portion of the molecule (compatible with Z907) and the hydrophilic  $-\text{OH}$  groups. Despite the improved wetting ability, the low  $J_{\text{sc}}$  value ( $\sim 2 \text{ mA cm}^{-2}$ ) indicated that some limitation could be derived from injection and/or collection processes. Even if the main recombination pathway has recently been proposed to be the reduction of free iodine (rather than the triiodide),<sup>208</sup> it was noted that the binding coefficient ( $K_{\text{M}}$ ) of  $\text{I}^-$  and  $\text{I}_2$  was much weaker in water ( $K_{\text{M}} = 10^3$ ) compared to what measured in organic solvents ( $K_{\text{M}} = 4 \times 10^6$  in ACN).<sup>209</sup> Thus, the recombination in aqueous electrolytes should result much faster than in organic electrolytes, accompanied by a substantial decrease in the collection efficiency. To better unravel this phenomenon,  $\text{I}_2$  concentration was reduced, resulting in increased  $J_{\text{sc}}$  (lower amount of free  $\text{I}_2$  led to slower recombination) and decreased  $J_{\text{dl}}$  ( $\text{I}_3^-$  is the limiting species for the diffusion current in the electrolyte). Similar experiments were performed using the D149 dye observing an analogous trend. Only higher  $J_{\text{dl}}$  values were obtained, due to the chemisorption of D149 by means of a single  $-\text{COOH}$  group, which resulted in a higher CDCA surface concentration. In general, the  $\text{I}_2$  concentration was maintained higher than 10 mM, as lower values gave unstable cells. Although the topic of dyes for aqueous cells will be comprehensively detailed in Section 10, it is appropriate to report here that this study was also carried out using an N719 sensitizer, stabilised by adding  $\text{HNO}_3$  (pH 3) in water.

Another strategy to optimize the photoanode/electrolyte interfacial characteristics is the introduction of novel additives in the electrolyte. In this respect, O'Regan and coworkers observed a

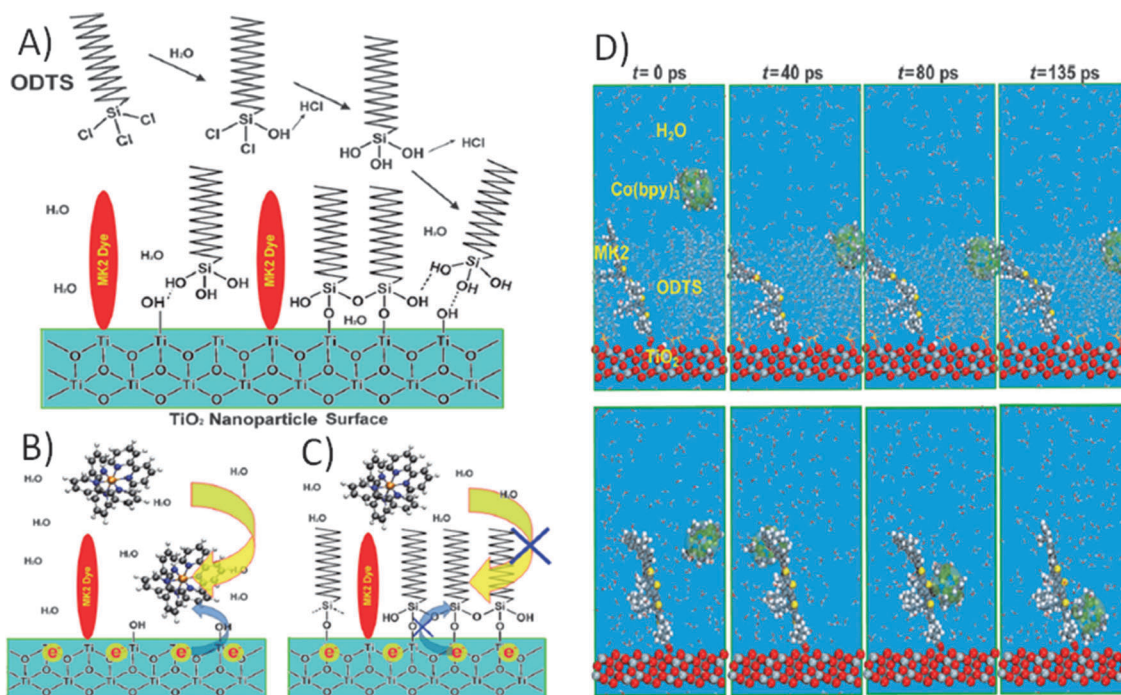
positive effect on both wetting and collection efficiency by means of guanidinium and iodide ions, respectively.<sup>206</sup> In particular, by using a high concentration of guanidinium iodide (GuI 8.0 M), a remarkable increase in the  $J_{\text{sc}}$  values (from 7.89 to  $10.02 \text{ mA cm}^{-2}$ ) was obtained. On the other hand,  $V_{\text{oc}}$  remained unchanged, due to the balance of the following two opposite phenomena: the reduction of the recombination rate due to the decrease of free iodine amount and the lowering of the redox potential of the solution due to the increased iodide concentration. Efficiencies up to 4.06% were obtained (GuI 8.0 M and  $\text{I}_2$  20 mM in  $\text{H}_2\text{O}$ ; dye: D149/CDCA), but the long-term stability of GuI-based cells was lower than that of GuSCN/NaI-based ones, more likely because – as suggested by the authors – GuI could cause the desorption of CDCA from the surface, thus leading to the dewetting of the inner pore structure. Based on these considerations, the reader can certainly appreciate the charming and delicate balance at the base of the fabrication of an efficient DSSC.

A completely different approach for the photoanode activation has been very recently proposed in the article by Spiccia and coworkers,<sup>210</sup> who modified the surface properties of  $\text{TiO}_2$  nanoparticles by means of octadecyltrichlorosilane (ODTS) in order to create an insulating layer able to reduce electron recombination by restricting the access of the cobalt redox couple at the titania surface. Condensation reaction occurred directly between  $\text{Ti}-\text{OH}$  groups and ODTS, and also by alkyl group intercalation between MK-2 dye molecules (Fig. 16A). This resulted in a strengthened insulating layer, thanks to the formation of  $\text{Si}-\text{O}-\text{Si}$  and  $\text{Si}-\text{O}-\text{Ti}$  crosslinkages induced by further condensation processes activated after the introduction of the fully aqueous electrolyte ( $[\text{Co}(\text{bpy})_3]^{2+}$  0.20 M,  $[\text{Co}(\text{bpy})_3]^{3+}$  40 mM, NMBI 0.70 M and PEG 300 1 wt%). As clearly visible in Table 11, the  $V_{\text{oc}}$  of ODTS-treated photoanodes increased with soaking time, while FF decreased due to mass transport limitations in the titania mesopores.<sup>211</sup> ODTS-treated cells showed improved  $J_{\text{sc}}$  values than ODTS-free ones, more likely because of a negative shift in the CB of the photoanode or a suppression of the interfacial electron recombination of the injected electrons with the oxidized cobalt species (Fig. 16B<sup>128</sup>). The first hypothesis was discarded due to the similar capacitance values provided by the different photoanodes. On the other hand, ODTS showed to be useful to improve both the electron recombination resistance and the electron lifetime by increasing soaking time values, due to a higher coverage of the exposed surface sites by the alkyl siloxane (Fig. 16C). Efficiencies up to 5.64% were obtained, which did not decrease even after 500 h of storage under dark. Moreover, molecular dynamics simulations were performed (Fig. 16D): for the untreated system, the distance  $d(\text{Co}-\text{TiO}_2)$  decreased significantly from 25 to 8 Å with the dynamic simulation time, while it remained almost constant for the ODTS-treated system. This confirmed that, for the ODTS-treated cells, the  $[\text{Co}(\text{bpy})_3]^{3+}$  ions did not come in contact with the titania surface, thus lowering the chance of recombination.

Until now, a semiconductor different from  $\text{TiO}_2$  has not been employed in aqueous DSSCs. To this purpose, a good material to be explored could be zinc oxide ( $\text{ZnO}$ ), whose







**Fig. 16** (A) Proposed reaction process for alkyl siloxane anchoring to the dye-coated TiO<sub>2</sub> NPs treated with an ODTs solution; (B) electron recombination in non-ODTS treated aqueous DSSCs; (C) inhibition of electron recombination by aqueous DSSCs fabricated with ODTs treated photoanodes; (D) snapshot of the simulated systems of the ODTs-untreated and treated TiO<sub>2</sub> cluster as a function of the simulation time. In the ODTs-untreated system (bottom), the MK-2 molecule was attached at the TiO<sub>2</sub> cluster, whereas the ODTs-treated dyed TiO<sub>2</sub> photoanode (top) was obtained by attaching the crosslinked hydrolysed ODTs molecules at the vacant sites. Both systems were immersed in an explicit water environment. Adapted and reprinted from ref. 210.

**Table 11** PV parameters ( $P_{in} = 1$  sun) of fully aqueous DSSCs assembled with ODTs-free or ODTs-treated photoanodes. Electrolyte: [Co(bpy)<sub>3</sub>]<sup>2+</sup> 0.20 M, [Co(bpy)<sub>3</sub>]<sup>3+</sup> 40 mM, NMBI 0.70 M and PEG 300 1 wt%. Dye: MK-2. Adapted and reprinted from ref. 210

Treatment time (min)	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
0	8.45	0.687	0.70	4.09
5	10.17	0.821	0.68	5.64
20	9.52	0.861	0.63	5.16

wettability and morphology can be highly tailored, as already demonstrated by research groups that usually employ this material in lithium batteries.<sup>216–218</sup>

## 10. Dyes and stability in water: still a long road to succeed

Representing the vital component of a DSSC, the sensitizer (or dye) has been extensively investigated in the last decades.<sup>216–218</sup> The main target of the scientific community efforts has been the discovery, elaboration and application of novel organometallic complexes,<sup>219–221</sup> the preparation of metal-free dyes,<sup>222–224</sup> the extension of the spectrum in the near IR regions<sup>225–227</sup> and the invention of new synthetic methodologies being green and readily up-scalable at the industrial level.<sup>228–230</sup> As regards aqueous DSSCs, the number of articles published until now that propose novel dyes *ad hoc* elaborated for the purpose has been very limited.

This is rather surprising. As reported in the previous sections of this review, several research groups more likely used common organometallic and organic dyes (maybe focusing rather on hydrophobic ones) for the fabrication of aqueous cells, the main focus being the modification of electrolyte components and the functionalization of the photoanode surface.

Bearing in mind the long-term stability as an utmost important target for a dye in aqueous DSSCs, Grätzel and coworkers initially focused their efforts on the introduction of long apolar chains able to laterally interact with Ru-based complexes; by this way, an aliphatic network was intended to form which might avoid both the TiO<sub>2</sub>-dye debonding and the approaching of triiodide to the photoanode surface.<sup>231</sup> A long-term stability test compared the performance of N3 and [Ru(H<sub>2</sub>dcbpy)(mhd bpy)(NCS)<sub>2</sub>] dyes (where H<sub>2</sub>dcbpy = 4,4'-dicarboxy-2,2'-bipyridine and mhd bpy = 4-methyl-4'-hexadecyl-2,2'-bipyridine) in the presence of increasing water contents in the electrolyte (I<sub>2</sub> 10 mM in HMII/H<sub>2</sub>O; HMII = 1-hexyl-3-methylimidazolium iodide). Data depicted in Fig. 17 show that, in the presence of electrolytes encompassing 5 and 10 vol% H<sub>2</sub>O, respectively, the performance of N3-based cells was lower with respect to that of the devices assembled with the hydrophobic dye, these latter being stable, thanks to the presence of the aliphatic chains which assured complete insolubility in water.

Thanks to their broad absorption spectra and excellent light-harvesting ability, Ru complexes would represent the sensitizer of choice for aqueous DSSCs. Nevertheless, in order to obtain cells demonstrating sufficient durability, efforts must be devoted



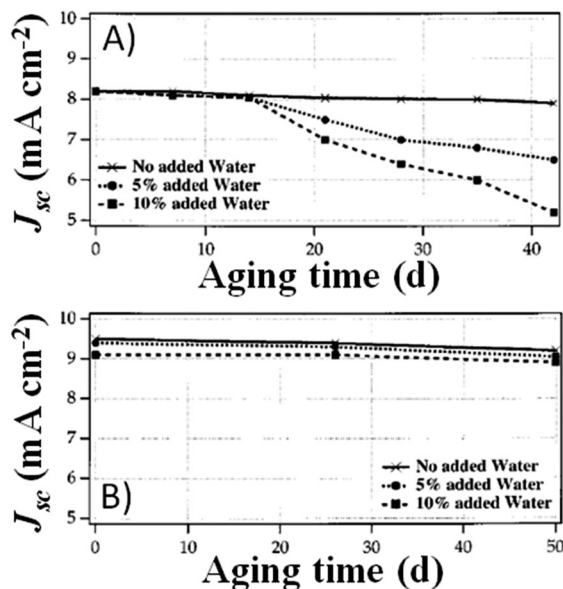


Fig. 17 Long-term stability ( $P_{in} = 0.015 \text{ mW cm}^{-2}$ ) of DSSCs assembled with RTIL-based electrolytes ( $I_2$  10 mM in HMIL) encompassing different  $H_2O$  contents. Dyes: (A) N3; (B) [Ru(H<sub>2</sub>dcbpy)(mhdcbpy)(NCS)<sub>2</sub>]. Adapted and reprinted from ref. 231.

to ameliorate the bonding between dye molecules and  $TiO_2$  NPs.<sup>232</sup> Miyasaka and coworkers compared two photoanodes having equal amounts of N719 and N3 sensitizer molecules adsorbed onto the surface of the  $TiO_2$  layer.<sup>138</sup> In the presence of a truly aqueous electrolyte (KI 0.50 M and  $I_2$  25 mM), efficiencies of 0.6% and 0.5% were calculated when using N3 and N719 dyes, respectively. The cell assembled using the N719 dye showed lower  $J_{sc}$  (upon adsorption, TBA groups caused a negative Fermi level shift of the semiconductor<sup>233</sup>) and higher  $V_{oc}$  values (TBA is a base capable of negatively shifting the Fermi level as well as the  $TiO_2$  CB) compared to the one using N3. The differences in  $J_{sc}$  were also ascribed to the adsorption strength of the dyes at the  $TiO_2$ /aqueous electrolyte interface; in fact, being more hydrophilic than N3, N719 has a higher solubility in water ( $3.5 \times 10^{-3}$  vs.  $1.2 \times 10^{-3}$  M). The four  $-COOH$  groups of the N3 dye molecule ensure a more efficient electronic interaction at the oxide interface which, as a result, guarantees a much more stronger adsorption at the interface with the active material particles, thus improved stability under water. Moreover, the performances of all the aqueous DSSCs were found to be pH-dependent (Fig. 18A), particularly in terms of  $J_{sc}$  values which were negatively affected when a high pH (adjusted by addition of phosphate buffer solutions) was adopted; in contrast,  $V_{oc}$  was not affected. The  $J_{sc}$  decrease reflected a positive shift of the CB potential of  $TiO_2$ , as reported in Fig. 18B. However, the detachment of the dye from the electrode could also be promoted by the experimented high pH values as well.

The behaviour upon aging of Ru-based aqueous DSSCs was investigated by Miyasaka and coworkers, who observed a 50% progressive decrease of the photocurrent after 2.5 months (under dark, RT).<sup>138</sup> Reference cells containing organic solvent-based electrolytes showed reduced lifetime, because of solvent evaporation. After several weeks the bleaching of iodine was

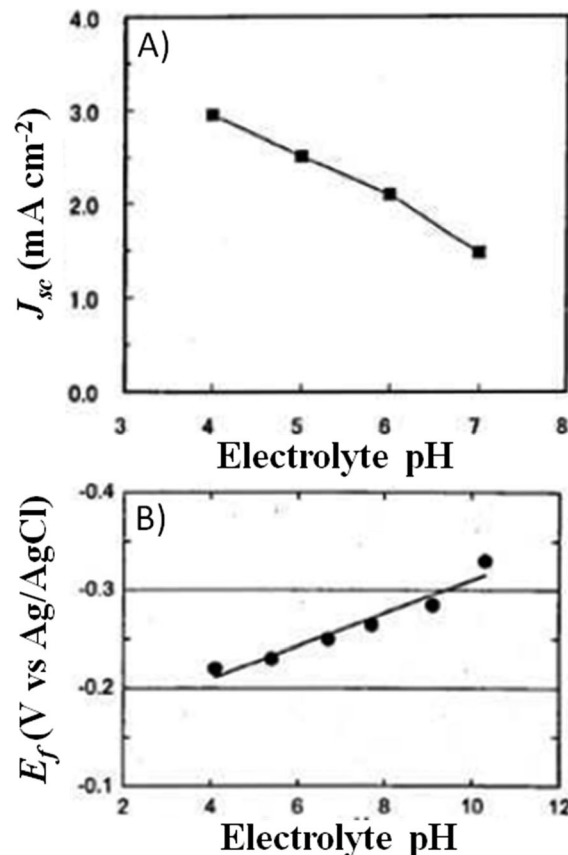


Fig. 18 (A) pH dependence of  $J_{sc}$  values ( $P_{in} = 1 \text{ sun}$ ) obtained for an aqueous DSSC sensitized with N719. Electrolyte: KI 0.50 M and  $I_2$  25 mM; (B) dependence of the Fermi level electrochemical potential ( $E_f$ ) of the mesoporous  $TiO_2$  electrode on the pH of the above reported electrolyte. The potential data were based on the measurement of the onset potential of dark cathodic current. Adapted and reprinted from ref. 138.

detected in aqueous DSSCs. Anyway, a significant intrinsic surplus value of DSSCs is that electrolyte can be fully replaced to restore cell performance, as it was confirmed in the article by Miyasaka and coworkers where the cell efficiency was recovered by replacing the degraded aqueous electrolyte with a freshly prepared one. Of course, the procedure of electrolyte replacement is much more easy and safe when an aqueous system is envisaged than an organic volatile one that carries around severe environmental hazards.

Further surface characterization of N3-, N719- and Z907-dyed electrodes was performed by Hahlin and coworkers by means of photoelectron spectroscopy (PES),<sup>234</sup> a useful technique to get specific information on the electronic as well as the molecular surface structures of the photoanode.<sup>235–237</sup> The dye-sensitized samples were exposed to a mixed  $H_2O$ /EtOH solution in the 30:70 ratio for 20 min, and then assembled in organic solvent-based DSSCs (TBAI 0.60 M, LiI 0.10 M,  $I_2$  50 mM, GuSCN 50 mM and TBP 0.50 M in ACN; TBAI = tetrabutylammonium iodide). Water exposure led to a decrease in  $J_{sc}$  exceeding 20% for the N3- and N719-based systems, while  $V_{oc}$  decreased only for the N719-based cell; Z907-sensitized electrodes did not show any appreciable variation. Additionally, a



20 nm shift of the IPCE maximum was observed for both cells, thus clearly indicating modification in the electronic structure of the adsorbed molecules. Changes in the amount of surface adsorbed N3, N719, and Z907 dyes were finely detected by measuring the photoemission intensity from the core level Ru-3d<sub>5/2</sub> relative to the Ti-2p<sub>3/2</sub>: only in the case of N3 and N719 dyes, the Ru/Ti ratio decreased by about 80% and 50%, respectively. As regards the hydrophobic Z907 dye, water-induced dye desorption was not detected, and by studying the S/Ru ratio it was concluded that no substantial permanent chemical modification, such as ligand exchange, occurred to the molecule. In agreement with the experiments of Miyasaka and coworkers,<sup>138</sup> it was observed that the N719 dye layer was more sensitive to water compared to the N3 one, and its S-2p and N-1s signals were mostly affected by the aqueous environment. As a result, clear shifts of the HOMO levels towards higher binding energies occurred for both the dyes (*i.e.*, 0.17 and 0.26 eV for N3 and N719, respectively), thus leading to an increased gap between the energy levels of the HOMO and the LUMO, and subsequently a blue shift in the absorption spectrum.

As previously mentioned, very little studies have been published on the preparation of dyes having specific characteristics to be effectively used in aqueous cells. A seminal work of Ko and coworkers reported about new organic sensitizers (JK-259 and JK-262) containing 4-(2-(2-methoxyethoxy)-ethoxy)phenylamine as the electron donor molecule and cyanoacrylic acid as the electron acceptor molecule bridged by the 9,9-bis(2-(2-methoxyethoxy)-ethyl)-9H-fluorenyl linker (Table 14).<sup>238</sup> The 2-(2-methoxyethoxy)ethyl unit was introduced to ameliorate the water compatibility, and a TBP treatment onto the TiO<sub>2</sub> films ensured the photoanode stability. JK-259 and JK-262 showed efficiency values of 1.16% and 2.10%, respectively, in a fully aqueous electrolyte (PMII 2.0 M, I<sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1 wt%). However, due to the very low  $J_{sc}$  values, these efficiencies were > 50% lower when compared to those measured in the corresponding organic solvent-based DSSCs. The authors justified the decrease in the photocurrent on the basis of detachment of the adsorbed dye through the hydrolysis of the TiO<sub>2</sub>-water surface linkage, which is rather contradictory to the aim of their work which was intended for the preparation of a dye stable in water. Apart from this curious aspect, we may argue that research in this field should be much more effective because plenty of possibilities are available for performance and stability improvements.

Ko and coworkers further investigated aqueous DSSCs using three different organic sensitizers, namely D5L6,<sup>239</sup> D21L6<sup>240</sup> and JK-310; in particular, the latter two contained (hexyloxy)-phenylamine and 4-(2-(2-methoxyethoxy)-ethoxy)phenylamine as electron donor units.<sup>241</sup> As clearly visible in Table 14, all of these dyes have a water-soluble substituent and were coupled with an aqueous electrolyte (PMII 2.0 M, I<sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1 wt% in MPN:H<sub>2</sub>O 50:50). PV measurements (Table 12) showed that  $V_{oc}$  gradually increased with the incremental addition of water (*i.e.*, from 0 to 50%); in contrast,  $J_{sc}$  sharply decreased under the same conditions. Again, dyes were found to easily detach due to their partial

**Table 12** PV parameters ( $P_{in} = 1$  sun) of DSSCs assembled with different organic dyes and liquid electrolytes. Electrolytes: PMII 2.0 M, I<sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1 wt% in MPN or MPN/H<sub>2</sub>O. Adapted and reprinted from ref. 241

Dye	H <sub>2</sub> O (vol%)	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
D5L6	0	10.50	0.66	0.75	5.20
	50	6.22	0.75	0.73	3.40
D21L6	0	12.57	0.71	0.74	6.56
	50	7.46	0.77	0.77	4.41
JK-310	0	12.28	0.70	0.72	6.18
	50	6.62	0.75	0.76	3.77

hydrophilic nature, resulting in the reduction of both photocurrent and efficiency. Such a result further confirmed that the step of tailor-making the dyes in order to get improved photoanode wettability must be carefully counterbalanced by the water solubility value of such organic molecules.

As an alternative to the synthesis of new dyes, an impressive work of modification of known sensitizers to make them efficient and stable in an aqueous environment started in 2014. Bisquert and coworkers demonstrated an efficient synthetic protocol to modify the existing cyanoacrylate moiety of organic dyes (whose carboxylate linkage is susceptible to hydrolysis<sup>242</sup>) with a highly water-stable hydroxamate anchoring group *via* a condensation reaction.<sup>243</sup> The well known MK-2 dye<sup>184,244,245</sup> was chosen as a target substrate, and its hydroxamate-derivative (MK-2HA, Table 14) was significantly (30–50%) less susceptible to desorption in water, as a result of the stronger interaction of the novel anchoring group with the surface of TiO<sub>2</sub>.<sup>246,247</sup> The enhanced water tolerance was also attributed to the higher  $pK_a$  of MK-2HA dye and to the less strained chelate bite angle in hydroxamic acids compared with carboxylic acid analogues. Interestingly, TAS measurements carried out on both dyes revealed that the lifetime of the charge-separated state increased with increasing immersion time in the DMF-H<sub>2</sub>O solution used to evaluate the water stability of sensitizers. Thus, such a “soaking and desorption” approach, which probably contributed to the removal of dye aggregates from the semiconductor surface,<sup>171</sup> was proposed as a potentially effective treatment to improve the recombination dynamics of DSSC photoanodes. In these experiments, MK-2HA-sensitized photoanodes showed no change in the electron injection efficiency upon exposure to the desorption solution, while MK-2 ones lost nearly 65%, due to the sensitivity of the dye-TiO<sub>2</sub> interface toward water. Cells with MK-2 and MK-2HA dyes were fabricated and water was purposefully added to the electrolyte (PMII 2.0 M, LiI 0.10 M, I<sub>2</sub> 0.20 M and TBP 0.50 M in ACN/H<sub>2</sub>O). In 200 h aging test under dark, MK-2-based DSSCs with 10 and 20 wt% water had decreased efficiency by 15% and 50% compared to the anhydrous control, mainly due to the 50% reduced  $J_{sc}$ . As regards MK-2HA-based cells, there was no significant difference in the efficiencies (slightly lower than 4%) measured with aqueous (10 wt%) and anhydrous electrolytes. Moreover, FF and  $V_{oc}$  of water-based DSSCs increased with time: authors hypothesized that the water content in the electrolyte could serve to accelerate the desorption of aggregates, leading to more favourable interfacial electron transfer dynamics.





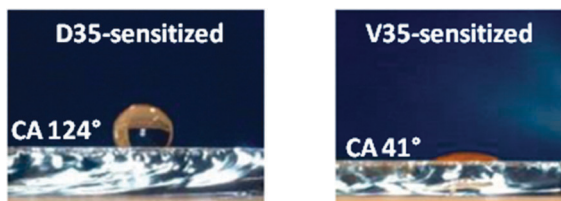


Fig. 19 Crossed sections of working electrodes sensitized with D35 (left) and V35 (right) with a drop of deionized water positioned on the top. CA values are also reported. Adapted and reprinted from ref. 249.

D35 is another well known dye in the DSSC field,<sup>248</sup> and Boschloo and coworkers synthesized its hydrophilic analogous, by substituting the hydrophobic alkyl chains with glycolic ones.<sup>249</sup> The resulting hydrophilic dye (V35, Table 14) showed an extraordinary interaction with water, and the authors claimed that the use of wettability-improver surfactants was not necessary (as can be seen in Fig. 19), thus reducing cell cost and avoiding possible mass transport problems. The new dye was initially coupled with a fully aqueous electrolyte containing only NaI and I<sub>2</sub>, and then gradually modified as reported in Table 13. Interestingly, efficiency increased when KI replaced NaI, probably due to the ability of glycolic chains (like crown ethers) to coordinate small cations (such as Na<sup>+</sup>).<sup>250,251</sup> Performance was further improved by doubling the concentration of KI, thus lowering the amount of free iodine. The addition of GuSCN had a negative effect, while CDCA improved efficiency up to 2.20%. Moreover, V35 dye was further investigated in aqueous DSSCs employing alternative cathodic materials at different pH values, as will be described in Section 11.

Pigments extracted from natural matrices may result in a valuable alternative to synthetic dyes.<sup>252,253</sup> Despite the efficiencies obtained are still lower compared to the reference Ru-based dyes, thanks to their low cost and ready availability, these pigments are nowadays very much considered by those research groups who are focused on the development of the so-called biophotovoltaic devices.<sup>181,254,255</sup> In Section 8, the very recent work of Su and Lai on natural pigments coupled with alternative redox mediators has been mentioned,<sup>178</sup> but the very first demonstration of the good compatibility between pigments and water was provided by Rabani and coworkers.<sup>256</sup> In 2001, they exploited the promising prospects as a sensitizer of the seed coats of the pomegranate (PG) fruit, which is a rich source of anthocyanins.<sup>257</sup> By operating under strong acidic conditions (pH 1) and after having ascertained that Na<sup>+</sup> was the most effective counter ion in photocurrent generation, the resulting aqueous DSSC (NaI 1.0 M and I<sub>2</sub> 0.10 M) demonstrated a  $J_{sc}$  value of

2.2 mA cm<sup>-2</sup> and a  $V_{oc}$  of 0.44 V (FF was not reported). Stability tests showed no appreciable decrease of the photocurrent after 24 h illumination. It is important to recall here that the size of the photoanode NPs is a key factor affecting the performances of natural pigment-based cells. In their investigation, Rabani and coworkers used 5 nm diameter NPs which guaranteed small pores, thus preventing or minimizing the adsorption of undesired molecules (*i.e.*, foreign impurity phases deriving from the original matrix) which could result in reduced photocurrent by means of visible light absorption competition.

An overview of the dyes used so far for aqueous DSSCs is given in Table 14, together with the redox mediators with which they have been tested. Very recently, novel metal-free dyes containing an anthracene/phenothiazine unit in the spacer have been synthesized and proposed for aqueous DSSCs, and a cell performance equal to 4.96% was achieved.<sup>258</sup>

## 11. Low-cost and water-compatible cathodes

Being the most popular choice for high-efficiency DSSCs, platinum has been widely recognized as the benchmark material at the cathode side, due to its high catalytic activity and excellent conductivity.<sup>259</sup> As a result, for many years, research on novel cathodic materials has been considered rather a secondary issue by the scientific community, especially if compared to the impressive efforts addressed to the improvement of the other cell components. Nevertheless, Pt presents a series of drawbacks, the most significant being the high cost and the scarce availability, which have restricted so far the mass production of DSSCs,<sup>260</sup> as already occurred to fuel cells and related systems using Pt as a catalyst.<sup>261</sup> Moreover, Pt may readily undergo severe dissolution in electrolytes containing the iodine-based redox couple, resulting in the formation of PtI<sub>4</sub> and reduced cell performances;<sup>262</sup> Pt is not compatible with the recently proposed sulphur-based redox shuttles as well.<sup>189</sup> For all these reasons, we may reasonably argue that the breakthrough in the widespread diffusion of DSSCs may be realised only when counter electrodes at sustainable costs and stable long-term performance are developed.<sup>263</sup> In this respect, transition metal compounds (*i.e.*, carbides, nitrides) have drawn considerable attention as alternatives to Pt cathodes, due to their excellent catalytic activity towards electrolytes based on both sulphur- and cobalt-based redox couples.<sup>264,265</sup> Organic polymers (*i.e.*, PEDOT, PPy, PANI, *etc.*) demonstrated promising prospects as flexible and transparent cathodes.<sup>266,267</sup> In the last two years, low-dimensional carbonaceous materials (*i.e.*, CNTs arrays and graphene films) started to be widely studied and applied, especially in iodine-free DSSCs.<sup>268,269</sup>

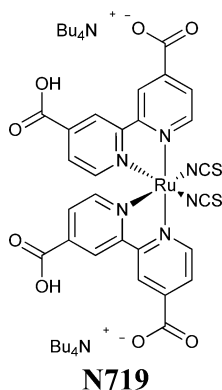
As previously reported in the course of this review (Section 8), redox couples to be used in aqueous DSSCs are often different from the standard ones conceived for aprotic media. The use of water as a solvent (sometimes mixed with ACN or MPN) makes the electrolyte/cathode compatibility a new topic to be deeply investigated. Obviously, aqueous electrolytes being a recent

Table 13 PV parameters ( $P_{in}$  = 1 sun) of V35-sensitized DSSCs assembled with different fully aqueous electrolytes. Adapted and reprinted from ref. 249

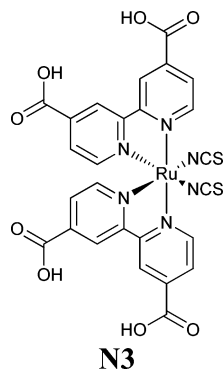
Electrolyte	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
NaI 2.0 M and I <sub>2</sub> 20 mM	2.30	0.500	0.67	0.80
KI 2.0 M and I <sub>2</sub> 20 mM	4.07	0.550	0.70	1.55
KI 4.0 M and I <sub>2</sub> 20 mM	4.78	0.570	0.65	1.76
KI 4.0 M, I <sub>2</sub> 20 mM and GuSCN 0.50 M	3.33	0.555	0.67	1.25
KI 4.0 M, I <sub>2</sub> 20 mM and CDCA sat.	4.86	0.600	0.76	2.20



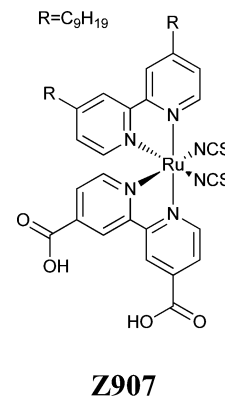
**Table 14** Structural formulas of sensitizers usually employed in aqueous DSSCs, together with the redox pairs with which were coupled. Further details about the other cell components and the PV performance are reported in the manuscript and in Table 20



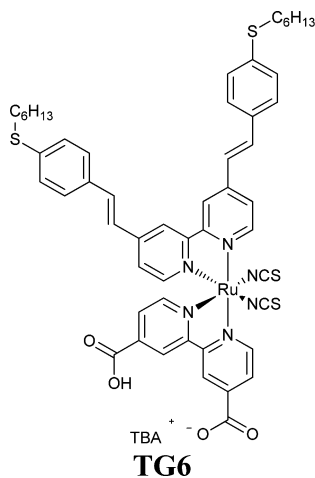
Always with  $\text{I}^-/\text{I}_3^-$  with increasing  $\text{H}_2\text{O}$  content: 0.018 wt%,<sup>172</sup> 4 wt%,<sup>156</sup> 10 wt%,<sup>145</sup> 65 wt%,<sup>138</sup> and in 100 wt%  $\text{H}_2\text{O}$ <sup>138,163,206</sup>



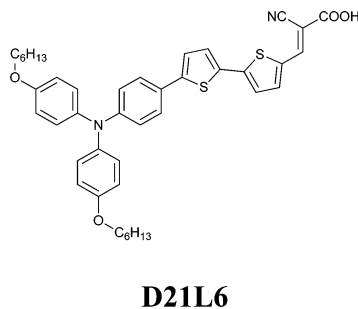
Always with  $\text{I}^-/\text{I}_3^-$  with increasing  $\text{H}_2\text{O}$  content: 3 wt%,<sup>124</sup> 4 wt%,<sup>43</sup> 5 wt%,<sup>303</sup> 10 wt%,<sup>294</sup> 65 wt%,<sup>138,203</sup> and in 100 wt%  $\text{H}_2\text{O}$ <sup>138,328</sup>



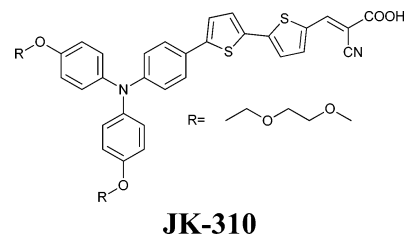
Always with  $\text{I}^-/\text{I}_3^-$  with increasing  $\text{H}_2\text{O}$  content: 10 wt%,<sup>128</sup> 50 wt%,<sup>310</sup> and in 100 wt%  $\text{H}_2\text{O}$ <sup>206</sup>



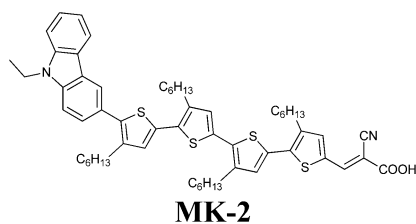
Always with  $\text{I}^-/\text{I}_3^-$  with increasing  $\text{H}_2\text{O}$  content: 20 wt%,<sup>120</sup> 50 wt%,<sup>318</sup> and in 100 wt%  $\text{H}_2\text{O}$ <sup>120,206</sup>



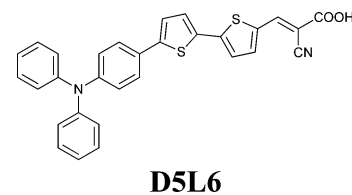
$\text{I}^-/\text{I}_3^- + 50 \text{ wt}\% \text{ H}_2\text{O}$ <sup>241</sup>



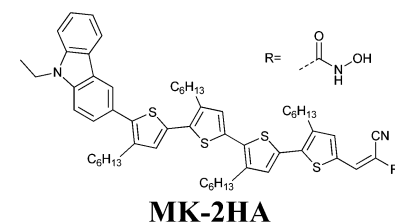
$\text{I}^-/\text{I}_3^- + 50 \text{ wt}\% \text{ H}_2\text{O}$ <sup>241</sup>



$\text{Fe}(\text{CN})_6^{4-}/\text{Fe}(\text{CN})_6^{3-}$  in 100 wt%  $\text{H}_2\text{O}$ <sup>182</sup>  
 $[\text{Co}(\text{bpy})_3]^{2+}/[\text{Co}(\text{bpy})_3]^{3+}$  in 100 wt%  $\text{H}_2\text{O}$ <sup>194,210</sup>

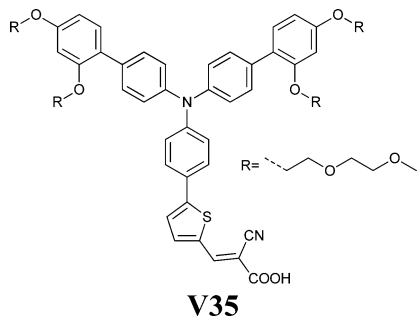
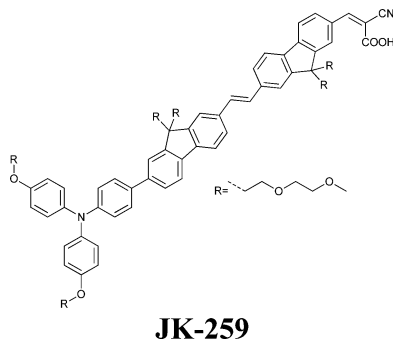
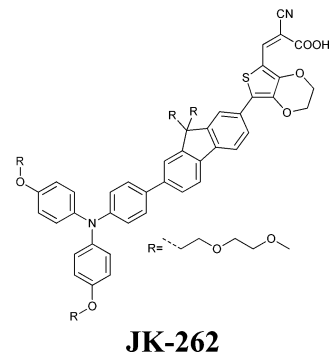
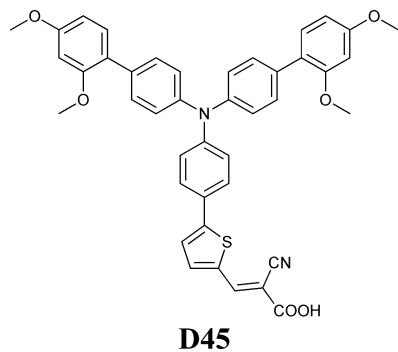
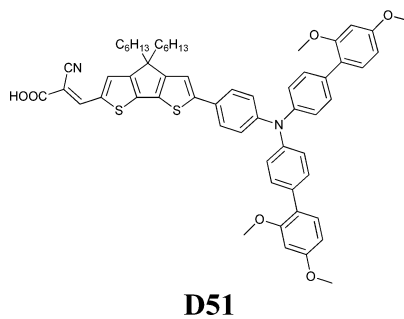
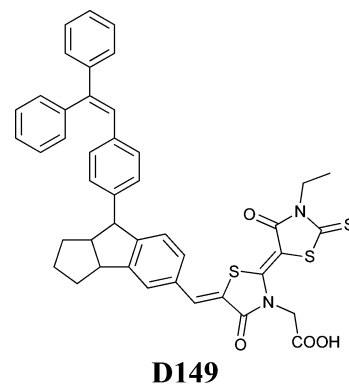
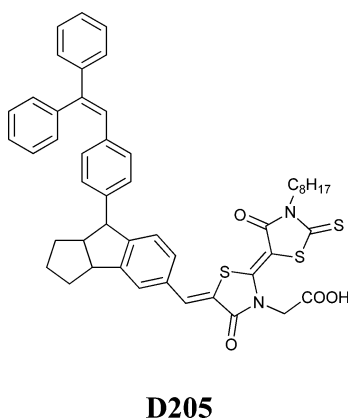
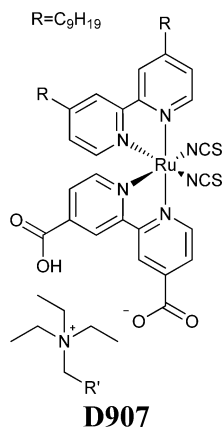
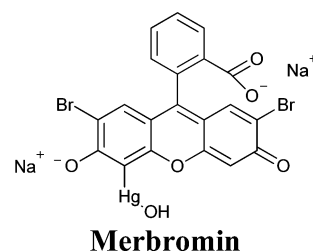
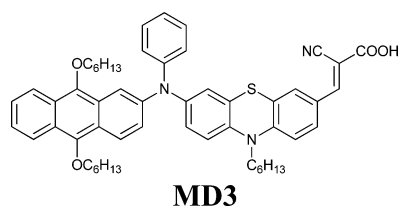


$\text{I}^-/\text{I}_3^- + 50 \text{ wt}\% \text{ H}_2\text{O}$ <sup>241</sup>



$\text{I}^-/\text{I}_3^- + 10 \text{ wt}\% \text{ H}_2\text{O}$ <sup>243</sup>

Table 14 (continued)


$$\text{I}^-/\text{I}_3^- \text{ in } 100 \text{ wt\% H}_2\text{O}^{249}$$

$$\text{I}^-/\text{I}_3^- \text{ in 100 wt\% H}_2\text{O}^{238}$$

$$\text{I}^-/\text{I}_3^- \text{ in } 100 \text{ wt\% H}_2\text{O}^{238}$$
TT<sup>-</sup>EMI<sup>+</sup>/DTT in 100 wt% H<sub>2</sub>O<sup>193</sup>TT<sup>-</sup>EMI<sup>+</sup>/DTT in 100 wt% H<sub>2</sub>O<sup>193</sup>
$$\text{I}^-/\text{I}_3^- \text{ in } 100 \text{ wt}\% \text{ H}_2\text{O}^{206}$$
TEMPOL/TEMPOL<sup>+</sup> in 100 wt% H<sub>2</sub>O<sup>274</sup>
$$\text{I}^-/\text{I}_3^- + 65 \text{ wt}\% \text{ H}_2\text{O}^{314}$$

$$\text{Fe}^{2+}/\text{Fe}^{3+} + 65 \text{ wt\% H}_2\text{O}^{204}$$
TEMPO/I<sup>-</sup>/I<sub>3</sub><sup>-</sup> in 100 wt% H<sub>2</sub>O<sup>258</sup>

### Natural dyes/pigments

Natural dyes/pigments  
CV-G with  $\text{Ce}^{3+}/\text{Ce}^{4+} + 30 \text{ wt}\% \text{H}_2\text{O}^{178}$   
RhS with  $\text{Ce}^{3+}/\text{Ce}^{4+} + 65 \text{ wt}\% \text{H}_2\text{O}^{174}$   
PG with  $\text{I}^-/\text{I}_3^-$  in  $100 \text{ wt}\% \text{H}_2\text{O}^{256}$



research interest, very few literature reports useful to identify an optimum cathodic material have been available so far. Notwithstanding, some interesting studies have been already proposed, which will be hereby briefly summarised.

When using Co complexes as aqueous redox shuttles, Spiccia and coworkers observed a high charge transport resistance between the water-based electrolyte and the Pt counter electrode.<sup>194</sup> Thus, they screen-printed a mesoporous ITO film onto the FTO substrate, and then added a thermally-deposited Pt layer. The resulting cathode (13.5  $\mu\text{m}$ -thick) led to an efficiency of 5.0% (4.2% with Pt only), which increased by another 0.1% after 48 h. The ITO/Pt cathode showed a  $R_{\text{CE}}$  equal to 1.6  $\Omega$ , around five times lower than that of pure Pt, along with an almost doubled exchange current (investigated by means of cyclic voltammetry), thus indicating improved electron transfer to the oxidized redox couple. The reason for this behaviour lied in the high surface area of the ITO mesoporous film, which enabled a higher Pt loading and facilitated the reduction of the oxidized species of the aqueous electrolyte at the counter electrode surface.

Poly(3,4-ethylenedioxythiophene) (PEDOT) is currently one of the most considered materials for the preparation of both rigid and flexible cathodes to be used in DSSCs based on alternative redox couples. Sun and coworkers tried to improve the FF of DSSCs assembled with a thiolate/disulphide redox couple by using PEDOT as a counter electrode.<sup>193</sup> However, they failed because of the poor stability of PEDOT in the aqueous electrolyte, which also resulted in its easy detachment from the FTO glass. Quite surprisingly, the opposite behavior was reported by Boschloo and coworkers with fully aqueous cells containing V35 dye and an iodide/triiodide redox couple.<sup>249</sup> Indeed, Table 15 shows that PEDOT counter electrodes outperformed Pt ones due to increased  $J_{\text{sc}}$  and  $V_{\text{oc}}$  values. Such a positive effect was attributed to the leaf-like PEDOT structure, which conferred a high-surface area to the cathode, thus increasing its catalytic activity. Moreover, a reduced tendency of the dye to desorb in the presence of PEDOT was observed: authors speculated that PEDOT partially trapped in its matrix the ions capable of being absorbed onto the surface of  $\text{TiO}_2$ ,<sup>270</sup> preventing in this way the desorption of the dye. V35 was also tested with the best electrolyte reported by O'Regan and coworkers (see Section 9,<sup>206</sup>); however, the elevated concentration of GuI decreased significantly  $V_{\text{oc}}$  values (Table 15) due to the absorption of guanidinium cations on the  $\text{TiO}_2$  surface.<sup>271</sup> Further optimization

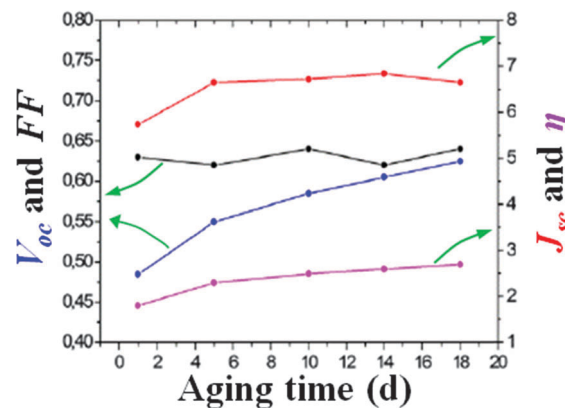


Fig. 20 Long-term stability under dark of DSSCs assembled with a fully aqueous electrolyte (KI 4.0 M and  $\text{I}_2$  20 mM at pH 8.0) and a PEDOT counter electrolyte. Dye: V35. PV parameters were measured under  $P_{\text{in}} = 1$  sun. Adapted and reprinted from ref. 249.

of iodine and CDCA concentrations yielded the highest efficiency recorded with V35 dye, namely 3.01% (4% under 0.5 sun). Noteworthy, all the electrolytes proposed by Boschloo and coworkers contained CDCA as a  $V_{\text{oc}}$ -improver agent: it did not shift significantly the  $\text{TiO}_2$  CB,<sup>272</sup> but reduced the recombination processes.

To further demonstrate the long-term stability of the PEDOT-based aqueous cells, Boschloo and coworkers set up several aging tests, also studying the effect of the pH of the electrolyte on the PV parameters.<sup>249</sup> As shown in Fig. 20, both  $V_{\text{oc}}$  and FF were higher in the case of electrolytes (KI 4.0 M and  $\text{I}_2$  20 mM) at pH 9.0; however, a lower photocurrent and an overall efficiency were obtained with respect to cells at pH 8.0. One very important aspect was given by fluctuations over time of the PV parameters (Fig. 20), and the better efficiencies were collected several days later device assembly. This is a typical characteristic of aqueous cells, thus scientific groups are suggested to monitor their devices over time rather than immediately abandoning their new materials due to low performance measured immediately after DSSC assembly.

Also materials other than PEDOT have surprisingly demonstrated increased performance and stability as cathodes in aqueous electrolyte-based DSSCs. In their pioneering work, Kim and coworkers revealed for the first time that the corrosion potential of silver metal increased in aqueous electrolytes containing Triton X-100.<sup>156</sup> The surfactant may in fact create a sort of protective layer on the Ag film surface which reduced the direct interaction with  $\text{I}_3^-$  ions, which in turn greatly diminished the dissolution of the metal. In the presence of the surfactant, an increased overpotential for the electron transfer from the Ag layer to  $\text{I}_3^-$  was additionally recorded. Such encouraging results unveiled the possibility of using Ag instead of the more expensive Pt in futuristic commercial DSSCs.

Very recently, the coating of the cathode surface with a polymeric film has been proposed to improve the electrode/electrolyte interfacial properties.<sup>273</sup> In this respect, Nishide and coworkers used 4-hydroxy-2,2,6,6-tetramethylpiperidinoxyl (TEMPOL, Fig. 21) as a redox mediator in an aqueous DSSC.<sup>274</sup>

Table 15 PV parameters ( $P_{\text{in}} = 1$  sun) of V35-sensitized DSSCs assembled with different electrodes and electrolytes. Adapted and reprinted from ref. 249

Electrolyte	Cathode	$J_{\text{sc}}$ ( $\text{mA cm}^{-2}$ )	$V_{\text{oc}}$ (V)	FF	$\eta$ (%)
KI 4.0 M, $\text{I}_2$ 20 mM and CDCA sat.	Pt	4.86	0.600	0.76	2.20
KI 4.0 M, $\text{I}_2$ 20 mM and CDCA sat.	PEDOT	5.26	0.625	0.74	2.45
KI 2.0 M, $\text{I}_2$ 10 mM and CDCA sat.	PEDOT	6.85	0.650	0.67	3.01
GuI 8.0 M, $\text{I}_2$ 20 mM and CDCA sat.	PEDOT	5.76	0.550	0.62	1.97



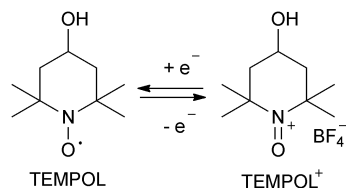


Fig. 21 Redox reaction of the TEMPOL mediator. Adapted from ref. 274.

TEMPOL is a hydrophilic TEMPO derivative, belonging to the class of nitroxide radical molecules, which have attracted remarkable attention as organic-based redox-active materials due to their rapid and reversible one-electron-transfer capability to form the corresponding oxoammonium cations.<sup>275–277</sup> This alternative redox mediator (to be added to the list shown in Section 8) was immobilized in a Nafion®:Pt two-layers cathode. Nafion® is typically used to prepare polymer electrolyte membranes,<sup>278</sup> but also as a trapping agent for electroactive cations in sensing and photoelectrochemical devices.<sup>279,280</sup> Exploiting its properties, a significant increase of both  $J_{sc}$  and FF values was evidenced with respect to the Pt-based cell, which was ascribed to the lower cell resistance due to the high efficiency in the regeneration reaction of the redox mediator as well as to the steep concentration gradient of the TEMPOL cation promoted by the Nafion® layer. In the presence of the Nafion®:Pt two-layers counter electrode and using the D205 dye, the overall cell efficiency increased from 0.11% ( $J_{sc} = 1.1 \text{ mA cm}^{-2}$ ,  $V_{oc} = 0.76 \text{ V}$ , FF = 0.14) to 2.1% ( $J_{sc} = 4.5 \text{ mA cm}^{-2}$ ,  $V_{oc} = 0.69 \text{ V}$ , FF = 0.64).

## 12. Cell sealing in the presence of water: a new intriguing challenge

Being the long-term stability a key objective of the present scientific research activity in the DSSC community, amounts of materials have been explored as sealants, such as thermoplastic hot-melt foils (*i.e.*, Surllyn®,<sup>281</sup> Bynel®,<sup>282</sup> *etc.*), UV curable glues<sup>37</sup> and glass frit (GF).<sup>283,284</sup> GF is believed to be one of the strongest candidate as a sealant material in DSSC glass modules, as it possesses the same characteristics of the substrate, thus optimum compatibility; moreover, it is non-permeable, stable under UV light and at elevated temperatures.<sup>285–287</sup> On the other hand, it has been quite difficult to find lead-free GF,<sup>288</sup> demonstrating at the same time low melting temperature and high chemical stability towards the redox mediator. Moreover, GF must not leach elements into the electrolyte, which could cause the depletion of the  $I_3^-$  ions.<sup>115,289</sup>

The use of an aqueous electrolyte opens up an amount of novel opportunities in the development of specific sealants for water-based DSSCs. A seminal work was proposed by Hinsch and coworkers, who fabricated  $\text{Bi}_2\text{O}_3\text{-SiO}_2\text{-B}_2\text{O}_3$  and  $\text{ZnO-SiO}_2\text{-Al}_2\text{O}_3$  GFs, with characteristic melting temperatures in the range of 400–520 °C.<sup>290</sup> When  $\text{Bi}_2\text{O}_3\text{-SiO}_2\text{-B}_2\text{O}_3$  was coupled with an aqueous electrolyte ( $\text{I}_2$  0.10 M, GuSCN 0.10 M and NBBI 0.50 M in MPPI/ACN/ $\text{H}_2\text{O}$ ), UV-Vis measurements revealed a significant decrease in the  $I_3^-$  absorbance with time (Fig. 22A),

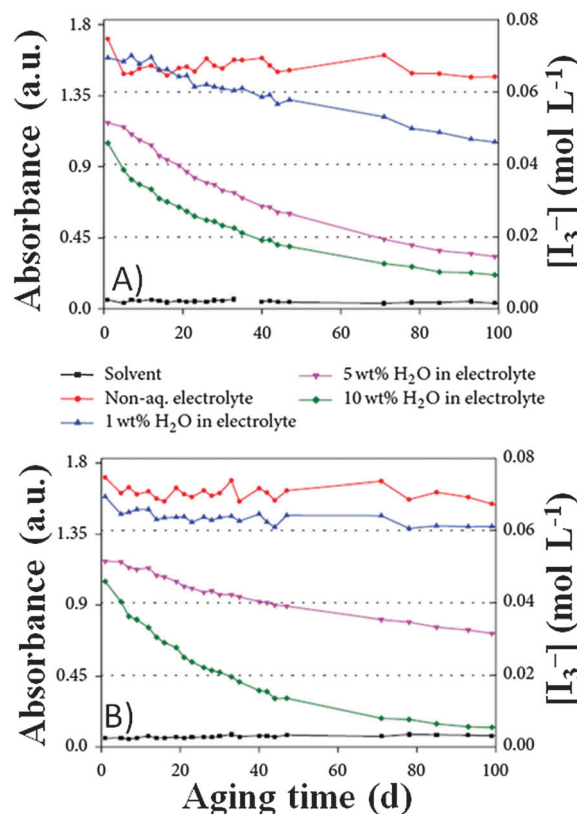


Fig. 22 Absorbance at 430 nm as a function of the aging time for DSSCs filled with solvent, non-aqueous electrolyte and redox electrolyte encompassing 1, 5 and 10 wt%  $\text{H}_2\text{O}$ , in the presence of different GFs as sealants: (A)  $\text{Bi}_2\text{O}_3\text{-SiO}_2\text{-B}_2\text{O}_3$ ; (B)  $\text{ZnO-SiO}_2\text{-Al}_2\text{O}_3$ . Adapted and reprinted from ref. 290.

while energy dispersive X-ray (EDX) analysis revealed a precipitate of bismuth and iodine. Indeed,  $\text{BiI}_4^-$  formation was observed, and its absorption band at 460 nm competed with the one characteristic for the sensitizer.<sup>291</sup> As regards the  $\text{ZnO-SiO}_2\text{-Al}_2\text{O}_3$  GF, the electrolyte bleached because of  $I_3^-$  depletion (Fig. 22B); EDX revealed the leakage of zinc from the GF. In turn, the metal formed a thermally stable compound with iodine,<sup>292</sup> being detrimental on the DSSC performance. Moreover, for both the GFs, the  $I_3^-$  depletion was enhanced while increasing the content of water in the electrolyte.

The GFs proposed by Hinsch and coworkers represent only the first example of the sealing material for aqueous DSSCs, thus other metal oxide formulations must be elaborated to assure the development of truly stable cells. However, in the case of aqueous DSSCs, also the polymeric sealants would return in vogue, since the water permeability would no longer be a problem for cell stability.

## 13. Quasi-solid electrolytes: the step forward

In Section 2, the main drawbacks of liquid electrolytes have been thoroughly discussed, volatility and difficulty of hermetic sealing being the most significant. We have already shown that



volatility may be remarkably reduced by introducing water as solvent of the redox mediator in place of ACN; nevertheless, the use of specifically developed quasi-solid electrolytes would clearly facilitate the operations of cell assembly and sealing, also guaranteeing a prolonged stability to the device. As a result, many research groups working on aqueous electrolytes have directed their efforts towards the realisation of water-based DSSCs in the quasi-solid state.

### 13.1 RTIL–water mixtures

The quasi-solidification of a liquid electrolyte is usually carried out through the introduction of RTILs or polymeric materials.<sup>18,48,68</sup> The pioneering work on the development of RTIL-laden polymer electrolytes was published by Mikoshiba and coworkers, who used water to face the slow  $I_3^-$  diffusion in the highly viscous RTILs.<sup>293</sup> By coupling MP11 with different components (e.g., LiI/TBP/ $I_2$ , TBP/ $I_2$ , LiI/ $I_2$ ,  $I_2$ ), it was observed that the addition of water improved the efficiency of N3-based cells, the best results being obtained using 5 wt%  $H_2O$  in the presence of LiI/ $I_2$ , while 10 wt% in the case of the LiI/TBP/ $I_2$  system. The improvement was attributed to the reduced electrolyte viscosity and to the increased  $V_{oc}$ : a remarkable efficiency of 4.2% was obtained.

A more detailed analysis regarding the effects of water on the RTIL-based electrolytes was conducted by Hayase and coworkers.<sup>294</sup> As shown in Table 16, several additives were introduced to increase the conductivity of MP11: among all, water was demonstrated to be the best one, besides being the one having the lowest environmental impact. Table 17 shows that increasing the water content led to reduced viscosity ( $\mu$ ) and increased ionic conductivity ( $\sigma$ , also reflected in the improved diffusion coefficient for  $I_3^-$ ). Other positive aspects were the  $R_{CE}$  decrease and  $E$  increase while increasing the

amount of water. As regards the  $TiO_2$  surface, when 8% of water was added in the electrolyte, it was observed that the flat band potential shifted positively from  $-1.11$  to  $-1.01$  eV, due to the adsorption of  $H_2O$  molecules onto the semiconductor.<sup>82,83</sup>

This modified the characteristics of the electron diffusion in the nanostructured photoanode: electron lifetime ( $\tau$ ), electron diffusion constant ( $D$ ) and electron diffusion length ( $L$ ) decreased upon the introduction of water. This was due to the replacement of the  $Li^+$  ions adsorbed onto the  $TiO_2$  surface by water molecules, resulting in a less effective ambipolar diffusion of the electrons which, in turn, led to an increased electron recombination probability.

Imidazolium-based RTILs are very popular due to their peculiar characteristics of being solvents and salts at the same time. However, the synergistic effect of using mixtures of different ionic liquids has been also proposed to possibly improve the PV performance. Among all, bistriflimide (TFSI $^-$ ) gave excellent performance when combined with imidazolium-based RTILs.<sup>295</sup> Even if TFSI $^-$ -based RTILs are generally considered as hydrophobic,<sup>296,297</sup> coulometric Karl Fischer titration enlighten the presence of significant amounts of water (i.e., around 7 mol%) most likely absorbed from the ambient air.<sup>298</sup> To better unravel this phenomenon, Kim and coworkers theoretically investigated the effects of water on the microstructure as well as the transport properties of a mixture of 1-ethyl-3-methylimidazolium (EMIm $^+$ ), TFSI $^-$ ,  $I^-$  and  $I_3^-$ .<sup>299</sup> By considering a 0–25% mole fraction ( $\chi_w$ ) of water, three regimes were obtained (Fig. 23A):

- ice-like regime ( $\chi_w < 7.69\%$ , Fig. 23B), with water molecules mostly isolated and intercalated between two EMIm $^+$  and two TFSI $^-$  units, resulting in an ice-like entropy.

- Nano-cluster regime ( $\chi_w = 7.69$ – $14.29\%$ , Fig. 23C), with nanosized water clusters bridged between two EMIm $^+$  and two TFSI $^-$  units.

- Liquid-like regime ( $\chi_w = 14.29$ – $25.00\%$ , Fig. 23D), that is clusters composed of several water molecules located between EMIm $^+$  and TFSI $^-$  ions.

In order to examine the effect of water absorption on the transport properties of the electrolyte, the self-diffusion coefficients were measured based on the Green–Kubo relationship,<sup>300</sup> and it was found that the addition of water up to 10 mol% enhanced the diffusivity of both EMIm $^+$  and TFSI $^-$ , with marginal variations in the diffusivity of  $I^-$  and  $I_3^-$ . More in detail, the increase of entropy and mobility of EMIm $^+$  caused local fluctuations in  $I^-$  and  $I_3^-$ , thus enhancing the rate of Grothuss-like electron transfer<sup>301</sup> as well as the rate of oxidized

**Table 16**  $\mu$  and  $\sigma$  values of MP11-based electrolytes added with different additives in the 10 wt% ratio. Adapted and reprinted from ref. 294

Additive	$\mu$ (mPa s)	$\sigma$ (mS cm $^{-1}$ )
Formamide	108	1.8
NMP	238	1.2
GBL	153	1.9
EC	104	1.5
PC	220	1.1
Diethoxyethane	139	2.1
EtOH	57	3.6
$H_2O$	18	15
Ethylene glycol	104	2.6

**Table 17**  $\mu$ ,  $\sigma$ , apparent diffusion constant for  $I_3^-$  [ $D(I_3^-)$ ],  $R_{CE}$ ,  $E$ ,  $\tau$ ,  $D$  and  $L$  values for MP11-based electrolytes with different water contents. Electrolytes tested were  $I_2$  0.50 M in MP11: $H_2O$  for  $\mu$ ,  $\sigma$  and  $D(I_3^-)$ ;  $I_2$  0.30 M in MP11: $H_2O$  for  $R_{CE}$ ; MP11 60 mM and  $I_2$  10 mM in ACN/ $H_2O$  for  $E$ ; LiI 0.50 M,  $I_2$  0.30 M, TBP 0.58 M in MP11/ $H_2O$  for  $\tau$ ,  $D$  and  $L$ .  $P_{in} = 1$  sun. Dye: N719. Note: we think that a factor of  $10^{-5/-7}$  is missing in the reported  $D(I_3^-)$  values. Adapted and reprinted from ref. 294

$H_2O$ (wt%)	$\mu$ (mPa s)	$\sigma$ (mS cm $^{-1}$ )	$D(I_3^-)$ (cm $^2$ s $^{-1}$ )	$R_{CE}$ ( $\Omega$ cm $^{-2}$ )	$E$ (mV)	$\tau$ (s)	$D$ (cm $^2$ s $^{-1}$ )	$L$ (cm)
0	564	0.7	6.5	3.04	—	0.32	1.36	0.66
1	285	1.35	9.5	1.99	0.09	—	—	—
5	52.8	5.81	23	0.24	0.17	0.12	1.23	0.38
10	19.2	14.12	34	0	0.24	0.12	1.23	0.38





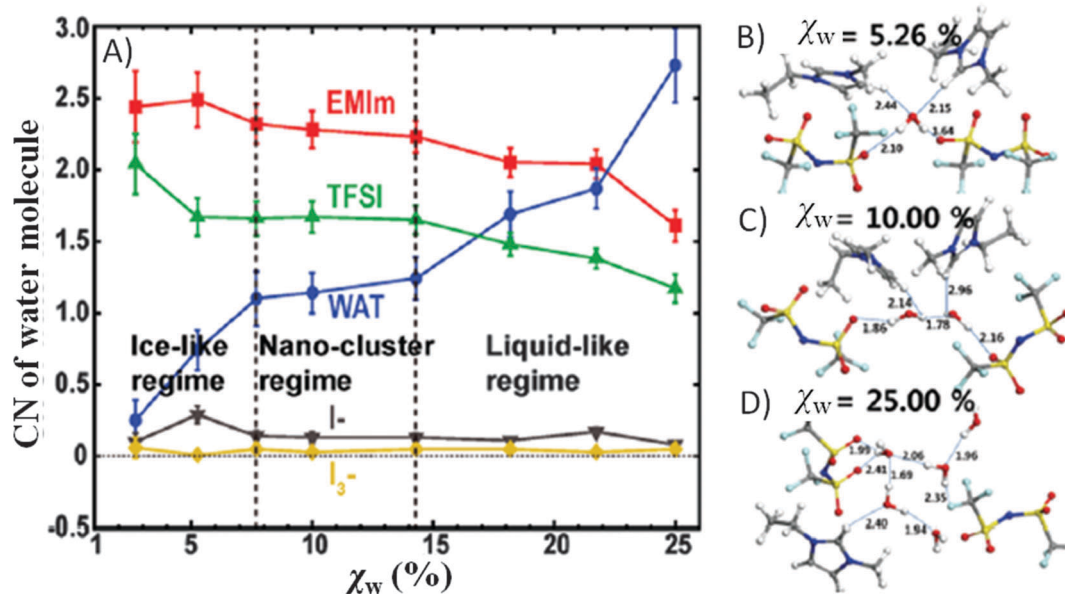


Fig. 23 (A) Dependence of water coordination (CN) on  $\chi_w$  in the presence of the following mole fractions: EMIm<sup>+</sup> 0.50, TFSI<sup>-</sup> 0.36, I<sup>-</sup> 0.13 and I<sub>3</sub><sup>-</sup> 0.01. Representative water structure mediating EMIm<sup>+</sup>–TFSI<sup>-</sup> interactions after 30 ns molecular dynamics for: (B) ice regime, (C) nanocluster regime, and (D) liquid-like regime. Adapted and reprinted from ref. 299.

dye reduction. On the other hand, when using high amounts of water, the large water clusters allowed water molecules to access the TiO<sub>2</sub> nanostructure, thus weakening the Lewis acid–base interaction of the carboxylic group of dye molecules with the anode particles. Based on all of these simulations, it was clear that the H<sub>2</sub>O–RTIL system provided the best performance in the nanocluster regime, because of allowing spontaneous water absorption into the RTIL, retention in the RTIL phase by binding as nanoclusters to EMIm<sup>+</sup> or TFSI<sup>-</sup> ions and lubricating fluctuations in the RTIL to enhance Grotthuss electron transport.

### 13.2 Gel-polymer aqueous electrolytes

The second category of quasi-solid electrolytes is based on a polymeric matrix, capable of gelifying the redox mediator solution and trapping it within the macromolecular network.<sup>302</sup> In 2004, Hayase and coworkers firstly proposed an aqueous gel-polymer electrolyte obtained by reacting poly(vinylpyridine) (PVP,  $M_n$  = 80 000) with 1,2,4,5-tetra(bromomethyl)benzene to make chemically crosslinked ionomer structures.<sup>303</sup> The resulting polymer<sup>304</sup> trapped 0.30 M I<sub>2</sub> in MPII–H<sub>2</sub>O mixtures, where water was useful to decrease the gel viscosity, thus guaranteeing a good physical contact between the gel and the mesopores of the photoanode. Moreover,  $D(I_3^-)$  was improved upon water addition, because of the phase separation between PVP and MPII, which in turn retarded the interaction between the cations fixed on the polymer matrix and I<sub>3</sub><sup>-</sup> ions.<sup>305</sup> Another advantage of water addition was the decrease in  $R_{CE}$ . As a further interesting aspect of their work, Hayase and coworkers carried out the treatment of the N719-sensitized photoanode with acetic acid, which bonded on the free TiO<sub>2</sub> sites. As a consequence, the electron recombination with I<sub>3</sub><sup>-</sup>, which is the most relevant drawback of RTIL-based electrolytes,

where high I<sub>2</sub> amounts are added to increase the limiting currents, was inhibited. An efficiency value of 2.4% ( $J_{sc}$  = 10.9 mA cm<sup>-2</sup>,  $V_{oc}$  = 0.52 V, FF = 0.42) was obtained in the presence of 5 wt% H<sub>2</sub>O.

In the field of gel-polymer electrolytes, PEG is one of the most successful material due to its ability to play the role as a host for several metal-salt systems, being at the same time a good binder for other phases.<sup>306–308</sup> Moreover, to achieve high ionic conductivity values, polymer blending with PEG is a valuable strategy.<sup>309</sup> With the aim of confirming the practical application of such an approach in an aqueous environment, Nateghi and coworkers prepared a gel-polymer electrolyte consisting of poly(vinylpyrrolidone) (PVPI,  $M_n$  = 40 000, 2 wt%), PEG 400 4 wt%, KI 0.20 M and I<sub>2</sub> 40 mM in ACN/H<sub>2</sub>O.<sup>310</sup> The effect of water concentration on the polyiodide formation was investigated by analyzing the intensity ratio between the polyiodide (I<sub>n</sub><sup>-</sup>) and the I<sub>3</sub><sup>-</sup> species: a decrease of the I<sub>n</sub><sup>-</sup>/I<sub>3</sub><sup>-</sup> ratio occurred upon water addition. Theoretical calculations indicated that I<sub>n</sub><sup>-</sup> species were more effective electron acceptors than I<sub>3</sub><sup>-</sup> due to more delocalized charges. This facilitated the reaction with electrons due to reduced repulsion;<sup>311</sup> moreover, the decrease of the I<sub>n</sub><sup>-</sup>/I<sub>3</sub><sup>-</sup> ratio contributed to reduce the charge recombination losses. As a consequence,  $V_{oc}$  values of the aqueous quasi-solid DSSCs increased because of water addition; this effect was also due to water adsorption onto the TiO<sub>2</sub> surface. On the other hand, the presence of water negatively affected the  $J_{sc}$  values, due to the lower concentration of I<sub>3</sub><sup>-</sup> in the aqueous electrolyte and the detachment of the adsorbed Z907 dye molecules. Overall, cells with 50 wt% H<sub>2</sub>O showed an efficiency equal to 2.31% ( $J_{sc}$  = 7.37 mA cm<sup>-2</sup>,  $V_{oc}$  = 0.63 V, FF = 0.50), while in the absence of water the average value was 2.88% ( $J_{sc}$  = 13.7 mA cm<sup>-2</sup>,  $V_{oc}$  = 0.58 V, FF = 0.35). When tested for their stability (under dark, 65 °C, 85% RH),



aqueous cells were able to retain the 63% of their initial efficiency after 168 h of operation, remarkably better than the 12% retention for the ACN-based quasi-solid DSSCs, thus further confirming the positive aspects of the lower volatility of aqueous electrolytes.

Amphiphilic block copolymers (ABCs) represent an emerging class of macromolecular matrices, because of their ability to self-assemble into liquid crystalline phases such as cubic, hexagonal and/or lamellar; in these configurations, polymer gels exhibit enhanced  $\sigma$  values with respect to other crystalline phases.<sup>312,313</sup> Being the behaviour of ABCs more relevant in water-based solvents, Soni and coworkers prepared gel-polymer electrolytes with Pluronic F77 [HO(CH<sub>2</sub>CH<sub>2</sub>O)<sub>52</sub>(CH<sub>2</sub>CH(CH<sub>3</sub>)O)<sub>35</sub>(CH<sub>2</sub>CH<sub>2</sub>O)<sub>52</sub>H] and Pluronic P-123 [HO(CH<sub>2</sub>CH<sub>2</sub>O)<sub>20</sub>(CH<sub>2</sub>CH(CH<sub>3</sub>)O)<sub>70</sub>(CH<sub>2</sub>CH<sub>2</sub>O)<sub>20</sub>H].<sup>314</sup> These are triblock copolymers (widely known as poloxamers) composed of a central hydrophobic chain of poly(propylene oxide) (PPO) flanked by two hydrophilic chains of poly(ethylene oxide) (PEO). F77 ( $M_n = 6600$ ), P-123 ( $M_n = 5750$ ) or pure PEG ( $M_n = 6000$ ) were introduced in the 35 wt% ratio in aqueous electrolytes containing BMII 2.0 M, I<sub>2</sub> 50 mM and TBP 0.50 M: under these conditions, the cubic phase was obtained, which is the crystalline phase of ABCs having the highest  $\sigma$ , due to the presence of interconnected bi-continuous channels. The conductivity trend showed in Table 18 followed the sequence P-123 > F77 > PEG: in fact, due to the lower amount of PEO units in the P-123 gel-polymer electrolyte, the degree of hydration per PEO chain was found to be higher when compared to that of F77, which promoted ion mobility. Moreover, the size of the F77 micellar core (Fig. 24A) was smaller than that of P-123. As regards PEG, it did not form a microcrystalline ordered gel, thus I<sub>3</sub><sup>-</sup> ions could not diffuse so faster as in P-123- and

F77-based electrolytes. However, as shown in Table 18, despite the lower  $\sigma$ , when introduced in quasi-solid DSSCs F77-based systems demonstrated higher  $J_{sc}$  and  $V_{oc}$  values than P-123-based ones. Indeed, while P-123 formed a gel with very high viscosity, F77 showed remarkable structural polymorphism (Fig. 24B): by lowering its temperature, a conversion into the simple micellar solution having reduced  $\mu$  occurred. Thus, F77 gels could diffuse into the photoanode nanopores at low temperature (ensuring the efficient regeneration of the oxidized dye in the whole electrode), while maintaining a gel-like consistence above 37 °C. Moreover, the higher PPO content in the P-123 gel hindered the accessibility of TBP, thus lowering the cell photovoltage with respect to that of the F77-based cell. Stability tests were carried out over 500 h and only around 3% reduction in the overall performance of DSSCs based on ABCs occurred; in contrast, dye desorption was observed in the case of PEG-based gels, due to the highly hydrated polymer chains.

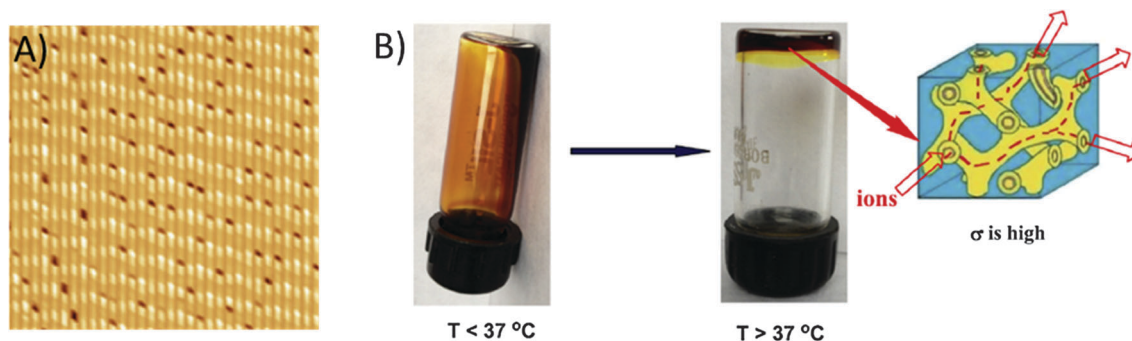
Another elegant strategy to prepare electrolytes being effectively water as well as solvent leakage resistant is the use of thixotropic three-dimensional (3D) networks,<sup>315</sup> the latter obtained by a chemical, photochemical or thermal route.<sup>316,317</sup> To this purpose, Ko and coworkers used xanthan gum ( $M_n = 2 \times 10^6$ ), a water soluble and environmentally friendly polysaccharide rich in hydroxyl groups ready to form a 3D network, the viscosity of which reversibly decreases upon application of an external stress.<sup>318</sup> After a thorough optimization of the stability of all the ingredients in the reactive formulation – a key aspect in this field, where apolar, polar and ionic substances are concurrently used – a 1:1 mixture of xanthan gum (3 wt% in H<sub>2</sub>O) and liquid electrolyte (PMII 4.0 M, I<sub>2</sub> 0.30 M, TBP 1.5 M

**Table 18** Effect of the ABCs: H<sub>2</sub>O 35:65 matrices on both electrolyte (BMII 2.0 M, I<sub>2</sub> 50 mM and TBP 0.50 M) and DSSC PV parameters ( $P_{in} = 1$  sun). An ACN-based cell is also reported for comparison purposes. Dye: D907. Adapted and reprinted from ref. 314

Matrix	$\sigma$ (mS cm <sup>-1</sup> )	$D$ (I <sub>3</sub> <sup>-</sup> ) (cm <sup>2</sup> s <sup>-1</sup> )	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
ACN	—	—	16.8	0.676	0.54	6.5
P-123	14.8	$4.3 \times 10^{-7}$	4.6	0.491	0.57	1.3
F77	11.1	$3.4 \times 10^{-7}$	6.2	0.595	0.53	2.1
PEG	8.8	$2.6 \times 10^{-7}$	2.1	0.600	0.44	0.6

**Table 19** Effect of liquid (PMII 4.0 M, I<sub>2</sub> 0.30 M, TBP 1.5 M and GuSCN 0.20 M in MPN or MPN: H<sub>2</sub>O 1:1) and quasi-solid (1:1 in xanthan gum 3 wt% in H<sub>2</sub>O and PMII 4.0 M, I<sub>2</sub> 0.30 M, TBP 1.5 M and GuSCN 0.20 M in MPN) electrolytes on different electrochemical and PV parameters ( $P_{in} = 1$  sun). Dye: TG6. Adapted and reprinted from ref. 318

Electrolyte	$D$ (I <sub>3</sub> <sup>-</sup> ) (cm <sup>2</sup> s <sup>-1</sup> )	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)
MPN	$1.15 \times 10^{-5}$	12.86	0.59	0.61	5.23
MPN:H <sub>2</sub> O	$5.60 \times 10^{-6}$	9.69	0.68	0.76	4.99
MPN:H <sub>2</sub> O:xanthan gum	$3.78 \times 10^{-6}$	9.49	0.65	0.77	4.78



**Fig. 24** (A) AFM image of a F77-based gel-polymer electrolyte coated onto a glass substrate. Black dark spots prove the existence of a circular area ranging from 3 to 5 nm, which might be the core of F77 micelles consisting of hydrophobic PPO moieties. The contrast of this area to the rest of the film could be due to the penetration of relatively hydrophobic I<sub>3</sub><sup>-</sup> into the PPO core. (B) Photos and schematic illustration of the structural polymorphism of a F77-based gel-polymer electrolyte. Adapted and reprinted from ref. 314.



**Table 20** PV performance ( $P_{in} = 1$  sun) of DSSCs assembled with aqueous electrolytes. Data are presented in order of increasing amounts of water in the electrolytes; in the case of equal water amount, data are presented in order of increasing efficiency. Efficiency loss with respect to the initial value ( $\eta_{loss}$ ) is also reported when aging tests were performed

Anode <sup>a</sup>	Dye <sup>b</sup>	Electrolyte	H <sub>2</sub> O (%)	Cathode <sup>c</sup>	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)	$\eta_{loss}$ <sup>d</sup>	Ref.
TiO <sub>2</sub> (11.5 $\mu$ m) + TiCl <sub>4</sub>	N719	BMII 0.70 M, I <sub>2</sub> 30 mM, GuSCN 0.10 M, TBP 0.50 M and AOT 2.0 mM in ACN:VAN	0.018	Pt	17.5	0.85	0.73	10.8	2% (1000 h, 1 sun)	172
TiO <sub>2</sub>	N3	LiI 0.50 M and 50 mM I <sub>2</sub> in MPN	3	—	14.1	0.54	0.59	4.5	—	124
TiO <sub>2</sub> (4.5 $\mu$ m)	N3	LiI 0.10 M and I <sub>2</sub> 10 mM in MPN	4	Pt foil	1.96	0.541	0.67	4.8	—	43
BL + TiO <sub>2</sub> (10 $\mu$ m)	N719	LiI 0.10 M, HDMII 0.60 M, I <sub>2</sub> 50 mM, TBP 0.50 M and Triton X-100 20 mM in MPN	4	Pt	11.77	0.81	0.62	5.9	29% (7 d, dark)	156
TiO <sub>2</sub> (9 $\mu$ m) + CH <sub>3</sub> COOH <sup>e</sup>	N3	I <sub>2</sub> 0.30 M, PVP 2% and TBMB 2% in MPN	5	Pt	10.9	0.52	0.42	2.4	—	303
TiO <sub>2</sub> (12 $\mu$ m)	N719	DMPII 0.50 M, LiI 0.10 M, I <sub>2</sub> 50 mM and BBEG <sub>n</sub> ( $n = 1$ ) 0.50 M in ACN	10	Pt	4.19	0.8	0.69	2.31	7% (135 h)	145
TiO <sub>2</sub> (12 $\mu$ m)	N719	DMPII 0.50 M, LiI 0.10 M, I <sub>2</sub> 50 mM and BBEG <sub>n</sub> ( $n = 3$ ) 0.50 M in ACN	10	Pt	5.75	0.8	0.64	2.96	40% (135 h)	145
TiCl <sub>4</sub> + TiO <sub>2</sub> (25 $\mu$ m) + MK-2HA		MPH 2.0 M, LiI 0.10 M, I <sub>2</sub> 0.20 M, TBP 0.50 M in ACN	10	Pt	8.1	0.69	0.72	4.02	2.5% (200 h, dark)	243
TiCl <sub>4</sub>	N3	LiI 0.50 M, TBP 0.58 M and I <sub>2</sub> 0.30 M in MPN	10	Pt	8.8	0.67	0.72	4.2 <sup>f</sup>	—	293
TiO <sub>2</sub>	N3	LiI 0.50 M, I <sub>2</sub> 0.30 M and TBP 0.58 M in MPN	10	Pt	8.8	0.67	0.72	4.2 <sup>f</sup>	—	294
BL + TiO <sub>2</sub> (10 $\mu$ m) + Z907 + CDCA		PMII 1.0 M, I <sub>2</sub> 0.15 M, GuSCN 0.10 M and NBBI 0.50 M in MPN or ACN:VAN	10	Pt	15.67	0.68	0.71	7.52	7% (1000 h, 1 sun)	128
TiCl <sub>4</sub>	TG6	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M and TBP 0.50 M in MPN	20	Pt	8.5	0.84	0.73	5.2	Gain 2% (750 h, 1 sun, 35 °C) <sup>g</sup>	120
ZnO <sub>2</sub> (17.3 $\mu$ m)	CV-G	Ce(NO <sub>3</sub> ) <sub>3</sub> 0.10 M and Ce(NO <sub>3</sub> ) <sub>4</sub> 50 mM in EtOH	30	Pt	0.52	0.624	0.53	0.688	—	178
TiCl <sub>4</sub> + TiO <sub>2</sub> (9 $\mu$ m) + 5 Z907		KI 0.20 M, I <sub>2</sub> 40 mM, PEG 4 wt% and PVP 2 wt% in ACN:VAN	50	Pt	7.368	0.625	0.5	2.306	37% (168 h, 1 sun)	310
TiO <sub>2</sub> (T + SL)	D5L6	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1% in MPN	50	Pt	6.22	0.75	0.73	3.4	—	241
TiO <sub>2</sub> (T + SL)	JK-310	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1% in MPN	50	Pt	6.62	0.75	0.76	3.77	—	241
TiO <sub>2</sub> (T + SL)	D21L6	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1% in MPN	50	Pt	7.46	0.77	0.77	4.41	—	241
TiO <sub>2</sub> (12 $\mu$ m) + 7 $\mu$ m SL + TiCl <sub>4</sub>	TG6	PMII 4.0 M, I <sub>2</sub> 0.30 M, TBP 1.5 M, GuSCN 0.20 M and xanthan gum 3 wt% in MPN	50	Pt	9.5	0.65	0.77	4.78	7% (288 h, dark, 65 °C, 85% RH)	318
TiO <sub>2</sub> (12 $\mu$ m) + 7 $\mu$ m SL + TiCl <sub>4</sub>	TG6	PMII 1.96 M, I <sub>2</sub> 0.15 M, TBP 0.75 M and GuSCN 0.10 M in MPN	50	Pt	9.7	0.68	0.76	4.99	48% (288 h, dark, 65 °C, 85% RH)	318
BL + TiO <sub>2</sub> (12 $\mu$ m) + TiCl <sub>4</sub>	D907	BMII 2.0 M, I <sub>2</sub> 50 mM and TBP 0.50 M in PEG	65	Pt	2.1	0.6	0.44	0.6	—	314
TiO <sub>2</sub> + Au NPs	MB	FeCl <sub>3</sub> 0.10 M, FeCl <sub>3</sub> 50 mM and LiNO <sub>3</sub> 0.10 M in EtOH	65	Ag	5.96	0.46	0.65	0.95	—	204
BL + TiO <sub>2</sub> (12 $\mu$ m) + TiCl <sub>4</sub>	D907	BMII 2.0 M, I <sub>2</sub> 50 mM and TBP 0.50 M in P123	65	Pt	4.6	0.491	0.57	1.3	—	314
TiO <sub>2</sub> (15 $\mu$ m)	N719	KI 0.50 M and I <sub>2</sub> 25 mM in EtOH	65	Pt	4.24	0.51	0.60	1.3	—	138
TiO <sub>2</sub> (1.8 $\mu$ m)	Rhs	Ce(NO <sub>3</sub> ) <sub>3</sub> 0.10 M and 50 mM Ce(NO <sub>3</sub> ) <sub>4</sub> in EtOH	65	Ag	10.9	0.496	0.27	1.49	—	174
TiO <sub>2</sub> (15 $\mu$ m)	N3	KI 0.50 M and I <sub>2</sub> 25 mM in EtOH	65	Pt	4.94	0.55	0.63	1.7	—	138
BL + TiO <sub>2</sub> (12 $\mu$ m) + TiCl <sub>4</sub>	D907	BMII 2.0 M, I <sub>2</sub> 50 mM and TBP 0.50 M in F77	65	Pt	6.2	0.595	0.53	2.1	3% (500 h)	314
TiO <sub>2</sub> (20 $\mu$ m) + UV/O <sub>3</sub>	N3 + TBP	KI 0.50 M and I <sub>2</sub> 25 mM in EtOH	65	Pt	5.8	0.6	0.63	2.2	—	203
TiO <sub>2</sub> (3.3 $\mu$ m)	PG	NaI 1.0 M and I <sub>2</sub> 0.10 M	100	Pt	2.2 <sup>h</sup>	0.44 <sup>h</sup>	—	—	0% (24 h, under light <sup>i</sup> )	256
TiO <sub>2</sub> (10 $\mu$ m)	N3	LiI 0.10 M, I <sub>2</sub> 10 mM, 0.5 wt% $\kappa$ -carrageenan and HNO <sub>3</sub> (pH 2)	100	Pt plate	2.69	0.442	0.48	0.586	—	328
TiO <sub>2</sub> (15 $\mu$ m)	N719	KI 0.50 M and I <sub>2</sub> 25 mM	100	Pt	2.14	0.44	0.64	0.6	—	138
TiO <sub>2</sub> (15 $\mu$ m)	N3	KI 0.50 M and I <sub>2</sub> 25 mM	100	Pt	3.61	0.47	0.65	1.1	50% (75 d, dark, RT)	138



Table 20 (continued)

Anode <sup>a</sup>	Dye <sup>b</sup>	Electrolyte	H <sub>2</sub> O (%)	Cathode <sup>c</sup>	<i>J</i> <sub>sc</sub> (mA cm <sup>-2</sup> )	<i>V</i> <sub>oc</sub> (V)	FF	$\eta$ (%)	$\eta_{\text{loss}}^d$	Ref.
TiCl <sub>4</sub> + TiO <sub>2</sub> (20 $\mu$ m T + 4 $\mu$ m SL) + TiCl <sub>4</sub>	JK-259	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1%	100	Pt	2.28	0.66	0.79	1.16	—	238
TiCl <sub>4</sub> + TiO <sub>2</sub> (3 $\mu$ m T + 5 $\mu$ m SL) + TiCl <sub>4</sub>	V35	KI 4.0 M and I <sub>2</sub> 20 mM, pH 8	100	PEDOT	5.60	0.485	0.63	1.71	Gain 58% (18 d, dark)	249
TiO <sub>2</sub> (8.9 $\mu$ m) + TiCl <sub>4</sub>	Z907 + CDCA	NaI 2.0 M, I <sub>2</sub> 20 mM, GuSCN 0.50 M and CDCA until saturation	100	Pt	4.91	0.62	0.64	1.88	—	206
TiO <sub>2</sub>	<i>cis</i> -Ru(II)(L <sub>2</sub> (H <sub>2</sub> O) <sub>2</sub> ) <sup>2+</sup> -i	KI 0.10 M and I <sub>3</sub> <sup>-</sup> 1.0 mM	—	100	Pt flag	0.38	0.52	0.7	2.0 <sup>f</sup>	0% (4 d, 0.07 sun)
118 TiO <sub>2</sub> (2.8 $\mu$ m T + 3.1 $\mu$ m SL)	D205	TEMPO 1.0 M and NaBF <sub>4</sub> 1.0 M	100	Pt/Teflon	4.5	0.69	0.64	2.1	—	274
TiCl <sub>4</sub> + TiO <sub>2</sub> (20 $\mu$ m T + 4 $\mu$ m SL) + TiCl <sub>4</sub>	JK-262	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1%	100	Pt	3.78	0.68	0.82	2.1	—	238
TiCl <sub>4</sub> + TiO <sub>2</sub> (3 $\mu$ m T + 5 $\mu$ m SL) + TiCl <sub>4</sub>	V35	KI 4.0 M, I <sub>2</sub> 20 mM and CDCA until saturation	100	Pt	4.86	0.600	0.76	2.20	—	249
TiO <sub>2</sub> (7 $\mu$ m) + TiCl <sub>4</sub>	TG6	PMII 2.0 M, I <sub>2</sub> 50 mM, GuSCN 0.10 M, TBP 0.50 M and Triton X-100 1%	100	Pt	4.7	0.74	0.69	2.4	—	120
TiCl <sub>4</sub> + TiO <sub>2</sub> (3 $\mu$ m T + 2 $\mu$ m SL) + TiCl <sub>4</sub>	D45	TT <sup>+</sup> EMI <sup>+</sup> 0.20 M, DTT 0.20 M, TBP 0.50 M and 1% Triton X-100	100	Pt	7.2	0.65	0.55	2.6	37% (4 h, 1 sun, RT)	193
TiO <sub>2</sub> (8.9 $\mu$ m) + TiCl <sub>4</sub>	TG6	NaI 2.0 M, I <sub>2</sub> 20 mM, GuSCN 0.50 M and CDCA until saturation	100	Pt	7.34	0.59	0.63	2.64	—	206
TiCl <sub>4</sub> + TiO <sub>2</sub> (3 $\mu$ m T + 5 $\mu$ m SL) + TiCl <sub>4</sub>	V35	KI 2.0 M, I <sub>2</sub> 10 mM and CDCA until saturation	100	PEDOT	6.85	0.650	0.67	3.01	—	249
TiO <sub>2</sub> (4.4 $\mu$ m) + TiCl <sub>4</sub>	N719	NaI 2.0 M, I <sub>2</sub> 20 mM, GuSCN 1.0 M, HNO <sub>3</sub> (pH 3) and CDCA until saturation	100	Pt	8.5	0.59	0.63	3.08	—	206
TiCl <sub>4</sub> + TiO <sub>2</sub> (3 $\mu$ m T + 2 $\mu$ m SL) + TiCl <sub>4</sub>	D51	TT <sup>+</sup> EMI <sup>+</sup> 0.20 M, DTT 0.60 M, TBP 0.50 M and 1% Triton X-100	100	Pt	9.5	0.61	0.59	3.5	—	193
TiO <sub>2</sub> (13.3 $\mu$ m)	N719 + CDCA	NaI 2.0 M, I <sub>2</sub> 0.20 M, GuSCN 0.10 M and FC-134 0.2 wt%	100	Pt	10.97	0.53	0.68	3.96	63% (50 d, 1 sun, RT, UV filter)	163
TiO <sub>2</sub> (4.5 $\mu$ m) + TiCl <sub>4</sub>	D149	GuI 8.0 M, I <sub>2</sub> 20 mM and CDCA until saturation	100	Pt	10.02	0.61	0.67	4.06	—	206
BL + TiO <sub>2</sub> (1.3 $\mu$ m T + 5 $\mu$ m SL) + TiCl <sub>4</sub>	MK-2	K <sub>4</sub> Fe(CN) <sub>6</sub> 0.40 M, K <sub>3</sub> Fe(CN) <sub>6</sub> 0.40 mM, KCl 0.10 M, Trizma-HCl buffer 50 mM (pH 8) and Tween 20 0.1%	100	Pt mirror	7.2	0.76	0.75	4.1	50% (2 h)	182
TiO <sub>2</sub> (1 $\mu$ m T + 3 $\mu$ m SL)	MK-2	[Co(bpy) <sub>3</sub> ] <sup>2+</sup> 0.20 M, [Co(bpy) <sub>3</sub> ] <sup>3+</sup> 40 mM, NMBI 0.70 M NMBI and PEG 300 1%	100	Pt	8.3	0.68	0.72	4.2	10% (90 d, dark)	194
TiO <sub>2</sub> (9 $\mu$ m T + 3 $\mu$ m SL)	MD3	TEMPO 0.40 M, NOBF <sub>4</sub> 0.40 M, LiI 0.10 M, I <sub>2</sub> 50 mM, DMPII 0.60 M, GuSCN 0.10 M and Tween 20 0.1%	100	Pt	9.56	0.77	0.67	4.96	—	258
TiO <sub>2</sub> (1 $\mu$ m T + 3 $\mu$ m SL)	MK-2	[Co(bpy) <sub>3</sub> ] <sup>2+</sup> 0.20 M, [Co(bpy) <sub>3</sub> ] <sup>3+</sup> 40 mM, NMBI 0.70 M NMBI and PEG 300 1%	100	Pt/ITO	9.8	0.69	0.74	5	Gain 2% (2 d, dark)	194
TiO <sub>2</sub> (1 $\mu$ m T + 3 $\mu$ m SL) + TiCl <sub>4</sub>	MK-2	[Co(bpy) <sub>3</sub> ](NO <sub>3</sub> ) <sub>3</sub> 0.20 M, [Co(bpy) <sub>3</sub> ](NO <sub>3</sub> ) <sub>3</sub> 40 mM, NMBI 0.70 M and PEG 300 1 wt%	100	Pt	10.17	0.821	0.68	5.64	0% (500 h, dark)	210

<sup>a</sup> T means transparent layer, SL scattering layer, BL blocking layer. When "TiCl<sub>4</sub>" is written before "TiO<sub>2</sub>", it means that the treatment has been carried out to fabricate a BL. When "TiCl<sub>4</sub>" is reported after "TiO<sub>2</sub>", it means that the treatment has been performed after mesoporous TiO<sub>2</sub> deposition. "TiO<sub>2</sub>" alone means that further data were not reported. <sup>b</sup> If a coadsorbent was employed, it has been reported in the table. <sup>c</sup> When "Pt" alone is reported, it means that Pt has been sputtered or thermally deposited following the traditional procedures. <sup>d</sup> If available, aging test conditions have been reported in the table. <sup>e</sup> Photoanodes were dipped in 1% acetic acid solution in toluene for 5 min, followed by rinsing with toluene. <sup>f</sup> Same PV data were reported by the same group in two different papers. <sup>g</sup> The cell was stored for 7 months in the dark before starting the aging test. <sup>h</sup> *P*<sub>in</sub> not reported. <sup>i</sup> L is the 2,2'-bipyridyl-4,4'-dicarboxylate ligand. <sup>j</sup> *P*<sub>in</sub> = 0.07 sun.



and GuSCN 0.20 M in MPN) was selected. As reported in Table 19, resulting aqueous DSSCs, both liquid and quasi-solid, showed higher  $V_{oc}$  and FF, but lower  $J_{sc}$  values with respect to the MPN-based liquid counterpart. The decrease in  $J_{sc}$  was related to the desorption of the dye from the  $TiO_2$  electrode surface. Actually, even if the hydrophobic TG6 dye was used, it was not possible to fully prevent the dye molecules from being desorbed; moreover, the  $I_3^-$  diffusion coefficient was decreased when water was introduced. As regards  $V_{oc}$ , both  $E$  of the electrolyte and the CB of the  $TiO_2$  positively shifted in the presence of aqueous electrolytes; however, the shift was found to be more significant for  $E$ , thus resulting in enhanced photovoltage values. Noteworthy, the quasi-solid aqueous cell exhibited a performance in terms of overall efficiency comparable with that of the liquid one (*i.e.*, 4.78% *vs.* 4.99%): this was ascribed to the thixotropic nature of the gel-polymer matrix, which could infiltrate as a liquid into the photoanode, in spite of the scarce wetting ability typically observed when solid polymer electrolytes are used,<sup>319,320</sup> being their macromolecular chain radius of gyration larger than the pore size of  $TiO_2$ .<sup>69,321,322</sup> During extreme 288 h aging tests (65 °C and 85% RH), the water-based liquid DSSC retained around 50% of its initial efficiency, while the quasi-solid one remarkably provided the 93% of its initial value. Such results demonstrated that the xanthan gum was able not only to prevent the leakage of the solvent from the DSSC, but also to reduce the number of dye molecules desorbed from the photoanode at high temperature.

As evidenced in the present section, the overall performances of quasi-solid water-based DSSCs are definitely interesting, particularly because of the excellent long-term stability demonstrated by these devices. Nevertheless, there is still room for further improvements. As an example, in terms of materials selection, a highly ambitious challenge would be the replacement of the oil-derived polymer matrixes by means of biosourced ones.<sup>57,323–326</sup> In the field of water-based DSSCs, a first attempt has been proposed by Kaneko and coworkers, who reported that polysaccharides such as agarose and  $\kappa$ -carrageenan<sup>327</sup> can form a tight and elastic solid able to retain the aqueous electrolyte (LiI 0.10 M and  $I_2$  10 mM in  $H_2O$ , pH 2).<sup>328</sup> Detachment of the N3 dye from the  $TiO_2$  electrode was not observed even after prolonged irradiation times; moreover EIS analysis showed that the electron donation from the  $I^-$  to the oxidized sensitizer took place in a similar way both in the quasi-solid and in the liquid state. Unfortunately, the authors published only a preliminary efficiency value of 0.586% ( $J_{sc} = 2.69 \text{ mA cm}^{-2}$ ,  $V_{oc} = 0.442 \text{ V}$ , FF = 0.48) in the presence of 0.5 wt%  $\kappa$ -carrageenan, without any optimization of the electrolyte composition which, in our opinion, could have led to definitely higher performance.

## 14. Conclusions

DSSC represents the most widely studied device for the conversion of solar energy into electricity, particularly when low costs and good performance are envisaged. In this review article, the key role of water, being one of the most promising research

strategy in the field of DSSCs, has been elucidated and thoroughly discussed by analysing the most significant literature reports, with particular attention to the impressive results achieved during the last three years.

After an exhaustive analysis of the interactions between water and the other cell components – previously considered exclusively harmful – we have shown how the solvent-of-life may adequately replace the traditionally used organic solvents. This would make DSSCs cheaper as well as less dangerous in terms of flammability and toxicity, thus even more environmentally friendly. In order to fabricate efficient aqueous DSSCs, several research groups worldwide are involved in an impressive scientific work, proposing new dyes, photoelectrodes, counter electrodes, redox couples, additives and sealants. As summarized in Table 20, the results obtained so far in terms of efficiency and durability are promising, sometimes outstanding, and fully justify the recent boom in the research and development of aqueous DSSCs.

Summarising, it seems that the main factor that negatively affects the efficiency of aqueous DSSC if compared to those based on organic solvents is the quality of the photoanode/electrolyte interface. Indeed, excessive hydrophilicity of the dye-sensitized surface favours sensitizer molecule desorption, thus decreasing the photocurrent and the stability over time; on the other hand, highly hydrophobic dyes do not allow the complete wettability of the electrode which, in turn, results in a less effective regeneration process for aqueous electrolytes. An optimum between these two extremes has not been achieved so far, and the creation of an intimate photoanode/electrolyte interface will be one of the main research goals in the coming years. At present, the most effective strategies towards realistic aqueous DSSCs include the use of cobalt complexes (preferably in the gel form) as redox mediators, hydrophobic dyes combined/functionalized with surfactants or weakly hydrophilic dyes obtained by the modification of already available sensitizers, and water-tolerant counter electrodes with a wide surface area. However, the study of aqueous DSSCs is at an early stage and comparative studies that could greatly improve the knowledge of these systems are still lacking.

The sum of the above reported intriguing features accounts for the promising prospects of the novel materials described here to be effectively implemented in the emerging business of aqueous DSSC manufacturing. The use of water in solar energy conversion devices was intended to be a big bet by a great part of the scientific community but, based on the results discussed in this review article, it may very soon become the key for success of this green technology to finally enter into the mass production stage.

## Abbreviations

ABC	Amphiphilic block copolymer
ACN	Acetonitrile
AOT	Bis(2-ethylhexyl) sulfosuccinate sodium salt
BBEG <sub>n</sub>	Bis-benzimidazole derivatives containing an ethylene glycol repeating unit



BMII	1-Butyl-3-methylimidazolium iodide	PVP	Poly(vinylpyridine)
CA	Contact angle	PVPi	Poly(vinylpyrrolidone)
CB	Conduction band	$R_{CE}$	Charge transfer resistance at the counter electrode
CDCA	Chenodeoxycholic acid	RH	Relative humidity
CPMD	Car-Parrinello molecular dynamics	RhS	Rhoeo spathacea
CTAB	Hexadecyltrimethylammonium bromide	$R_s$	Series resistance
CV-G	Green part of <i>Codiaeum variegatum</i>	RT	Room temperature
$D$	Electron diffusion constant	RTIL	Room temperature ionic liquid
$D(\text{ion})$	Apparent diffusion constant for the given ion	TAS	Transient adsorption spectroscopy
DMHII	3-Hexyl-1,2-dimethylimidazolium iodide	TBA	Tetrabutylammonium
DMPH	1,2-Dimethyl-3-propylimidazolium iodide	TBAI	Tetrabutylammonium iodide
DRIFT	Diffuse-reflectance infrared Fourier transform	TBP	4- <i>tert</i> -Butylpyridine
DSSC	Dye-sensitized solar cell	TCO	Transparent conductive oxide
DTT	3,3'-Dithiobis[4-methyl-(1,2,4)-triazole]	TDDFT	Time-dependent density functional theory
$E$	Redox mediator potential	TEMPOL	4-Hydroxy-2,2,6,6-tetramethylpiperidinoxyl
$E_c$	CB energy	TFSI <sup>-</sup>	Bistriflimide
$E_f$	Fermi level electrochemical potential	TT <sup>-</sup> EMI <sup>+</sup>	1-Ethyl-3-methylimidazolium 4-methyl-1,2,4-triazole-3-thiolate
EC	Ethylene carbonate	UV-Vis	Ultraviolet-visible
EDX	Energy dispersive X-ray analysis	VAN	Valeronitrile
EIS	Electrochemical impedance spectroscopy	$V_{oc}$	Open-circuit voltage
EMIIm <sup>+</sup>	1-Ethyl-3-methylimidazolium	3D	Three-dimensional
FC-134	<i>N,N,N</i> -Trimethyl-3-(perfluorooctyl sulfonamido)-propan-1-aminium iodide	$\eta$	Cell efficiency
FF	Fill factor	$\lambda_{max}$	Absorption maximum
FK-1	Triethylammonium perfluorooctane sulphonate	$\mu$	Viscosity
FTIR	Fourier transform infrared	$\sigma$	Ionic conductivity
GBL	$\gamma$ -Butyrolactone	$\tau$	Electron lifetime
GF	Glass frit	$\chi_w$	Mole fraction of water
GuI	Guanidinium iodide		
GuSCN	Guanidinium thiocyanate		
HDMII	1-Hexyl-2,3-dimethylimidazolium iodide		
HMII	1-Hexyl-3-methylimidazolium iodide		
IPCE	Incident photon to current efficiency		
$I_{sc}$	Short-circuit current		
$J_{dl}$	Diffusion limited current		
$J_{sc}$	Short-circuit current density		
$L$	Electron diffusion length		
MAN	Methoxyacetonitrile		
MPH	1-Methyl-3-propylimidazolium iodide		
MPN	3-Methoxypropionitrile		
NBBI	<i>N</i> -Butylbenzimidazole		
NMBI	<i>N</i> -Methylbenzimidazole		
NMP	<i>N</i> -Methylpyrrolidone		
NPs	Nanoparticles		
ODTS	Octadecyltrichlorosilane		
PC	Propylene carbonate		
PEDOT	Poly(3,4-ethylenedioxythiophene)		
PEG	Poly(ethylene glycol)		
PEO	Poly(ethylene oxide)		
PES	Photoelectron spectroscopy		
PG	Pomegranate		
$P_{in}$	Irradiation intensity		
PMH	1-Propyl-3-methylimidazolium iodide		
PPO	Poly(propylene oxide)		
PSC	Perovskite solar cell		
PV	Photovoltaic		

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