


Cite this: *Nanoscale*, 2023, **15**, 6521

Alternatives to water oxidation in the photocatalytic water splitting reaction for solar hydrogen production

Yaqiang Wu, ^a Takuya Sakurai, ^a Takumi Adachi^a and Qian Wang ^{*a,b}

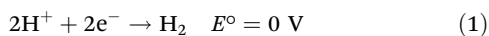
The photocatalytic water splitting process to produce H₂ is an attractive approach to meet energy demands while achieving carbon emission reduction targets. However, none of the current photocatalytic devices meets the criteria for practical sustainable H₂ production due to their insufficient efficiency and the resulting high H₂ cost. Economic viability may be achieved by simultaneously producing more valuable products than O₂ or integrating with reforming processes of real waste streams, such as plastic and food waste. Research over the past decade has begun to investigate the possibility of replacing water oxidation with more kinetically and thermodynamically facile oxidation reactions. We summarize how various alternative photo-oxidation reactions can be combined with proton reduction in photocatalysis to achieve chemical valorization with concurrent H₂ production. By examining the current advantages and challenges of these oxidation reactions, we intend to demonstrate that these technologies would contribute to providing H₂ energy, while also producing high-value chemicals for a sustainable chemical industry and eliminating waste.

Received 17th January 2023,
Accepted 4th March 2023

DOI: 10.1039/d3nr00260h

rsc.li/nanoscale

As humanity moves forward into the 21st century, the supplementation of clean and sustainable energy is one of our greatest scientific and technical challenges. The photocatalytic water splitting process using nanoparticulate photocatalysts and solar energy is a leading candidate to achieve low-carbon production of H₂ as a clean and sustainable energy carrier. In this process, water is split into H₂ and O₂ via the following redox reactions (eqn (1) and (2); pH 0 in aqueous solution *versus* (normal hydrogen electrode) NHE, 25 °C, 1 atm gas pressure, and 1 M for other solutes):



Water splitting is a non-spontaneous chemical reaction involving water oxidation to O₂, which requires four electrons to simultaneously transfer from at least two water molecules. Photocatalysis is a light-driven chemical process that involves oxidation and reduction reactions by the photogenerated electrons and holes. To achieve the photocatalytic water splitting reaction, the conduction band minimum must be more negative

than the H⁺ to H₂ reduction potential, while the valence band maximum must be more positive than the H₂O to O₂ oxidation potential. Consequently, the minimum theoretical energy required to initiate the water-splitting reaction is 1.23 eV. However, O₂ evolution from water leads to sluggish kinetics and high additional kinetic overpotentials,^{1,2} making photocatalytic H₂ evolution need the use of sacrificial reagents to provide an electron source.^{3–5} Specifically, the overpotential losses of the oxygen evolution reaction (OER) can reach up to 30%, resulting in a significant amount of wasted energy.⁶ In addition, the lack of effective methods to separate the produced O₂ and H₂ gases is a key problem for the practical application of photocatalytic water splitting.⁷ As a result of these challenges, increasing attention is being focused on emerging replacements for the OER that may support an expanding H₂ economy globally.

In this minireview, we highlight a variety of key reactions that are well suited as potential replacements for the OER, focusing on the recent developments in the study of photoreforming and photochemical oxidation reactions to produce value-added organic and inorganic products that have received considerable attention in the literature, such as formic acid (~1.1 \$ per kg) production from waste PET (≤0 \$ per kg) and H₂O₂ (~0.7 \$ per kg) formation by water (~2.9 × 10^{−4} \$ per kg) oxidation.^{8,9} These reactions are appealing because they would enable (1) the production of more valuable chemicals than O₂ (~0.1 \$ per kg) alongside the production of H₂; (2) the elimin-

^aGraduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan. E-mail: wang.qian@material.nagoya-u.ac.jp; Tel: +81-527893250

^bInstitute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan



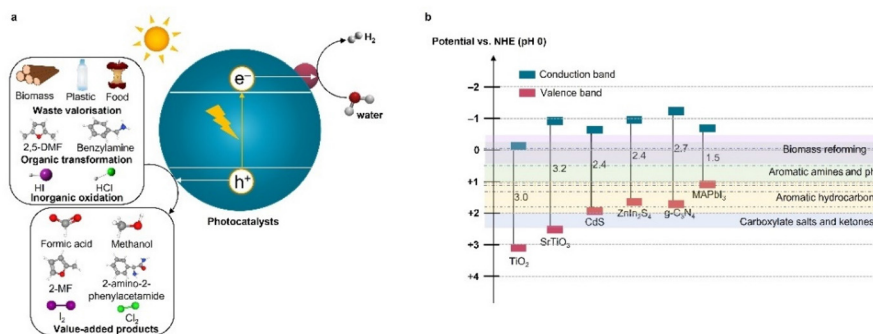
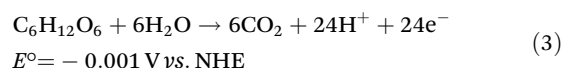


Fig. 1 (a) Diagram of the photooxidation reactions rather than water-to-O₂ oxidation combining with solar H₂ production. (b) Band structures of representative photocatalysts and standard redox potentials for some common oxidation reactions. Data were obtained from ref. 6.

ation of the need for a H₂ and O₂ mixture separation unit, thereby lowering the cost, improving the safety, and simplifying the design of photocatalytic processes; and (3) reduced overpotential due to the simpler 1 or 2 electron net oxidation mechanisms, which would result in an increased conversion efficiency and reaction rate.⁶ Under light irradiation, an inorganic or organic substrate is oxidized by the photoexcited holes at the valence band, which subsequently generated valuable chemicals or CO₂ or intermediate products and protons (Fig. 1a). The protons are reduced by electrons at the conduction band to produce H₂. While the direct oxidation of alternative substrates combined with the production of clean H₂ can be feasibly carried out using various technologies including electrolysis, photoelectrochemical and photocatalytic systems,^{6,7,10} we have targeted cases that have been demonstrated using nanoparticulate photocatalysts due to their potential for large-scale operations.

Photoreforming

Photocatalytic reforming that harnesses solar energy to convert sustainable or waste feedstocks for H₂ generation has become one of the most rapidly evolving applications in the field due to its ability to valorize a range of feedstocks especially biomass, food and plastics (≤ 0 \$ per kg) to both energy and value-added products (such as formic acid (~1.1 \$ per kg), methanol (~0.6 \$ per kg), acetaldehyde (~2 \$ per kg) and lactic acid (~3 \$ per kg)), as listed in Table 1.⁹ Research trends highlight the shift from the early work which focused on simple model substrates such as ethanol, glycerol, and cellulose to more recent work that utilizes real waste, making the process more complex but more economically and environmentally sustainable.¹¹ The energetics of coupling the oxidation of a variety of common organic waste substrates with H₂ evolution are nearly neutral (Fig. 1b), for example, glucose oxidation (eqn (3)), making it more favorable than water splitting, although these oxidation reactions involve multiple electron transfer steps.¹² Theoretically, coupling photoreforming with H₂ production would no longer restrict the use of semiconductors with deep valence bands, allowing the application of those with a smaller bandgap. The photocatalytic reforming could therefore be driven by a large portion of incident sunlight including visible and IR parts.



Initially, photocatalytic reforming research centered on the production of H₂ from a variety of lignocellulose biomass-derived feedstocks, the most abundant and non-edible biomass resource, including monosaccharides, such as pentoses (ribose and arabinose) and hexoses (glucose, fructose, galactose, and mannose), alcohols (methanol, propanol, ethanol, and butanol) and organic acids (formic acid and acetic acid).^{12–19} Theoretically, in the proposed biomass photoreforming process, photoexcited holes lead to the oxidation of biomass components and derivatives (denoted as C_xH_yO_z),



Qian Wang

Qian Wang is currently an Associate Professor at Nagoya University, Japan. She received her Ph.D. in 2014 from the University of Tokyo, Japan and then worked as a postdoctoral researcher for the Japan Technological Research Association of Artificial Photosynthetic Chemical Processes (ARPChem) project at the University of Tokyo. In 2018, she became a Marie Skłodowska-Curie Research Fellow at the

University of Cambridge. She joined Nagoya University as an Associate Professor in May 2021 and established her research group, which is currently developing new materials, approaches, and technologies for solar energy storage in the form of renewable fuels via artificial photosynthesis.



Table 1 Performance metrics for some recent representative solar fuel production systems using alternative photooxidation reactions to the OER

| Substrates | Photocatalysts | Reaction conditions | Products | Efficiency | Reaction time | Ref. |
|----------------------------|--|--|--|--|---------------------------------|----------------|
| Glucose | Pt/C ₃ N ₄ (~1 µm) | 40 W blue LED (λ = 427 nm) | H ₂ : 3.39 mmol g ⁻¹ h ⁻¹ | Glucose conversion: 100% | 16 hours | 28 |
| Microcrystalline cellulose | Pt/TiO ₂ | 10 M KOH 16 W UV-A lamp (λ = 365 nm) | Lactic acid H ₂ : 13.3 µmol h ⁻¹ | Selectivity (lactic acid): 86% QE: 42.8% at 365 nm | 5 hours | 25 |
| Cellulose | Pt/S- and N-doped graphene oxide dots (2–7 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) pH 12.5 | H ₂ : 100 µmol h ⁻¹ | QE: 23.3% at 420 nm | 6 days | 108 |
| Glucose | TiO ₂ /Co(terpyridine) ₂ (~20 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) Aqueous sodium acetate and MeCN purged with CO ₂ | Acetaldehyde, methanol, formate, etc. H ₂ : ~0.43 mmol per g _{catalyst} per 24 h CO: ~0.43 mmol per g _{catalyst} per 24 h | Glucose conversion efficiency: 20% QE: 0.22–0.41% at 360 nm for CO; 1.05–1.45% at 360 nm for formate | 24 hours | 48 |
| Cellobiose | TiO ₂ /Co(terpyridine) ₂ (~20 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) Aqueous sodium acetate and MeCN purged with CO ₂ | Formate: ~1.18 mmol per g _{catalyst} per 24 h H ₂ : ~0.72 mmol per g _{catalyst} per 24 h CO: ~0.92 mmol per g _{catalyst} per 24 h | Cellobiose conversion efficiency: 8.6% | 24 hours | 48 |
| Glycerol | Cu/TiO ₂ nanorods | LED irradiation (λ = 365 nm) MeCN–water solution | Formate: ~1.03 mmol per g _{catalyst} per 24 h H ₂ : 22 mmol per g _{catalyst} per 12 h | QE: 3.4% at 365 nm | 12 hours | 49 |
| Cellulose | Pt/ ^N CN ₄ CN _x | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) LiBr and LiOH in 0.1 M H ₂ SO ₄ solution | Methanol, CO, and CO ₂ H ₂ : ~190 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 24 hours | 50 |
| Cellulose | NiP/carbon dots (<10 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | Formic acid, lactic acid, arabinose, erythrose, etc. | | 24 hours | 26 |
| Glucose | NiP/carbon dots (<10 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~5 µmol per 24 h C ₆ H ₁₂ O ₆ and C ₆ H ₁₀ O ₅ compounds | | 24 hours | 26 |
| Cellulose | Pt/P25 TiO ₂ (20–30 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) UV–vis light (250 W iron doped halide lamp) | H ₂ : ~6 µmol per 24 h C ₆ H ₁₂ O ₆ and C ₆ H ₁₀ O ₅ compounds | | 10 hours | 35 |
| α-Cellulose | Cds/CdO _x quantum dots (diameter ~5 nm) | 0.6 M H ₂ SO ₄ solution 403 K; 3.0 bar Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~170 µmol per 10 h HMF, erythrose, and arabinose | | 6 days | 24 |
| Fructose | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~2.57 mmol g _{catalyst} ⁻¹ h ⁻¹ | Formate, carboxylic acid, CO ₂ , etc. | 20 hours | 45 |
| Starch | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~1070 mmol per g _{substrate} per 20 h | Formate, etc. | 20 hours | 45 |
| Apple | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~462 mmol per g _{substrate} per 20 h | Formate, etc. | 20 hours | 45 |
| Cheese | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~6070 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 20 hours | 45 |
| Artificial mixed waste | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~9350 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 20 hours | 45 |
| Municipal waste | Cds/CdO _x quantum dots | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~9900 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 20 hours | 45 |
| Wooden branch | Cds/CdO _x quantum dots (diameter ~5 nm) | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | H ₂ : ~5920 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 20 hours | 45 |
| Municipal solid waste PLA | CN _x /Ni ₂ P Cds/CdO _x quantum dots (diameter ~5 nm) | 10 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) 0.5 M KOH Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) 10 M NaOH | H ₂ : ~5.59 mmol g _{catalyst} ⁻¹ h ⁻¹ Formate, carbonate, etc. H ₂ : 130 mmol h ⁻¹ m ⁻² H ₂ : ~64.3 mmol g _{catalyst} ⁻¹ h ⁻¹ Pyruvate, etc. | QE: 15.0% at 430 nm | 24 hours 20 hours 4 hours | 24 39 37 |



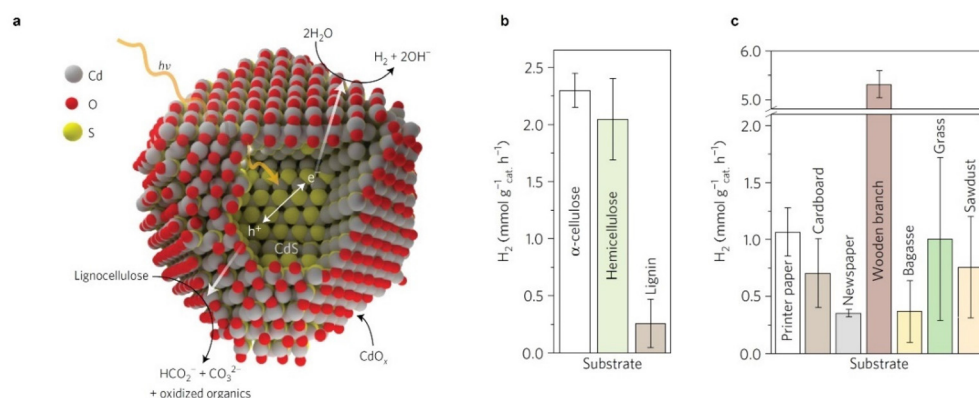
Table 1 (Contd.)

| Substrates | Photocatalysts | Reaction conditions | Products | Efficiency | Reaction time | Ref. |
|-------------------|--|---|--|--|---------------|------|
| PET | CdS/CdO _x quantum dots (diameter ~5 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) 10 M NaOH | H ₂ : ~3.42 mmol g _{catalyst} ⁻¹ h ⁻¹ | QE: 3.74% at 430 nm | 4 hours | 37 |
| PUR | CdS/CdO _x quantum dots (diameter ~5 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) 10 M NaOH | Formate, glycolate, ethanol, acetate, and lactate H ₂ : ~0.85 mmol g _{catalyst} ⁻¹ h ⁻¹ | QE: 0.14% at 430 nm | 4 hours | 37 |
| PET water bottle | CdS/CdO _x quantum dots (diameter ~5 nm) | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) 10 M NaOH | Formate, acetate, pyruvate, and lactate H ₂ : ~4.13 mmol g _{catalyst} ⁻¹ h ⁻¹ | QE: 2.17% at 430 nm | 24 hours | 37 |
| | | | Formate, glycolate, ethanol, acetate, lactate, glyoxylate, methylglyoxal, and methanol | Conversion: 5.15% | | |
| Methanol | CoP/Zn ₂ In ₂ S ₅ nanosheets | Simulated sunlight (AM 1.5G) | H ₂ : ~21 mmol g _{catalyst} ⁻¹ h ⁻¹ Ethylene glycol: 18.9 mmol g _{catalyst} ⁻¹ h ⁻¹ HCHO: ~4 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 12 hours | 67 |
| Ethanol | CoP/Zn ₂ In ₂ S ₃ nanosheets | 300 W Xe lamp (λ = 400–780 nm) | H ₂ : ~8.5 mmol g _{catalyst} ⁻¹ h ⁻¹ 2,3-Butanediol: 3.2 mmol g _{catalyst} ⁻¹ h ⁻¹ CH ₃ CHO: ~5 mmol g _{catalyst} ⁻¹ h ⁻¹ | | 12 hours | 67 |
| Benzyl alcohol | Zn _{0.3} In ₂ S _{3.2} | 6 W LED (λ = 365 ± 5 nm) | H ₂ yield: 172% Benzoin yield: 61% Deoxybenzoin yield: 30% Benzaldehyde yield: 9% | | 12 hours | 58 |
| Furfural alcohol | Ti ₃ C ₂ T _x /CdS nanosheets (~60 nm) | 300 W Xe lamp (λ ≥ 420 nm) | H ₂ : 773 μmol per g _{catalyst} per 4 h Furfural: 777 μmol per g _{catalyst} per 4 h | | 4 hours | 54 |
| Cetophenone | Pd/TiO ₂ | 6 W LED (λ = 365 ± 5 nm) Ethanol | H ₂ : ~0.25 mmol per 3 h Phenethanol: ~0.55 mmol per 3 h Ethylbenzene: ~0.05 mmol per 3 h | | 3 hours | 109 |
| DMF | Ni/CdS nanosheets | 300 W Xe lamp (λ ≥ 420 nm) | Acetaldehyde: ~0.4 mmol per 3 h H ₂ : ~1 mmol per 3 h | QE: ~44% at 420 nm | 3 hours | 69 |
| Benzyl alcohol | Zn ₃ In ₂ S ₆ (1–3 μm) | 300 W Xe lamp (λ > 380 nm) | N-Benzylidenbenzylamine: ~2 mmol per 5 h H ₂ : 708.8 μmol per 4 h Benzaldehyde: 732 μmol per 4 h | QE: 6.48% at 380 nm 5.46% at 400 nm 4.02% at 420 nm 1.03% at 450 nm | 4 hours | 64 |
| DMA | Pt/CN _x | 14.4 W blue LED (λ _{max} = 470 nm) | H ₂ : ~12 μmol per 10 h | | 10 hours | 59 |
| THF | Pt/CN _x | 14.4 W blue LED (λ _{max} = 470 nm) | Minisci oxidation products: ~15 μmol per 10 h H ₂ : ~9 μmol per 10 h | | 10 hours | 59 |
| 2,5-DMF | Ru-ZnIn ₂ S ₄ (0.6–1.6 μm) | 9 W blue LED (λ = 455 nm) | Minisci oxidation products: ~9.5 μmol per 10 h H ₂ : ~6.0 mmol g _{catalyst} ⁻¹ h ⁻¹ DFPs: ~1.04 g g _{catalyst} ⁻¹ h ⁻¹ | QE: 15.2% at 452 nm | 6 hours | 68 |
| 2-MF | Ru-ZnIn ₂ S ₄ (0.6–1.6 μm) | 9 W blue LED (λ = 455 nm) | H ₂ : ~1.2 mmol g _{catalyst} ⁻¹ h ⁻¹ DFPs: ~0.1 g g _{catalyst} ⁻¹ h ⁻¹ | QE: 1.9% at 452 nm | 12 hours | 68 |
| HMF | Pt/porous carbon nitride | Simulated sunlight (λ > 400 nm, 100 mW cm ⁻²) | H ₂ : 12 μmol m ⁻² h ⁻¹ DFE: 1.3 μmol m ⁻² h ⁻¹ | DFE yield: 13.8% after 6 h Selectivity >99% | 6 hours | 53 |
| Benzylamine | Ni/CdS nanoparticles | 1.85 W Xe lamp (λ > 420 nm) | H ₂ : 21.4 mmol g _{catalyst} ⁻¹ h ⁻¹ Imine | Conversion: 99% Selectivity for imine: 97% | 45 minutes | 60 |
| Benzyl mercaptane | PtS/ZnIn ₂ S ₄ nanocomposites | 5 W LED (λ = 450 nm) | H ₂ yield: 100% Dibenzyl disulfide | QE: 11.2% at 450 nm Conversion: ~100% after 6 h Selectivity of dibenzyl disulfide: ~100% | 6 hours | 61 |
| Methanol | MoS ₂ foam/CdS nanorods | 300 W Xe lamp (λ = 420–780 nm) | H ₂ : 12 mmol g _{catalyst} ⁻¹ h ⁻¹ Ethylene glycol, etc. | QE: 0.28% at 400 nm | 12 hours | 66 |
| MBA | RuCat/Pt-g-C ₃ N ₄ | 300 W Xe lamp (λ > 400 nm) | H ₂ : 56 μmol per 10 h MBAd | | 10 hours | 65 |
| Furfural alcohol | Ni/CdS nanosheets (thickness ~1 nm) | 8 W blue LED (λ = 450 nm) | H ₂ : ~5 mL per 8 h | | 8 hours | 52 |
| HMF | Ni/CdS nanosheets (thickness ~1 nm) | 8 W blue LED (λ = 450 nm) | Furfural H ₂ : ~0.5 mL per 8 h | | 8 hours | 52 |
| 4-MBA | NiP/ ¹⁸ CN _x | Simulated sunlight (AM 1.5G, 100 mW cm ⁻²) | DFE H ₂ : ~21.3 μmol per 24 h 4-MBAd: ~19.8 μmol per 24 h | QE: 15% at 360 nm | 24 hours | 57 |
| H ₂ O | CdS/ZnIn ₂ S ₄ nanosheets | 300 W Xe lamp (λ > 400 nm) | H ₂ : ~0.5 mmol g _{catalyst} ⁻¹ h ⁻¹ H ₂ O ₂ : ~0.6 mmol g _{catalyst} ⁻¹ h ⁻¹ | QE: 1.63% at 400 nm | 12 hours | 86 |
| HI | MoS ₂ /MAPbI ₃ | 280 W Xe lamp (λ ≥ 420 nm) | H ₂ : ~29.4 mmol g _{catalyst} ⁻¹ h ⁻¹ I ₃ ⁻ | QE: 13–22% in the range of 420–850 nm STH: 7.55% | 90 hours | 102 |



The ideal feedstock for photoreforming comes from waste streams that cannot be recycled or reused in any other way.¹¹ To this end, the photooxidation of food waste and nonrecycled plastics has recently become an emerging topic in the field.^{11,37–44} The chemical composition of food waste varies greatly. Due to their hydrophobicity and typically chemically inert hydrocarbon chain, photoreforming fats in an aqueous solution is more difficult than photoreforming proteins composed of long chains of amino acid residues (Table 1).¹¹ Under simulated solar irradiation, simultaneous production of H₂ and the oxidation of a variety of carbohydrates, proteins and fats as well as real-world waste (apples, bread, and cheese) to generate formate and CO₂ or carbonate was observed over CdS/CdO_x quantum dots and Ni₂P/CN_x.⁴⁵ The carbon footprints of these processes were estimated to be 44 600–68 800 g_{CO2} per kWh H₂ with a conversion efficiency of 1.9–22% after 3 days, which were still high due to the need for alkaline solutions as well as energy for stirring, and pre-treatment (accounts for more than 90% of the values).⁴⁵ The carbon footprint can be reduced to a negative value of –3200 g_{CO2} per kWh H₂ if the waste in the water is 100% converted to H₂ and formate.

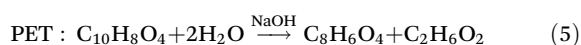
Reports on using raw biomass as the substrate for photoreforming are limited. Although direct H_2 production from unprocessed biomass has the advantage of lower production costs, it is limited by low substrate solubility. Additionally, light is scattered and absorbed by insoluble biomass and colored components, lowering the light absorption efficiency. The recalcitrance of raw biomass may lead to a large overpotential for biomass oxidation.¹² TiO_2 is frequently used as a photocatalyst for raw biomass reforming, despite its large bandgap (around 3.2 eV) and limited sunlight utilization ability. The H_2 evolution rates of TiO_2 for the photoreforming



Nanoscale, 2023, 15, 6521-6535 | 6525

Therefore, improvements in the conversion efficiency and photooxidation process selectivity are required.

In comparison with the photodegradation of plastics that converts plastics into CO₂ and H₂O, photoreforming can not only reduce plastic pollution but also produce fuels and products with added value, including pyruvate (~190 \$ per kg), glycolate (~450 \$ per kg), formic acid (~1.1 \$ per kg), ethanol (~1.2 \$ per kg) and acetic acid (~1.2 \$ per kg) (Table 1),⁹ allowing for a substantial economic advantage and a higher atom economy. While hydrocarbon chains such as polyethylene (PE), polystyrene (PS), and polypropylene (PP) in plastics are currently difficult to reform due to their highly stable C–C bonds, the oxygen-containing esters including polyethylene terephthalate (PET) (eqn (5) and (6)), polylactic acid (PLA) (eqn (7) and (8)) and polyurethane (PUR) (eqn (9) and (10)) can facilitate photoreforming after proper hydrolysis treatment.³⁷



The reforming of plastics conjugating with proton reduction to H₂ is also nearly energy neutral.⁴⁰ For instance, the Gibbs free energy changes for the reforming of ethylene glycol (a monomer of PET) and lactic acid (a monomer of PLA) are +9.2 kJ mol⁻¹ and +27 kJ mol⁻¹, respectively. A variety of plastics including PLA, PET, PUR, and a PET water bottle were

oxidized by photogenerated holes in CdS/CdO_x quantum dots into a range of substrate-dependent organic products (*e.g.*, formate, glycolate, ethanol, acetate, and pyruvate) in 10 M NaOH aqueous solution, while the photogenerated electrons reduced protons to produce H₂ with a rate of 3–65 mmol g_{catalyst}⁻¹ h⁻¹ (Table 1, and Fig. 3).³⁷ A Ni₂P/CN_x photocatalyst which is inexpensive and nontoxic has also shown promising activities for visible-light-driven PET and PLA reforming to produce H₂ fuel and a variety of organic chemicals under alkaline aqueous conditions.⁴⁶ The challenge in plastic photoreforming is the competition with plastic dehydrogenation to H₂ and selective oxidation to a single product rather than CO₂.⁴⁷ The reported conversion of plastics was up to 30%–40%, which requires further improvement. Furthermore, these studies imply that photoreactions can cleave C–C, C–N, and C–O bonds in the aliphatic chains of plastics as effectively as hydrolysis.

It is suggested that a theoretical maximum of 310–650 Mt of H₂ could be produced each year (the equivalent of ~6–13% of annual global energy consumption) if the above biomass, food and plastic components were all utilized for photoreforming.¹¹ The preliminary techno-economic and life cycle assessment of photoreforming has shown that it has a lower carbon footprint than or is comparable to existing methods for producing H₂, converting waste to fuel, and managing waste, but the improvement in production costs and energy balance is still required before industrial applications can be envisaged. Although the product of the oxidation reaction in photoreforming is typically CO₂, it is preferred that valuable organic chemicals can be produced instead of CO₂ to improve the sustainability and overall process value of the system.^{26,28,37,46,48–50} For example, Cu dispersed on titanium oxide nanorods was reported to be effective for the conversion of polyols and sugars into syngas and methanol under UV light irradiation and ambient conditions.⁴⁹ Decreased water content inhibited the formation of CO₂, whereas the copper loading amount controlled the decomposition way of the formic acid intermediate. Controlling the oxidation half-reaction is essential to produce



Fig. 3 (a) Diagram of the photoreforming of plastic waste using a CdS/CdO_x quantum dot photocatalyst. (b) Photoreforming of polymers to H₂ using CdS/CdO_x quantum dots under simulated solar light (AM 1.5G, 100 mW cm⁻²). Reproduced with permission from ref. 37. Copyright 2018 The Royal Society of Chemistry.



high-value organic products instead of CO₂.^{21,41} In addition, pre-treatment, including physical pre-treatment (such as crushing, shredding, and grinding) and chemical pre-treatment (such as hydrolysis and solubilization under highly alkaline or acidic conditions), is one of the most critical barriers to the practical application of the current photocatalytic reforming systems, adding significant cost and time to the overall process. Recently, it was demonstrated that metal salt hydrate solutions allowed for the complete solubilization of biomass and could be used as a reaction medium for the photocatalytic reforming of lignocellulose to produce H₂ and organic products under more benign conditions than the typically required extremely alkaline aqueous solutions, though the photocatalysts suffered from partial deactivation due to metal salt hydrate adsorption, necessitating future development.⁵⁰

Organic transformation

Since the pioneering work of Kolbe that reported the electrochemical oxidation of organic molecules with the goal of developing new methods for synthesizing organic small molecules,⁵¹ a larger body of research has grown around this topic in the ensuing decades. Over the past decade, photocatalytic processes that use light as the energy input have emerged as a new alternative approach in the repertoire of the organic synthesis toolbox. In particular, interest has been aroused in

waste biomass valorization in order to produce high-value commodity chemicals instead of CO₂. Researchers have succeeded in converting biomass-derived small molecules such as 5-hydroxymethylfurfural (HMF) and furfural alcohol into higher-value materials (*e.g.*, aldehydes and acids) (Fig. 4a).^{52–54} For example, photocatalytic H₂ evolution coupled with HMF (7110 \$ per kg) oxidation to 2,5-diformylfuran (DFF) (198 000 \$ per kg)⁵⁵ using porous carbon nitride was reported to reach a DFF yield of 13.8% with >99% selectivity after 6 h under visible light.⁵³

Recent research has revealed a wide range of photocatalysts for oxidizing alcohols in conjunction with H₂ production.^{57,58,62–65} Alcohols such as methanol have been widely used as sacrificial reagents for photocatalytic H₂ generation from water due to the lower thermodynamic requirements, and alcohols are oxidized to CO₂.^{3–5} We will not discuss these examples because the focus of this work is on the co-production of high-value chemicals with H₂. For instance, under visible light irradiation, the coupling of H₂ generation with the oxidation of benzyl alcohol (273 \$ per kg) yielded deoxybenzoin (57 200 \$ per kg) over ZnIn sulfides,^{55,58} and 4-methylbenzyl alcohol (2110 \$ per kg) was converted into an aldehyde (4-methylbenzaldehyde; 3440 \$ per kg) over a cyanamide surface functionalized with melon-type carbon nitride.^{55,57} Multi-carbon alcohols and polyalcohols have been reported to be photocatalytically produced by selectively activating the inert sp³ α-C–H bonds of alcohols and directly forming C–C bonds with the



Fig. 4 (a) Photocatalytic oxidation of biomass-derived intermediate compounds.^{52,54,56} HMF: 5-hydroxymethylfurfural; DFF: 2,5-diformylfuran. (b) Photocatalytic oxidation of alcohols.^{57,58} (c) Photocatalytic Minisci coupling.⁵⁹ (d) Photocatalytic C–N coupling reactions.^{56,60} (e) Photocatalytic S–S coupling reactions.^{56,61}



coupling partners (Fig. 4b).⁶² For instance, $\text{Zn}_2\text{In}_2\text{S}_5$ and CdS were reported as visible-light-responsive photocatalysts for the selective activation of the $\alpha\text{-C-H}$ bond of methanol to generate ethylene glycol with a selectivity of as high as 90%.^{66,67} The CdS-based photocatalytic system was beneficial for the activation of the C-H bond in methanol without affecting the O-H group, forming ethylene glycol *via* a $\cdot\text{CH}_2\text{OH}$ radical intermediate with a yield of 16% and a quantum efficiency (QE) of above 5.0% at wavelengths ≤ 450 nm.⁶⁶ The high ethylene glycol selectivity (90%) was maintained throughout the 100-hour reaction, with a yield of 16% after 100 hours, demonstrating an alternative nonpetroleum strategy for ethylene glycol synthesis. The $\text{CoP}/\text{Zn}_2\text{In}_2\text{S}_5$ photocatalyst also was

demonstrated to be the first example of the visible-light-driven dehydrogenative coupling of ethanol to 2,3-butanediol with a selectivity of 53%.⁶⁷ The $\alpha\text{-C-H}$ bond of ethanol was selectively activated to form $\cdot\text{CH}(\text{OH})\text{CH}_3$ radicals for subsequent coupling to 2,3-butanediol, presenting that the $\alpha\text{-C-H}$ bond can be preferentially activated in the presence of the O-H group under mild conditions.

Aside from alcohols, the C-H bonds in furanics can also be activated for C-C coupling reactions through photocatalysis. The production of diesel fuel precursors from 2,5-dimethylfuran (2,5-DMF) and 2-methylfuran (2-MF), with concurrent H_2 production, over a $\text{Ru-ZnIn}_2\text{S}_4$ photocatalyst was demonstrated under visible light irradiation (Fig. 5).⁶⁸ Dehydrocoupling of



Fig. 5 (a) Schematic representation of the photocatalytic transformation of 2,5-DMF/2-MF into diesel fuel. (b–d) Photocatalytic dehydrocoupling of 2,5-DMF as a substrate: standard experiment (b), catalyst lifetime evaluation (c), and selectivity to oxygenated DFPs and branched-chain DFPs (d). Reproduced with permission from ref. 68. Copyright 2019 Springer Nature Limited.



2,5-DMF and 2-MF yielded mainly H₂, dimers and trimers as products with a small number of tetramers produced in 12 h. Photogenerated holes oxidized the furfuryl C–H bond of 2,5-DMF/2-MF, delivering protons and furfuryl radicals that, through C–C coupling, form the desired DFPs. Over Ru–ZnIn₂S₄, the QE for the dehydrocoupling of 2,5-DMF was 15.2% at 452 nm, which was approximately double that of ZnIn₂S₄ because Ru dopants substituted for indium ions in the ZnIn₂S₄ matrix facilitated charge separation efficiency and thus accelerated C–H activation. Diesel fuel precursors were produced with selectivities of more than 96% in conjunction with H₂ generation and were subsequently transformed into diesel fuels composed of straight- and branched-chain alkanes that were comparable to petroleum diesel in terms of alkane constituents. Future work should focus on improving the yields of C–C coupling products and the QE by the use of more efficient catalysts.

Lately, it has been demonstrated that H₂ production could be coupled with more complex organic synthesis. The Minisci reaction is a known strategy for the direct functionalization of C–H bonds in heteroarenes, involving the radical coupling of electron-deficient heteroarenes with oxidatively-generated nucleophilic radicals.⁵⁹ A visible light-mediated Minisci coupling of N-heteroarenes with ethers, alcohols, and amides in the presence of aerobic oxygen as an oxidant was reported to conjugate with proton reduction to H₂ using a cyanamide functionalized carbon nitride photocatalyst (Fig. 4c).⁵⁹

Photocatalytic C–N coupling of amines for the efficient synthesis of imines may have important applications in pharmaceutical and agricultural chemistry research (Fig. 4d).⁵⁶ Ni/CdS was reported to photocatalyze the non-oxygen coupling of amines to yield their corresponding imines under visible light irradiation, concurrent with H₂ generation.^{60,69} In particular, the photocatalyst showed a high conversion of benzylamine (99%) with 97% selectivity for imines, associated with a QE of 11.2% at 450 nm for simultaneous H₂ evolution.⁶⁰ By constructing *in situ* photoimmobilized Ni clusters on two-dimensional ultrathin CdS nanosheets, the generation of imines was dramatically improved with a QE of ~44% at 420 nm for the conversion of 4-methoxybenzylamine.⁶⁹ It was proposed that photogenerated holes initiated the oxidation of amines *via* the deprotonation process with the creation of C-centered α-amine radicals to form aldimine intermediates and release protons. The protons were reduced by the photogenerated electrons and produced H₂ with the assistance of a Ni cocatalyst. Additionally, the photocatalytic system converted a wide range of primary and secondary amines (*i.e.*, heterocyclic, aliphatic, and N-heterocycles) to form their corresponding imines with high yields (≥84%) and selectivity (≥95%), thereby offering a promising and versatile pathway for organic chemical synthesis.

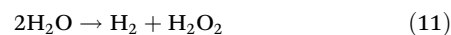
The photocatalytic synthesis of disulfides through the coupling of thiols is also of interest because disulfides function as protecting groups in synthetic applications and as vulcanizing agents for rubber (Fig. 4e). One of the examples is the visible-

light irradiation of CdSe quantum dots to result in virtually quantitative coupling of a variety of thiols, exemplified by 3-mercaptopropionic acid (MPA), to produce disulfides and H₂ in aqueous solution.⁷⁰ The conversion of MPA reached 99% in 1.5 hours and the yield of 3,3'-dithiodipropionic acid was near 100%. Likewise, PtS/ZnIn₂S₄ completely transformed benzyl mercaptan to produce dibenzyl disulfide in 6 h with a selectivity of ~100% under optimal conditions.⁶¹ These examples demonstrated an attractive alternative to existing procedures for synthesizing disulfides from thiols.

Controlling the selectivity of products is the most important issue of organic synthesis, as well as the existence of various potential reactive oxygen species in photocatalysis, including superoxide radicals ([•]O₂[−]), hydrogen peroxide (H₂O₂), hydroxyl radicals ([•]OH) and singlet oxygen (¹O₂).⁷¹ For selective oxidation, the reactive oxygen species and adsorption–desorption behavior must be carefully controlled.

Inorganic oxidation

Photocatalytic H₂ production along with more valuable inorganic products rather than O₂ *via* a two-electron oxidation pathway represents an alternatively appealing way. For instance, hydrogen peroxide (H₂O₂) production from water *via* the two-electron oxidation process is kinetically more favorable than the water-splitting reaction, which requires four electrons to produce O₂, despite the O₂ generation (1.23 eV *vs.* NHE) showing a thermodynamic advantage over the H₂O₂ production (1.78 eV *vs.* NHE). The photocatalytic reaction to simultaneously produce H₂ and H₂O₂ from water (eqn (11)) has attracted increasing attention in recent years because it obtains clean H₂ energy by utilizing abundant water resources and inexhaustible sunlight,^{72,73} as well as being environmentally friendly for producing the value-added H₂O₂ (~0.7 \$ per kg),⁹ which was widely utilized in the chemical industry, and disinfection, energy, and environmental fields.^{74–77} In addition, this reaction not only realizes the automatic separation of the oxidation product with gaseous H₂ but also effectively avoids the reverse reaction of generated H₂ and O₂ existing in the thoroughly overall water splitting reaction.^{78,79}



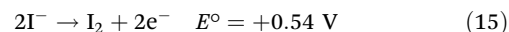
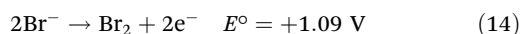
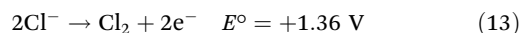
Recent efforts, including optimizing reaction conditions, doping, heterojunctions, cocatalyst loading, and using biological hybrids, have been made to enhance the carrier utilization efficiency of the photocatalyst and increase the selectivity for H₂O₂ production, thereby advancing this technology. Graphitic carbon nitride (g-C₃N₄), for example, as a notable photocatalyst with advantageous features of low cost and tunable optical and electronic properties was widely employed in this field. A sulfur doping treatment was performed on thin g-C₃N₄ nanosheets to compensate for the light absorption loss caused by the exfoliation process while improving the charge transfer efficiency.⁸⁰ Moreover, Co_xNi_yP nanoclusters were loaded onto



a P-doped g-C₃N₄ photocatalyst, and the doping and cocatalyst effects enhanced the photocatalytic water reduction and oxidation with a H₂ evolution rate of 239.3 μmol g_{catalyst}⁻¹ h⁻¹ and stoichiometric H₂O₂ production.⁸¹ It is also reported that the living *Chlorella vulgaris* could accelerate the photocatalytic activity of g-C₃N₄ to produce H₂O₂ and H₂ from water, giving a QE of 0.86% at 420 nm.⁸² The defect control is also a proposed way applicable to increase H₂O₂ production. Although defects are typically regarded as charge recombination sites, it has been demonstrated that if properly controlled, they can also contribute to photocatalytic reactions.⁸³ Defects can introduce mid-gap states in the forbidden band of semiconductor photocatalysts to harness more visible light, serve as active sites for reactants, and offer more trapping sites to hamper the recombination of carriers.⁸⁴ For example, the introduced carbon vacancies in C₃N₄ can not only extend the light absorption range and improve carrier separation efficiency but also alter the H₂O₂ production pathway from a two-step indirect reaction to a one-step direct reaction, thereby enhancing the H₂O₂ production.⁸⁵ Construction of heterojunctions appears to be an effective strategy for inorganic semiconductor photocatalysts to generate H₂ and H₂O₂ simultaneously. For instance, a system consisting of CdS and ZnIn₂S₄ hollow cubes was employed for the stoichiometric generation of H₂ and H₂O₂ from pure water, achieving a QE of 1.63% at 400 nm.⁸⁶ Noble metal deposition remains a common but effective way to promote photocatalytic reactions. Production of H₂ and H₂O₂ with rates of 9.8 μmol mg_{catalyst}⁻¹ h⁻¹ and 8.2 μmol mg_{catalyst}⁻¹ h⁻¹, respectively, from pure water (pH ~ 7) was realized using Pt/porous brookite TiO₂ nanoflutes as a photocatalyst, and the QE reached 43.4% at 365 nm.⁸⁷ The simulation and experimental results revealed that a two-electron reaction is kinetically favorable on the surface of brookite TiO₂ due to the unique surficial chemistry micro-circumstance, promoting the adsorption of activated hydroxyl groups and the subsequent step of hydrogen peroxide generation.

Though some promising progress has been made, photocatalytic H₂O₂ production is still far from the market requirement for practical applications, and the industrial production of H₂O₂ still mainly relies on the anthraquinone oxidation process (accounting for over 95% of production).⁸⁸ Facing the same problems with other semiconductor photocatalysis, photocatalytic H₂O₂ production also suffers from the drawbacks of low light utilization ability and the high recombination of photogenerated carriers. Another tricky problem is the rapid decomposition of the generated H₂O₂ occurs at the surface of the photocatalyst/cocatalyst, which can be caused by UV irradiation. More efforts should be devoted to the surface modification and fine control of the photocatalyst/cocatalyst and new cocatalyst development to promote H₂O₂ evolution and inhibit its decomposition process. For example, the combination of common inorganic semiconductor photocatalysts with bacteria, biomaterials, and organic semiconductors may have some positive effects. Additionally, a deeper understanding of the photocatalytic mechanism and H₂O₂ evolution

process is significant and will contribute to the optimization and design of highly active photocatalysts.



Photocatalytic hydrohalic acid (HX, X = Cl⁻, Br⁻, I⁻) splitting (eqn (12)) is another attractive approach for producing H₂ with a valuable byproduct X₂, which has numerous applications in the energy and hygiene industries.^{89–91} Halide ion (Br⁻, I⁻) oxidation (eqn (13)–(15)) is thermodynamically much easier than H₂O oxidation, and more importantly, these photocatalytic reactions are conducted under the conditions of a relatively high H⁺/X⁻ concentration, allowing for a faster reaction rate in dynamics. In addition, the oxidation of halide ions does not involve a net proton transfer, distinct from the H–O breakage and proton loss during O₂ formation in H₂O splitting, and thus are kinetically favorable. As an example, chloride oxidation catalyzed by silver ions in concentrated Cl⁻ solution has been reported, and the chloride complex-assisted catalysis mechanism has been proposed.⁹² The research on chloride oxidation could promote the development of photocatalytic seawater splitting, which is still in its infancy due to its low product yield and a plausible catalytic mechanism involving the effect of inorganic ions, yet having been studied for years.^{93,94}

Photocatalytic HBr and HI splitting to produce H₂ based on halide perovskites has aroused a new research upsurge in recent years since the first report about the hydrogen generation from hydriodic acid using MAPbI₃ as a photocatalyst in 2016 (Fig. 6a–c).⁹⁵ Subsequently, material compositing and heterojunction construction were extensively employed to boost hydrohalic acid splitting. Reduced graphene oxide (rGO) was first used to composite with MAPbI₃ perovskites for the photocatalytic hydrogen evolution reaction, resulting in a hydrogen evolution rate (93.9 μmol h⁻¹ under visible-light irradiation) 67 times higher than that of pure MAPbI₃.⁹⁶ Afterwards, various materials such as TiO₂, Ni₃C, carbon dots, black phosphorus, MoS₂, and CoP were used as cocatalysts or heterojunction counterparts to promote carrier separation.^{97–103} In particular, a MoS₂/MAPbI₃ composite exhibited a remarkable photocatalytic hydrogen evolution activity of 29.4 μmol g_{catalyst}⁻¹ h⁻¹ under visible light and an H₂ production of 103 mL day⁻¹ under outdoor natural sunlight irradiation.¹⁰³ In addition to the heterostructures, composition regulation is also a feasible way. For instance, a graded and gradient halide ion distribution was realized in both organometal and all-inorganic mixed halide perovskites,^{104,105} and a resulting bandgap funneling was constructed for efficient carrier transfer, causing an enhanced photocatalytic activity and a solar-to-H₂ conversion efficiency (STH) of 1.05% for MAPbBr_{3–x}I_x/Pt.¹⁰⁴ In addition, single-atom decoration is also an effective strategy to improve the perovskite photocatalytic HI splitting efficiency,^{106,107} an excellent photocatalytic H₂





Fig. 6 (a) Schematic band diagram of MAPbI₃ powder for the HI splitting photocatalytic reaction. (b) Quantitative comparison between the evolved H₂ and I₃⁻. (c) Stable photocatalytic H₂ evolution produced by MAPbI₃ powder in the saturated solution for 160 h (H₃PO₂ was added to the HI solution). Reproduced with permission from ref. 95. Copyright 2016 Springer Nature Limited. (d) Mechanism illustration of the synthesis process of Pt/FAPbBr_{3-x}I_x. (e) Photocatalytic H₂ evolution activities of ω-FPBI (FAPbBr_{3-x}I_x loaded ω% Pt in mass percentage). Reproduced with permission from ref. 107. Copyright 2022 The Royal Society of Chemistry.

evolution rate of 682.6 mmol h⁻¹ under simulated sunlight irradiation (area of π cm) and a corresponding STH of 4.5% were recorded using Pt/FAPbBr_{3-x}I_x (Fig. 6d and e).¹⁰⁷

Halide perovskites possess several excellent material properties, such as a wide light absorption range, a high absorption coefficient, and a long carrier diffusion length, allowing them to be ideal photocatalysts. However, satisfactory performance of this kind of material for photocatalytic H₂ production has not been achieved. More efforts should be devoted to the investigation of the mechanism and fundamental principles of the physical/chemical process during photocatalysis for this special system, where exists a dynamic equilibrium of dissolution-crystallization between the catalyst and the corresponding saturated solution.

Conclusions and outlook

Although the research in this field is at too early a stage to be towards industry-level operation and deployment, exciting work in combining H₂ fuel generation with value-added chemical production or waste valorization is already showing to have a wide impact on large-scale challenges in global energy (Table 1). When looking at both inorganic and organic chemistries, the water-to-O₂ conversion can be replaced by a variety of photoreactions that can occur in an aqueous solution.

In any proton-to-H₂ generation, the availability of substrates at the scale required for the process is a key consideration. Biomass, food, and plastic wastes are abundant, inexpensive, and carbon- and hydrogen-rich feedstocks. Photocatalytic methods offer upcycling routes that yield higher-value products, as opposed to conventional mechanical strategies that typically downcycle to lower-quality products.^{11,40} In recent

years, much effort has been devoted to the study of the simultaneous production of H₂ and chemicals with added value through reduction and oxidation, respectively. A preliminary techno-economic assessment demonstrates that photoreforming of waste can become economically competitive with existing technologies if the efficiency and lifetime can be substantially improved.¹¹ For large-scale applications to be economically and environmentally viable, H₂ evolution rates must increase by a factor of at least 50 (rates of >0.004 mol H₂ g_{substrate}⁻¹ h⁻¹, conversions of >50% per day, and QEs of >50%). It will be imperative to develop more effective and durable photocatalytic systems. In addition, the current pre-treatments commonly reported for photoreforming to improve the solubilization of the feedstock are unlikely to be economically viable on a large scale.

The photocatalytic oxidation of organic compounds, including alcohols, hydrocarbons, aromatics, and amines, differs from conventional methods conducted at high temperatures and pressures in that it is environmentally friendly, operates under mild conditions, and is sustainable. However, selective photocatalytic oxidations present huge challenges. Ideally, the oxidation process would selectively produce a single high-value product. Controlling reactive oxidation species and adsorption-desorption behavior is the primary challenge in selective oxidation. Therefore, it may be necessary to observe the reaction mechanism *in situ* for a better understanding of the reaction kinetics.⁷¹ To yield a single higher-value product in both organic transformation and waste valorization processes, selective oxidation cocatalysts may be required.

For inorganic reactions, the H₂O-to-H₂O₂ conversion and halide oxidation present themselves as an attractive alternative to O₂ evolution due to the higher value of the products and the simpler mechanism resulting from the lower electron demand.



Table 2 Summary of the developed alternative photooxidation reactions to the OER

| Oxidation reaction | Substrates | Main products | Challenges |
|--------------------|--|---|---|
| Reforming | Lignocellulose biomass-derived feedstocks (pentoses, hexoses, alcohols, and organic acids) | CO ₂ | • Costly and inefficient lignocellulose refining processes required • Low-value products |
| | Cellulose, hemicellulose, and lignin | CO ₂ | • Low substrate solubility • Low-value products |
| | Raw biomass | CO ₂ | • Low substrate solubility • Costly and environmentally unfriendly pre-treatment processes required • Low-value products |
| | Waste streams (biomass, food, and plastic) | CO ₂ , formate | • Low substrate solubility • Costly and environmentally unfriendly pre-treatment processes required • Competition with water reduction and plastic dehydrogenation to H ₂ • Low selectivity |
| Organics | Alcohols Furans Amines Thiols | Dimers and trimers Imine Disulfides | • Low selectivity |
| Inorganics | Water HX (X = Cl ⁻ , Br ⁻ , I ⁻) | H ₂ O ₂ X ₂ | |

Nonetheless, the reaction efficiency of these reactions must be enhanced.

The H₂ production cost for a waste photoreforming pilot plant (400 m², 200 kg_{waste} per day, 14.4 kg_{H₂} per day) was estimated to be £11.80 per kg, which is more than H₂ sale targets of £3–5 per kg and predictions for H₂ produced by photocatalytic water splitting (£1–3 per kg).^{1,11} It can, however, be reduced by increasing the plant scale and photoreforming efficiency. If the plant scale is enlarged 30 times, the cost of producing H₂ can be decreased to £3 per kg. Furthermore, economic gains can be realized by producing high-value compounds such as pharmaceutical components at the same time. As an example, oxidizing biomass to 3-hydroxybutyrolactone (3-HBL), a precursor for chiral drugs, could cut H₂ production costs to £3 per kg even if the photoreforming conversion efficiency is as low as 0.2% per day. However, although 3-HBL and its hydrolyzed form 3,4-dihydroxybutyric acid (3,4-DHBA) have been reported to be produced from biomass (glucose, glycolic acid, and xylose) *via* biological synthesis using bacteria (*Escherichia coli*), enzymes and yeast, its production *via* a photocatalytic process has not yet been realized.^{110–112} Future efforts would combine photocatalysts with microbes to create abiotic–biotic hybrids capable of producing photocatalytic H₂ while oxidizing biomass to 3-HBL. Likewise, the H₂ production costs can be reduced by photocatalytic transformations to produce value-added organic and inorganic chemicals. For instance, a recent techno-economic analysis suggested that by oxidizing water to produce H₂O₂ instead of O₂ using the photoelectrochemical technique, a levelized cost of hydrogen of \$6.19 per kg can be obtained with an STH of 10.1% and an H₂O₂ price of \$0.85 per kg, which is a significant improvement over the values found in an analogy of the photoelectrochemical water splitting system.¹¹³ Aside from producing cost-effective H₂, the procedures would also reduce the cost of

organic and inorganic products. A minimal selling price of glucaric acid was predicted to be \$6.94 per kg under a base case scenario employing a potential photo-biorefinery approach for sunlight-driven electro-oxidation of glucose, which was 70% lower than the current market price.¹¹⁴

In spite of the obstacles listed in Table 2, significant progress has been made in the study of coupling H₂ production with diverse oxidation chemistry and will continue. With continued material and technological advancements, these technologies have the potential to produce fuels and chemicals with added value, while also reducing waste.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the JSPS Leading Initiative for Excellent Young Researchers Program (to Q. W.), the JST Fusion Oriented REsearch for Disruptive Science and Technology Program (no. 21470281, to Q. W.), and the JSPS Grant-in-Aid for Young Scientists (Start-up) (no. 21K20485; to Q. W.).

References

- Q. Wang and K. Domen, *Chem. Rev.*, 2020, **120**, 919–985.
- H. Inoue, T. Shimada, Y. Kou, Y. Nabetani, D. Masui, S. Takagi and H. Tachibana, *ChemSusChem*, 2011, **4**, 173–179.
- X. Chen, S. Shen, L. Guo and S. S. Mao, *Chem. Rev.*, 2010, **110**, 6503–6570.



- 4 K. Zhang and L. Guo, *Catal. Sci. Technol.*, 2013, **3**, 1672–1690.
- 5 Y. Xu, Y. Huang and B. Zhang, *Inorg. Chem. Front.*, 2016, **3**, 591–615.
- 6 C. R. Lhermitte and K. Sivula, *ACS Catal.*, 2019, **9**, 2007–2017.
- 7 A. Y. Ru Ng, B. Boruah, K. F. Chin, J. M. Modak and H. S. Soo, *ChemNanoMat*, 2020, **6**, 185–203.
- 8 V. Andrei, Q. Wang, T. Uekert, S. Bhattacharjee and E. Reisner, *Acc. Chem. Res.*, 2022, **55**, 3376–3386.
- 9 . ChemAnalyst, <https://www.chemanalyst.com>, (accessed February 10, 2023).
- 10 L. M. Reid, T. Li, Y. Cao and C. P. Berlinguette, *Sustainable Energy Fuels*, 2018, **2**, 1905–1927.
- 11 T. Uekert, C. M. Pichler, T. Schubert and E. Reisner, *Nat. Sustain.*, 2021, **4**, 383–391.
- 12 M. F. Kuehnel and E. Reisner, *Angew. Chem., Int. Ed.*, 2018, **57**, 3290–3296.
- 13 D. I. Kondarides, V. M. Daskalaki, A. Patsoura and X. E. Verykios, *Catal. Lett.*, 2008, **122**, 26–32.
- 14 M. R. St. John, A. J. Furgala and A. F. Sammells, *J. Phys. Chem.*, 1983, **87**, 801–805.
- 15 H. Bahruji, M. Bowker, P. R. Davies, L. S. Al-Mazroai, A. Dickinson, J. Greaves, D. James, L. Millard and F. Pedrono, *J. Photochem. Photobiol., A*, 2010, **216**, 115–118.
- 16 T. Shiragami, T. Tomo, H. Tsumagari, R. Yuki, T. Yamashita and M. Yasuda, *Chem. Lett.*, 2012, **41**, 29–31.
- 17 Q. Xu, Y. Ma, J. Zhang, X. Wang, Z. Feng and C. Li, *J. Catal.*, 2011, **278**, 329–335.
- 18 Y. Li, D. Gao, S. Peng, G. Lu and S. Li, *Int. J. Hydrogen Energy*, 2011, **36**, 4291–4297.
- 19 R. Su, R. Tiruvalam, A. J. Logsdail, Q. He, C. A. Downing, M. T. Jensen, N. Dimitratos, L. Kesavan, P. P. Wells, R. Bechstein, H. H. Jensen, S. Wendt, C. R. A. Catlow, C. J. Kiely, G. J. Hutchings and F. Besenbacher, *ACS Nano*, 2014, **8**, 3490–3497.
- 20 A. V. Puga, *Coord. Chem. Rev.*, 2016, **315**, 1–66.
- 21 W. Deng, H. Zhang, L. Xue, Q. Zhang and Y. Wang, *Chin. J. Catal.*, 2015, **36**, 1440–1460.
- 22 X. Wu, N. Luo, S. Xie, H. Zhang, Q. Zhang, F. Wang and Y. Wang, *Chem. Soc. Rev.*, 2020, **49**, 6198–6223.
- 23 T. Kawai and T. Sakata, *Nature*, 1980, **286**, 474–476.
- 24 D. W. Wakerley, M. F. Kuehnel, K. L. Orchard, K. H. Ly, T. E. Rosser and E. Reisner, *Nat. Energy*, 2017, **2**, 17021.
- 25 L. Lan, H. Chen, D. Lee, S. Xu, N. Skillen, A. Tedstone, P. Robertson, A. Garforth, H. Daly, C. Hardacre and X. Fan, *ACS Sustainable Chem. Eng.*, 2022, **10**, 4862–4871.
- 26 D. S. Achilleos, W. Yang, H. Kasap, A. Savateev, Y. Markushyna, J. R. Durrant and E. Reisner, *Angew. Chem., Int. Ed.*, 2020, **59**, 18184–18188.
- 27 Q. Cheng, Y.-J. Yuan, R. Tang, Q.-Y. Liu, L. Bao, P. Wang, J. Zhong, Z. Zhao, Z.-T. Yu and Z. Zou, *ACS Catal.*, 2022, **12**, 2118–2125.
- 28 E. Wang, A. Mahmood, S.-G. Chen, W. Sun, T. Muhmood, X. Yang and Z. Chen, *ACS Catal.*, 2022, **12**, 11206–11215.
- 29 H. Kasap, D. S. Achilleos, A. Huang and E. Reisner, *J. Am. Chem. Soc.*, 2018, **140**, 11604–11607.
- 30 C. Rao, M. Xie, S. Liu, R. Chen, H. Su, L. Zhou, Y. Pang, H. Lou and X. Qiu, *ACS Appl. Mater. Interfaces*, 2021, **13**, 44243–44253.
- 31 S. R. Kadam, V. R. Mate, R. P. Panmand, L. K. Nikam, M. V. Kulkarni, R. S. Sonawane and B. B. Kale, *RSC Adv.*, 2014, **4**, 60626–60635.
- 32 C. Li, H. Wang, S. B. Naghadeh, J. Z. Zhang and P. Fang, *Appl. Catal.*, 2018, **227**, 229–239.
- 33 N. Skillen, H. Daly, L. Lan, M. Aljohani, C. W. J. Murnaghan, X. Fan, C. Hardacre, G. N. Sheldrake and P. K. J. Robertson, *Top. Curr. Chem.*, 2022, **380**, 33.
- 34 A. Speltini, M. Sturini, D. Dondi, E. Annovazzi, F. Maraschi, V. Caratto, A. Profumo and A. Buttafava, *Photochem. Photobiol. Sci.*, 2014, **13**, 1410–1419.
- 35 J. Zou, G. Zhang and X. Xu, *Appl. Catal., A*, 2018, **563**, 73–79.
- 36 K. Tomoji and S. Tadayoshi, *Chem. Lett.*, 1981, **10**, 81–84.
- 37 T. Uekert, M. F. Kuehnel, D. W. Wakerley and E. Reisner, *Energy Environ. Sci.*, 2018, **11**, 2853–2857.
- 38 C. M. Pichler, S. Bhattacharjee, M. Rahaman, T. Uekert and E. Reisner, *ACS Catal.*, 2021, **11**, 9159–9167.
- 39 T. Uekert, M. A. Bajada, T. Schubert, C. M. Pichler and E. Reisner, *ChemSusChem*, 2021, **14**, 4190–4197.
- 40 S. Chu, B. Zhang, X. Zhao, H. S. Soo, F. Wang, R. Xiao and H. Zhang, *Adv. Energy Mater.*, 2022, **12**, 2200435.
- 41 C. M. Pichler, S. Bhattacharjee, E. Lam, L. Su, A. Collauto, M. M. Roessler, S. J. Cobb, V. M. Badiani, M. Rahaman and E. Reisner, *ACS Catal.*, 2022, **12**, 13360–13371.
- 42 M. Han, S. Zhu, C. Xia and B. Yang, *Appl. Catal., B*, 2022, **316**, 121662.
- 43 Y. Li, S. Wan, C. Lin, Y. Gao, Y. Lu, L. Wang and K. Zhang, *Sol. RRL*, 2021, **5**, 2000427.
- 44 B. Cao, S. Wan, Y. Wang, H. Guo, M. Ou and Q. Zhong, *J. Colloid Interface Sci.*, 2022, **605**, 311–319.
- 45 T. Uekert, F. Dorchies, C. M. Pichler and E. Reisner, *Green Chem.*, 2020, **22**, 3262–3271.
- 46 T. Uekert, H. Kasap and E. Reisner, *J. Am. Chem. Soc.*, 2019, **141**, 15201–15210.
- 47 K. Su, H. Liu, C. Zhang and F. Wang, *Chin. J. Catal.*, 2022, **43**, 589–594.
- 48 E. Lam and E. Reisner, *Angew. Chem., Int. Ed.*, 2021, **60**, 23306.
- 49 M. Wang, M. Liu, J. Lu and F. Wang, *Nat. Commun.*, 2020, **11**, 1083.
- 50 C. M. Pichler, T. Uekert and E. Reisner, *Chem. Commun.*, 2020, **56**, 5743–5746.
- 51 H. Kolbe, *Justus Liebigs Ann. Chem.*, 1849, **69**, 257–294.
- 52 G. Han, Y.-H. Jin, R. A. Burgess, N. E. Dickenson, X.-M. Cao and Y. Sun, *J. Am. Chem. Soc.*, 2017, **139**, 15584–15587.
- 53 V. R. Battula, A. Jaryal and K. Kailasam, *J. Mater. Chem. A*, 2019, **7**, 5643–5649.
- 54 Y.-H. Li, F. Zhang, Y. Chen, J.-Y. Li and Y.-J. Xu, *Green Chem.*, 2020, **22**, 163–169.



- 55 MilliporeSigma, <https://www.sigmaaldrich.com/US/en>, (accessed February 10, 2023).
- 56 J.-H. Tang and Y. Sun, *Mater. Adv.*, 2020, **1**, 2155–2162.
- 57 H. Kasap, C. A. Caputo, B. C. M. Martindale, R. Godin, V. W.-h. Lau, B. V. Lotsch, J. R. Durrant and E. Reisner, *J. Am. Chem. Soc.*, 2016, **138**, 9183–9192.
- 58 N. Luo, T. Hou, S. Liu, B. Zeng, J. Lu, J. Zhang, H. Li and F. Wang, *ACS Catal.*, 2020, **10**, 762–769.
- 59 A. Vijeta and E. Reisner, *Chem. Commun.*, 2019, **55**, 14007–14010.
- 60 W. Yu, D. Zhang, X. Guo, C. Song and Z. Zhao, *Catal. Sci. Technol.*, 2018, **8**, 5148–5154.
- 61 L. Xu, X. Deng and Z. Li, *Appl. Catal., B*, 2018, **234**, 50–55.
- 62 Z. Gao, N. Luo, Z. Huang, S. H. Taylor and F. Wang, *ACS Sustainable Chem. Eng.*, 2021, **9**, 6188–6202.
- 63 D. Antón-García, E. Edwardes Moore, M. A. Bajada, A. Eisenschmidt, A. R. Oliveira, I. A. C. Pereira, J. Warnan and E. Reisner, *Nat. Synth.*, 2022, **1**, 77–86.
- 64 X. Ye, Y. Chen, Y. Wu, X. Zhang, X. Wang and S. Chen, *Appl. Catal., B*, 2019, **242**, 302–311.
- 65 F. Li, Y. Wang, J. Du, Y. Zhu, C. Xu and L. Sun, *Appl. Catal., B*, 2018, **225**, 258–263.
- 66 S. Xie, Z. Shen, J. Deng, P. Guo, Q. Zhang, H. Zhang, C. Ma, Z. Jiang, J. Cheng, D. Deng and Y. Wang, *Nat. Commun.*, 2018, **9**, 1181.
- 67 H. Zhang, S. Xie, J. Hu, X. Wu, Q. Zhang, J. Cheng and Y. Wang, *Chem. Commun.*, 2020, **56**, 1776–1779.
- 68 N. Luo, T. Montini, J. Zhang, P. Fornasiero, E. Fonda, T. Hou, W. Nie, J. Lu, J. Liu, M. Heggen, L. Lin, C. Ma, M. Wang, F. Fan, S. Jin and F. Wang, *Nat. Energy*, 2019, **4**, 575–584.
- 69 Y. Huang, C. Liu, M. Li, H. Li, Y. Li, R. Su and B. J. A. C. Zhang, *ACS Catal.*, 2020, **10**, 3904–3910.
- 70 X. B. Li, Z. J. Li, Y. J. Gao, Q. Y. Meng, S. Yu, R. G. Weiss, C. H. Tung and L. Z. Wu, *Angew. Chem., Int. Ed.*, 2014, **126**, 2117–2121.
- 71 L. Xiong and J. Tang, *Adv. Energy Mater.*, 2021, **11**, 2003216.
- 72 Y. F. Zhang and S. J. Park, *J. Mater. Chem. A*, 2018, **6**, 20304–20312.
- 73 J. Chen, N. Kang, J. Fan, C. Lu and K. Lv, *Mater. Today Chem.*, 2022, **26**, 101028.
- 74 K. P. Bryliakov, *Chem. Rev.*, 2017, **117**, 11406–11459.
- 75 Z. Tang, P. Zhao, H. Wang, Y. Liu and W. Bu, *Chem. Rev.*, 2021, **121**, 1981–2019.
- 76 J. Xu, X. Zheng, Z. Feng, Z. Lu, Z. Zhang, W. Huang, Y. Li, D. Vuckovic, Y. Li, S. Dai, G. Chen, K. Wang, H. Wang, J. K. Chen, W. Mitch and Y. Cui, *Nat. Sustain.*, 2021, **4**, 233–241.
- 77 J. Y. Tang, T. S. Zhao, D. Solanki, X. B. Miao, W. G. Zhou and S. Hu, *Joule*, 2021, **5**, 1432–1461.
- 78 K. Li, M. Han, R. Chen, S. L. Li, S. L. Xie, C. Mao, X. Bu, X. L. Cao, L. Z. Dong, P. Feng and Y. Q. Lan, *Adv. Mater.*, 2016, **28**, 8906–8911.
- 79 R. Shi, H.-F. Ye, F. Liang, Z. Wang, K. Li, Y. Weng, Z. Lin, W.-F. Fu, C.-M. Che and Y. Chen, *Adv. Mater.*, 2018, **30**, 1705941.
- 80 C. Feng, L. Tang, Y. Deng, J. Wang, Y. Liu, X. Ouyang, H. Yang, J. Yu and J. Wang, *Appl. Catal., B*, 2021, **281**, 119539.
- 81 F. Xue, Y. Si, M. Wang, M. Liu and L. Guo, *Nano Energy*, 2019, **62**, 823–831.
- 82 Y. Fu, C. a. Liu, M. Zhang, C. Zhu, H. Li, H. Wang, Y. Song, H. Huang, Y. Liu and Z. Kang, *Adv. Energy Mater.*, 2018, **8**, 1802525.
- 83 Z. Pei, L. Ding, J. Hu, S. Weng, Z. Zheng, M. Huang and P. Liu, *Appl. Catal., B*, 2013, **142–143**, 736–743.
- 84 H. Hou, X. Zeng and X. Zhang, *Angew. Chem., Int. Ed.*, 2020, **59**, 17356–17376.
- 85 S. Li, G. Dong, R. Hailili, L. Yang, Y. Li, F. Wang, Y. Zeng and C. Wang, *Appl. Catal., B*, 2016, **190**, 26–35.
- 86 E. Zhang, Q. Zhu, J. Huang, J. Liu, G. Tan, C. Sun, T. Li, S. Liu, Y. Li, H. Wang, X. Wan, Z. Wen, F. Fan, J. Zhang and K. Ariga, *Appl. Catal., B*, 2021, **293**, 120213.
- 87 S. Cao, T.-S. Chan, Y.-R. Lu, X. Shi, B. Fu, Z. Wu, H. Li, K. Liu, S. Alzuabi, P. Cheng, M. Liu, T. Li, X. Chen and L. Piao, *Nano Energy*, 2020, **67**, 104287.
- 88 J. M. Campos-Martin, G. Blanco-Brieva and J. L. G. Fierro, *Angew. Chem., Int. Ed.*, 2006, **45**, 6962–6984.
- 89 B. Huskinson, J. Rugolo, S. K. Mondal and M. J. Aziz, *Energy Environ. Sci.*, 2012, **5**, 8690–8698.
- 90 G. R. Taylor and M. Butler, *Epidemiol. Infect.*, 1982, **89**, 321–328.
- 91 R. Yeo and D. T. Chin, *J. Electrochem. Soc.*, 1980, **127**, 549.
- 92 J. Du, Z. Chen, C. Chen and T. J. Meyer, *J. Am. Chem. Soc.*, 2015, **137**, 3193–3196.
- 93 Y. Wang, L. Shi, H. Hu, *et al.*, Binary trinuclear metal-oxo sub-nanomaterials for photocatalytic hydrogen and chlorine production from seawater, *SusMat*, 2022, **2**, 708–719.
- 94 J. Zhang, Y. Lei, S. Cao, W. Hu, L. Piao and X. Chen, *Nano Res.*, 2022, **15**, 2013–2022.
- 95 S. Park, W. J. Chang, C. W. Lee, S. Park, H.-Y. Ahn and K. T. Nam, *Nat. Energy*, 2016, **2**, 16185.
- 96 Y. Wu, P. Wang, X. Zhu, Q. Zhang, Z. Wang, Y. Liu, G. Zou, Y. Dai, M.-H. Whangbo and B. Huang, *Adv. Mater.*, 2018, **30**, 1704342.
- 97 C. Cai, Y. Teng, J.-H. Wu, J.-Y. Li, H.-Y. Chen, J.-H. Chen and D.-B. Kuang, *Adv. Funct. Mater.*, 2020, **30**, 2001478.
- 98 Z. Zhao, J. Wu, Y.-Z. Zheng, N. Li, X. Li and X. Tao, *ACS Catal.*, 2019, **9**, 8144–8152.
- 99 X. Wang, H. Wang, H. Zhang, W. Yu, X. Wang, Y. Zhao, X. Zong and C. Li, *ACS Energy Lett.*, 2018, **3**, 1159–1164.
- 100 R. Li, X. Li, J. Wu, X. Lv, Y.-Z. Zheng, Z. Zhao, X. Ding, X. Tao and J.-F. Chen, *Appl. Catal., B*, 2019, **259**, 118075.
- 101 Y. Zhao, Q. Zeng, Y. Yu, T. Feng, Y. Zhao, Z. Wang, Y. Li, C. Liu, J. Liu, H. Wei, S. Zhu, Z. Kang, H. Zhang and B. Yang, *Mater. Horiz.*, 2020, **7**, 2719–2725.
- 102 W. Guan, Y. Li, Q. Zhong, H. Liu, J. Chen, H. Hu, K. Lv, J. Gong, Y. Xu, Z. Kang, M. Cao and Q. Zhang, *Nano Lett.*, 2021, **21**, 597–604.
- 103 X. L. Zhao, S. Chen, H. J. Yin, S. Y. Jiang, K. Zhao, J. Kang, P. F. Liu, L. X. Jiang, Z. J. Zhu, D. D. Cui, P. R. Liu,



- X. J. Han, H. G. Yang and H. J. Zhao, *Matter*, 2020, **3**, 935–949.
- 104 Y. Wu, P. Wang, Z. Guan, J. Liu, Z. Wang, Z. Zheng, S. Jin, Y. Dai, M.-H. Whangbo and B. Huang, *ACS Catal.*, 2018, **8**, 10349–10357.
- 105 Z. Guan, Y. Wu, P. Wang, Q. Zhang, Z. Wang, Z. Zheng, Y. Liu, Y. Dai, M.-H. Whangbo and B. Huang, *Appl. Catal., B*, 2019, **245**, 522–527.
- 106 P. Zhou, H. Chen, Y. Chao, Q. Zhang, W. Zhang, F. Lv, L. Gu, Q. Zhao, N. Wang, J. Wang and S. Guo, *Nat. Commun.*, 2021, **12**, 4412.
- 107 Y. Wu, Q. Wu, Q. Zhang, Z. Lou, K. Liu, Y. Ma, Z. Wang, Z. Zheng, H. Cheng, Y. Liu, Y. Dai, B. Huang and P. Wang, *Energy Environ. Sci.*, 2022, **15**, 1271–1281.
- 108 V.-C. Nguyen, D. B. Nimbalkar, L. D. Nam, Y.-L. Lee and H. Teng, *ACS Catal.*, 2021, **11**, 4955–4967.
- 109 H. Li, Z. Gao, L. Lei, H. Liu, J. Han, F. Hong, N. Luo and F. Wang, *Green Chem.*, 2020, **22**, 3802–3808.
- 110 T. Yukawa, T. Bamba, M. Matsuda, T. Yoshida, K. Inokuma, J. Kim, J. Won Lee, Y.-S. Jin, A. Kondo and T. Hasunuma, *Biotechnol. Bioeng.*, 2023, **120**, 511–523.
- 111 C. H. Martin, H. Dhamankar, H.-C. Tseng, M. J. Sheppard, C. R. Reisch and K. L. J. Prather, *Nat. Commun.*, 2013, **4**, 1414.
- 112 H. Dhamankar, Y. Tarasova, C. H. Martin and K. L. J. Prather, *Metab. Eng.*, 2014, **25**, 72–81.
- 113 K. Wenderich, W. Kwak, A. Grimm, G. J. Kramer, G. Mul and B. Mei, *Sustainable Energy Fuels*, 2020, **4**, 3143–3156.
- 114 M. A. Khan, T. A. Al-Attas, N. G. Yasri, H. Zhao, S. Larter, J. Hu and M. G. Kibria, *Sustainable Energy Fuels*, 2020, **4**, 5568–5577.

