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Promoting H₂O₂ direct synthesis through Fe incorporation into AuPd catalysts†

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In recent years growing interest has been placed on the role of dopant concentrations of tertiary precious and base metals in modifying the performance of supported AuPd nanoalloys towards the direct synthesis of H₂O₂. Within this contribution, we expand on these earlier studies, with a focus on Fe-containing systems. Through rational catalyst design, an optimal 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ formulation has been developed, which not only outperforms the parent bimetallic analogue but also offers increased reactivity compared to alternative trimetallic formulations previously reported, including those which incorporate Pt. Such observations may be surprising given the propensity for Fe to decompose H₂O₂ *via* Fenton pathways. However, detailed analysis by CO-DRFITS and XPS reveals that the enhanced activity can be attributed to the electronic modification of Pd and the formation of domains of mixed Pd²⁺/Pd⁰ oxidation state, upon Fe introduction. Notably, the resulting improvement in catalytic performance which results from dopant Fe incorporation, is seen to result from an increase in H₂ utilisation, rather than improved catalytic selectivity towards H₂O₂.

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- (1) To date, despite the improved catalytic performance that results from their application, the investigation of tertiary metal modifiers into AuPd nanoalloys in H₂O₂ direct synthesis, has largely been restricted to precious metals, such as Pt.
- (2) This work demonstrates that through the incorporation of Fe considerable improvements in reactivity, may be achieved, with the optimised AuPdFe catalyst outperforming both the parent AuPd material and Pt-based analogues.
- (3) Further catalyst design is required to ensure that the increased reactivity of the catalyst does not result from compromises in selectivity towards H₂O₂.

Introduction

The direct synthesis of H₂O₂ from the elements represents an attractive alternative to the current industrial route to producing this powerful, environmentally friendly oxidant, the Anthraquinone Oxidation (AO) Process, theoretically offering

total atomic efficiency and allowing for localised production. In particular, the direct route may find the greatest application for transformations which rely on the continual *in situ* supply of low levels of the oxidant,^{1–3} and where the presence of the proprietary stabilisers present in commercial, preformed H₂O₂ would preclude application.⁴

In recent years a growing number of catalyst formulations have been reported that offer near-total selectivity towards H₂O₂,^{5–9} overcoming one of the major hurdles that have prevented industrial adoption of the direct route; the undesirable degradation of H₂O₂ to H₂O *via* decomposition and hydrogenation pathways. However, for the direct approach to be competitive with the AO Process, H₂O₂ concentrations of approximately 5 vol% must be obtained to minimise the energy requirements associated with product separation and concentration prior to shipping. To date, such concentrations have only been achieved through the use of H₂/O₂ gas mixtures within the explosive regime, which is clearly not practical at scale.

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To address performance limitations the introduction of a growing number of secondary metal promoters into supported Pd-catalysts has been studied,^{6,10–12} with AuPd-based systems perhaps attracting the greatest attention,^{13–15} with the synergistic enhancements that result from the formation of AuPd alloys considerable and often attributed to a combination of electronic and isolation effects, with the disruption of contiguous Pd domains, widely considered to be key in preventing the cleavage of the O–O bond (in *O₂, *H₂O₂, or *OOH) and the resultant formation of H₂O.

By comparison, the use of trimetallic formulations for the direct synthesis of H₂O₂ has received far less attention, although there are growing reports of the enhanced performance which can be achieved through the introduction of low quantities of dopant promoters, particularly into AuPd nanoalloys. Building on early work which focussed on AuPdPt systems,^{16,17} attention has recently shifted towards the use of more abundant transition metals as promoters for AuPd species, which have identified the promotive role of Cu, Zn and Ni dopants in the direct synthesis reaction, with optimised formulations offering improved reactivity compared to AuPdPt analogues.^{18,19} Based on these earlier we now turn our attention to the role of Fe as a promoter for AuPd catalysts.

Experimental

Catalyst preparation

A series of bi- and tri-metallic 1%AuPd–X%Fe/TiO₂ (X = 0.01–1.0) catalysts have been prepared by a wet co-impregnation procedure, based on a methodology previously reported in the literature.¹⁶ The procedure to produce the 0.5%Au–0.5%Pd–1%Fe/TiO₂ catalyst (2 g) is outlined below, in all cases the Au : Pd ratio is 1 : 1 (wt/wt), with a similar methodology to that outlined below utilised for all catalysts investigated.

Aqueous solutions of HAuCl₄·3H₂O (0.806 mL, [Au] = 12.4 mg mL⁻¹, Strem Chemicals), PdCl₂ (1.713 mL, [Pd] = 5.8 mg mL⁻¹, Sigma Aldrich) and FeCl₃ (0.0599 g, Sigma Aldrich) were mixed in a 50 mL round bottom flask and heated to 65 °C with stirring (1000 rpm) in a thermostatically controlled oil bath, with total volume fixed to 16 mL using H₂O (HPLC grade, Fischer Scientific). Upon reaching 65 °C, TiO₂ (1.96 g, P25, Degussa) was added over the course of 10 minutes with constant stirring. The resulting slurry was stirred at 65 °C for a further 15 min, following this the temperature was raised to 85 °C for 16 h to allow for complete evaporation of water. The resulting solid was ground prior to heat treatment in a reductive atmosphere (5%H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹).

Catalyst testing

Note 1: reaction conditions used within this study operate under the flammability limits of gaseous mixtures of H₂ and O₂.

Note 2: the conditions used within this work for H₂O₂ synthesis and degradation have previously been investigated, with

the presence of CO₂ as a diluent for reactant gases and a methanol co-solvent identified as key to maintaining high catalytic efficacy towards H₂O₂ production.²⁰ In particular the CO₂ gaseous diluent, has been found to act as an *in situ* promoter of H₂O₂ stability through dissolution in the reaction medium and the formation of carbonic acid. We have previously reported that the use of the CO₂ diluent has a comparable promotive effect to that observed when acidifying the reaction solution to a pH of 4 using HNO₃.²¹

Regarding the choice of the solvent alcohol-based solvents have been widely studied for the direct synthesis of H₂O₂, in part this choice is due to the improved solubility of gaseous reagents, compared to that in water, and assist in preventing mass transfer limitations. However, more recently, Flaherty and co-workers have demonstrated the direct involvement of the solvent within the direct synthesis mechanism, which resembles the two-electron oxygen reduction reaction (ORR), where H₂O₂ is formed by kinetically relevant proton (from solvent molecules)—electron (provided by heterolytic hydrogen oxidation, H₂ ↔ 2H⁺ + 2e⁻) transfer to surface-bound hydroperoxy intermediates. The reader is directed to the seminal work by Flaherty and co-workers for an in-depth discussion of the H₂O₂ direct synthesis mechanism.²²

Direct synthesis of H₂O₂

Hydrogen peroxide synthesis was evaluated using a Parr Instruments stainless steel autoclave with a nominal volume of 100 mL, equipped with a PTFE liner so that the total volume is reduced to 66 mL, and a maximum working pressure of 2000 psi. To test each catalyst for H₂O₂ synthesis, the autoclave liner was charged with catalyst (0.01 g) and solvent (methanol (5.6 g, HPLC grade, Fischer Scientific) and H₂O (2.9 g, HPLC grade, Fischer Scientific)). The charged autoclave was then purged three times with 5%H₂/CO₂ (100 psi) before filling with 5%H₂/CO₂ to a pressure of 420 psi, followed by the addition of 25%O₂/CO₂ (160 psi), with the pressure of 5%H₂/CO₂ and 25%O₂/CO₂ given as gauge pressures. The reactor was not continually fed with reactant gases. The reaction was conducted at a temperature of 2 °C for 0.5 h with stirring (1200 rpm). The above reaction parameters are based on optimum conditions we have previously reported for the synthesis of H₂O₂. H₂O₂ productivity was determined by titrating aliquots of the final solution after reaction with acidified Ce(SO₄)₂ (0.0085 M) in the presence of ferroin indicator. Catalyst productivities are reported as mol_{H₂O₂} kg_{cat}⁻¹ h⁻¹. To collect a series of data points, as in the case of Fig. 3, it should be noted that individual experiments were carried out and the reactant mixture was not sampled on-line.

The catalytic conversion of H₂ and selectivity towards H₂O₂ were determined using a Varian 3800 GC fitted with TCD and equipped with a Porapak Q column.

H₂ conversion (eqn (1)) and H₂O₂ selectivity (eqn (2)) are defined as follows:

$$\text{H}_2 \text{ conversion (\%)} = \frac{\text{mmol}_{\text{H}_2}(t(0)) - \text{mmol}_{\text{H}_2}(t(1))}{\text{mmol}_{\text{H}_2}(t(0))} \times 100 \quad (1)$$



$$\text{H}_2\text{O}_2 \text{ selectivity (\%)} = \frac{\text{H}_2\text{O}_2 \text{ detected (mmol)}}{\text{H}_2 \text{ consumed (mmol)}} \times 100 \quad (2)$$

The total autoclave capacity was determined *via* water displacement to allow for accurate calculation of H₂ conversion and H₂O₂ selectivity. When equipped with the PTFE liner the total volume of an unfilled autoclave was determined to be 93 mL, which includes all available gaseous space within the autoclave.

Gas replacement experiments for the direct synthesis of H₂O₂

An identical procedure to that outlined above for the direct synthesis reaction was followed for a reaction time of 0.5 h. After this, stirring was stopped and the reactant gas mixture was vented prior to replacement with the standard pressures of 5% H₂/CO₂ (420 psi) and 25% O₂/CO₂ (160 psi). The reaction mixture was then stirred (1200 rpm) for a further 0.5 h. To collect a series of data points, as in the case of Fig. 7, it should be noted that individual experiments were carried out and the reactant mixture was not sampled on-line.

Degradation of H₂O₂

Catalytic activity towards H₂O₂ degradation was determined in a similar manner to the direct H₂O₂ synthesis activity of a catalyst. The autoclave liner was charged with solvent (methanol (5.6 g, HPLC grade, Fischer Scientific) and H₂O (2.21 g, HPLC grade, Fischer Scientific)) and H₂O₂ (50 wt% 0.69 g, Sigma Aldrich), with the solvent composition equivalent to 4 wt% H₂O₂. From the solution, two 0.05 g aliquots were removed and titrated with acidified Ce(SO₄)₂ solution using ferroin as an indicator to determine an accurate concentration of H₂O₂ at the start of the reaction. Subsequently the catalyst (0.01 g) was added to the reaction media and the autoclave was purged with 5% H₂/CO₂ (100 psi) prior to being pressurised with 5% H₂/CO₂ (420 psi). The reaction medium was cooled to a temperature of 2 °C, prior to stirring (1200 rpm) for 0.5 h. After the reaction was complete the catalyst was removed from the reaction mixture and two 0.05 g aliquots were titrated against the acidified Ce(SO₄)₂ solution using ferroin as an indicator. The degradation activity is reported as mol_{H₂O₂} kg_{cat}⁻¹ h⁻¹.

Catalyst reusability in the direct synthesis and degradation of H₂O₂

In order to determine catalyst reusability, a similar procedure to that outlined above for the direct synthesis of H₂O₂ was followed utilising 0.05 g of catalyst. Following the initial test, the catalyst was recovered by filtration, washed with DI water, and dried (30 °C, 16 h, under vacuum); from the recovered catalyst sample 0.01 g was used to conduct a standard H₂O₂ synthesis or degradation test, as outlined above.

Note 3: in all cases the reactor temperature was controlled using a HAAKE K50 bath/circulator using an appropriate coolant.

In all cases reactions were run multiple times, a minimum of three, over multiple batches of catalyst, a minimum of two, with the data being presented as an average of these experi-

ments. The catalytic activity toward the direct synthesis and subsequent degradation of H₂O₂ was found to be consistent to within ±2% on the basis of multiple reactions.

Characterisation

X-ray photoelectron spectroscopy (XPS) measurements were performed on a Kratos Axis Ultra-DLD photoelectron spectrometer utilising monochromatic Al K_α X-ray source operating at 144 W (12 mA × 12 kV). Samples were pressed onto silicone free double sided Scotch tape, and analysed using the hybrid spectroscopy mode, giving an analysis area of *ca.* 700 × 300 microns. High resolution and survey spectra were acquired at pass energies of 40 eV (step size 0.1 eV) and 160 eV (step size 1 eV) respectively. Charge compensation was performed using low energy electrons and the resulted spectrum calibrated to the lowest C(1s) peak from the fitted carbon core-level spectra, taken to be 284.8 eV. The suitability of the C(1s) referencing was confirmed by a secondary reference point, taken to be the Ti(2p_{3/2}) peak with a binding energy of 458.7 eV, characteristic of that for virgin TiO₂. All data was processed using CasaXPS v2.3.24 using a Shirley background and modified Wagner factors as supplied by the instrument manufacturer. Peak fits were performed using a combination of Voigt-type functions (LA line shape in CasaXPS) and models derived from bulk reference samples where appropriate.

The bulk structure of the catalysts was determined by powder X-ray diffraction using a (θ-θ) PANalytical X'pert Pro powder diffractometer using a Cu K_α radiation source, operating at 40 keV and 40 mA. Standard analysis was carried out using a 40 min run with a back filled sample, between 2θ values of 20–80°. Phase identification was carried out using the International Centre for Diffraction Data (ICDD).

Note 4: X-ray diffractograms of the as-prepared catalysts are reported in Fig. S1,† with no reflections associated with active metals, indicative of the relatively low total loading of the immobilised metals.

Transmission electron microscopy (TEM) was performed on a JEOL JEM-2100 operating at 200 kV. Samples were prepared by dispersion in ethanol by sonication and deposited on 300 mesh copper grids coated with holey carbon film. To allow for the determination of mean particle size, a minimum of 300 particles were measured. Aberration-corrected scanning transmission electron microscopy (AC-STEM) was performed using a probe-corrected Hitachi HF5000 S/TEM, operating at 200 kV. The instrument was equipped with bright field (BF), high angle annular dark field (HAADF) and secondary electron (SE) detectors for high spatial resolution STEM imaging experiments. This microscope was also equipped with a secondary electron detector and dual Oxford Instruments XEDS detectors (2 × 100 mm²) having a total collection angle of 2.02 sr. Energy dispersive X-ray spectroscopy (XEDS) was performed using an Oxford Instruments X-Max^N 80 detector and the data analysed using Aztec software.

Transmission ⁵⁷Fe Mössbauer spectra were collected at 50 and 4.2 K with a conventional constant-acceleration spectrometer using a ⁵⁷Co(Rh) source. Velocity calibration was carried



out using an α -Fe foil at room temperature. The Mössbauer spectra were fitted using the Mosswin 4.0 program.²³

CO-DRIFTS measurements were taken on a Bruker Tensor 27 spectrometer fitted with a mercury cadmium telluride (MCT) detector. The sample was loaded into the Praying Mantis high temperature (HVC-DRP-4) *in situ* cell before exposure to N₂ and then 1% CO/N₂ at a flow rate of 50 cm³ min⁻¹. A background spectrum was obtained using KBr, and measurements were recorded every 1 min at room temperature. Once the CO adsorption bands in the DRIFT spectra ceased to increase in intensity, the gas feed was changed back to N₂, in order to evacuate gaseous CO. Measurements were repeated until no change in subsequent spectra was observed.

Total metal leaching from the supported catalyst was quantified *via* inductively coupled plasma mass spectrometry (ICP-MS). Post-reaction solutions were analysed using an Agilent 7900 ICP-MS equipped with I-AS auto-sampler. All samples were diluted by a factor of 10 using HPLC grade H₂O (1% HNO₃ and 0.5% HCl matrix). All calibrants were matrix-matched and measured against a five-point calibration using certified reference materials purchased from PerkinElmer and certified internal standards acquired from Agilent.

To allow for quantification of total metal loading catalytic samples were digested *via* an aqua-regia-assisted microwave digestion method using a Milestone Connect Ethos UP microwave with an SK15 sample rotor. Digested samples were analysed by inductively coupled plasma-optical emission spectroscopy (ICP-MS). All calibrants were matrix-matched and measured against a five-point calibration using certified reference materials purchased from PerkinElmer and certified internal standards acquired from Agilent. Actual metal loadings of key catalytic samples are provided in Table S1.†

Results and discussion

Under conditions that have previously been optimised to ensure H₂O₂ stability,²⁰ our initial investigations established the ability of dopant concentrations of Fe to promote the performance of AuPd-based catalysts towards H₂O₂ production (Fig. 1A), with the optimal 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ formulation achieving rates of H₂O₂ synthesis (122 mol_{H₂O₂} kg⁻¹ cat⁻¹), far greater than that offered by the parent 0.5%Au–0.5%Pd/TiO₂ catalyst (70 mol_{H₂O₂} kg⁻¹ cat⁻¹). Interestingly, catalytic activity towards H₂O₂ degradation was found to follow a similar trend to that observed for H₂O₂ synthesis, with both metrics reaching a maximum at a Fe loading of 0.02 wt%, before decreasing considerably with further Fe incorporation. Notably, the high Fe-loaded 0.5%Au–0.5%Pd–1%Fe/TiO₂ catalyst was found to offer H₂O₂ synthesis rates (65 mol_{H₂O₂} kg⁻¹ cat⁻¹), somewhat lower than that observed over the bimetallic parent catalyst. Determination of catalytic selectivity towards H₂O₂ and H₂ conversion during H₂O₂ synthesis is presented in Fig. 1B, with these measurements, alongside our evaluation of H₂O₂ synthesis and degradation activity (Fig. 1A), revealing that the improved performance that results from the introduction of dopant quantities of Fe can be primarily associated with increased rates of H₂ utilisation (an indicator of catalytic activity), rather than through an enhancement in H₂O₂ selectivity. The improved performance of the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst is further highlighted through a comparison of calculated reaction rates (Table S2†), at a reaction time (5 minutes), where it may be assumed (1) that there is no contribution from subsequent H₂O₂ degradation reactions and (2) that the reaction is not limited by gaseous reagent availability.

Evaluation of the as-prepared AuPdFe/TiO₂ catalysts by X-ray photoelectron spectroscopy (XPS) is shown in Fig. 2 and reveals the presence of a significant proportion of Pd²⁺ for all formulations, despite the exposure of the catalysts to a rela-

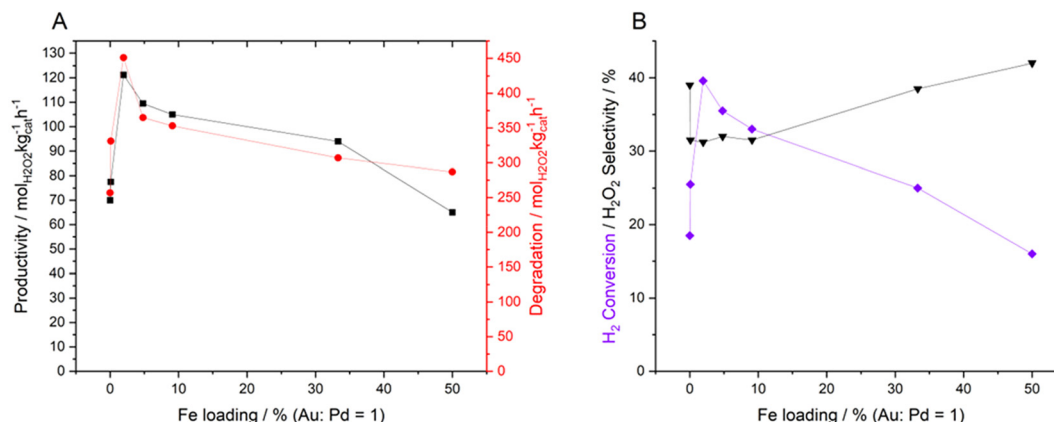


Fig. 1 The effect of Fe loading on the performance of 1%AuPd/TiO₂ catalysts towards (A) the direct synthesis and subsequent degradation of H₂O₂, with a determination of H₂ and H₂O₂ selectivity during H₂O₂ synthesis shown in (B). Key: H₂O₂ synthesis (black squares), H₂O₂ degradation (red circles), H₂ conversion (black inverted triangles), H₂O₂ selectivity (purple diamonds) H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 0.5 h, 2 °C 1200 rpm. H₂O₂ degradation reaction conditions: catalyst (0.01 g), H₂O₂ (50 wt% 0.69 g) H₂O (2.21 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 0.5 h, 2 °C 1200 rpm. Note: additional data is reported in Table S2.†



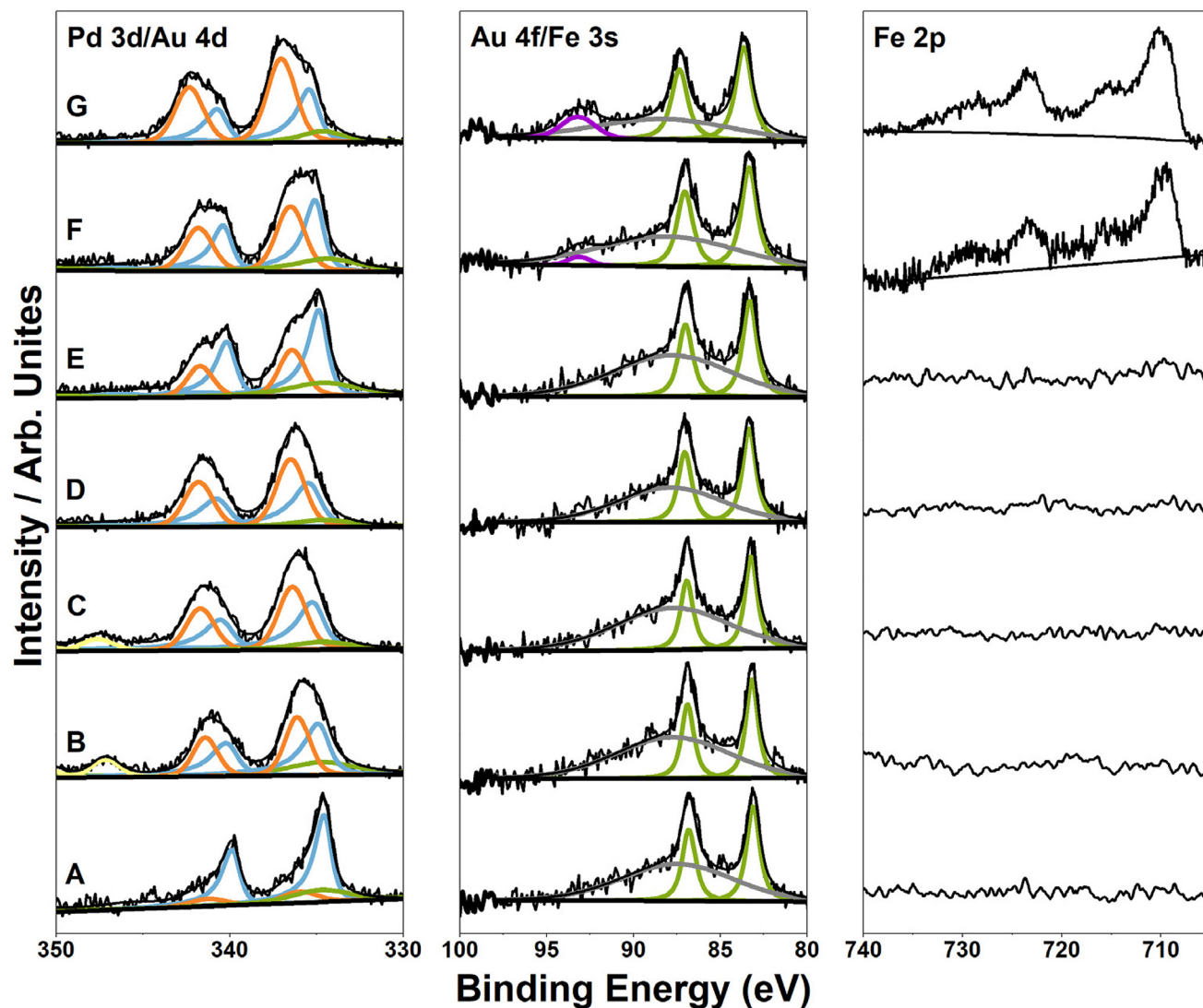


Fig. 2 XPS analysis of the as-prepared AuPdFe/TiO₂ catalysts. (A) 0.5%Au–0.5%Pd/TiO₂, (B) 0.5%Au–0.5%Pd–0.01%Fe/TiO₂, (C) 0.5%Au–0.5%Pd–0.02%Fe/TiO₂, (D) 0.5%Au–0.5%Pd–0.05%Fe/TiO₂, (E) 0.5%Au–0.5%Pd–0.1%Fe/TiO₂, (F) 0.5%Au–0.5%Pd–0.5%Fe/TiO₂ and (G) 0.5%Au–0.5%Pd–1.0%Fe/TiO₂. Key: Au(4d) & Au(4f) (green); Fe(3s) (purple); Pd⁰ (blue); Pd²⁺ (orange); loss of structure (grey); Ca²⁺ (yellow). Note 1: catalysts exposed to a reductive heat treatment prior to use (5%H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹). Note 2: Ca²⁺ signal results from the use of distilled water during catalyst preparation.

tively high-temperature reductive heat treatment (5%H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹), likely in part due to preparation for analysis under standard laboratory conditions. However, it is evident the incorporation of Fe results in a clear shift in Pd speciation, towards Pd²⁺, with such observations aligning well with our earlier studies investigating the role of alternative transition metals as promoters for AuPd nanoalloys.^{18,19} Notably, the performance of Pd-based catalysts towards H₂O₂ synthesis is well known to be highly dependent on Pd oxidation state, with domains of mixed Pd²⁺–Pd⁰ species typically offering improved performance compared to those with a predominance of Pd in either oxidation state.²⁴ As such, it is possible, at least in part, to attribute the improved activity, which results from the incorporation of dopant levels of Fe into AuPd alloys to the control of Pd speciation. In the case of the Fe spe-

ciation, we observe a distinct signal at a binding energy of 710.8 eV and satellite structure at *ca.* 719 eV, characteristic of Fe³⁺. However, here we wish to highlight the propensity of Fe to readily oxidise under ambient conditions and the surface sensitivity of XPS. The broadness of the Fe 2p core-level spectra suggests a lower oxidation state could be present, as such, we cannot rule out the presence of lower Fe oxidation states based on XPS analysis alone. Additionally, it should also be noted that active metal speciation of the as-prepared materials is likely not fully representative of those under reaction conditions.

With our evaluation by XPS unable to provide sufficient information about the nature of the Fe in the AuPdFe formulations, we subsequently employed ⁵⁷Fe Mössbauer spectroscopic analysis to gain further insight. Notably, these samples



contain identical Fe loadings as analogues investigated for H₂O₂ synthesis but were prepared with ⁵⁷FeCl₃ as the metal precursor, with comparisons made to a monometallic 0.02%⁵⁷Fe/TiO₂ formulation (Table 1 and Fig. 3).

Interestingly, the spectra of the monometallic Fe sample (0.02%Fe/TiO₂) were fitted with contributions of Fe²⁺ only, aligning with earlier works by Vanleerberghe *et al.*,²⁵ and indicative of the strong interaction between the immobilised Fe and TiO₂ support, possibly through the formation of iron titanates. By comparison, the spectra of the trimetallic 0.5% Au–0.5%Pd–0.02%Fe/TiO₂ formulation is far more complex. In addition to the Fe²⁺ (iron titanate) species observed in the monometallic Fe sample, contributions indicative of a Fe–Pd (Au) phase (magnetic sextuplet) contribution of 31.4 T, isolated Fe³⁺ species (paramagnetic doublet at 4.2 K) and Fe³⁺ oligomers (broad sextuplet) are also visible. Notably, these Fe³⁺ species were not present in the 0.02%Fe/TiO₂ sample, further indicating the electronic interaction between Fe and the precious metals. Additionally, Au/Pd–Fe dimers (paramagnetic doublet) and Au–Pd–Fe oligomers (broad sextuplet) were also found to be present, aligning well with earlier investigations into AuFe structures.²⁶ Contrastingly, the spectra of the 0.5% Au–0.5%Pd–1.0%Fe/TiO₂ sample was dominated by isolated and oligomeric Fe³⁺ species, in addition to contributions from the iron (Fe²⁺) titanate species observed in alternative formulations, with minor contributions from Fe⁰. Notably, we were unable to observe the Fe–Pd(Au) phase present in the optimal 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ formulation.

Returning to our non-isotopically labelled samples CO-DRIFTS was subsequently employed to further probe the electronic interaction that results from the incorporation of Fe into AuPd nanoalloys (Fig. S2,† which includes CO-DRIFTS analysis of a 1%Fe/TiO₂ catalyst for comparative purposes). Perhaps unsurprisingly, given the low loading of Fe in the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst, no clear variation in the DRIFTS spectra was observed between the optimal trimetallic catalyst and bimetallic AuPd analogue, with both spectra

dominated by Pd–CO bands. The bands observed at approximately 2060 cm⁻¹ represent CO bonded linearly to low co-ordination Pd sites (*i.e.* edge or corner sites, denoted Pd–CO), while the broad feature, which is centred around 1925 cm⁻¹ represents the 2- and 3-fold adsorption of CO on Pd.^{27,28} Notably, no bands associated with the adsorption of CO onto the TiO₂ support (>2200 cm⁻¹ and previously reported by Cerrato *et al.*²⁹ and Green *et al.*³⁰) or gaseous CO₂ (2350 cm⁻¹)³¹ were observed, likewise we do not observe bands which may be associated with the redox process of FeOx, (typically at 3700 cm⁻¹).³² Interestingly upon the introduction of large quantities of Fe, a clear red-shift in the bands related to the linearly bonded CO on Pd and the bridging CO species can be observed, which may be attributed to charge-transfer to Pd d-orbitals, resulting in an enhanced back donation to 2π CO molecular orbitals, such observations align well with our earlier analysis by XPS which indicated the electronic modification of Pd species as a result of Fe incorporation.

Further analysis of the as-prepared catalytic series by transition electron microscopy (TEM), prior to use in the H₂O₂ direct synthesis reaction, is reported in Table 2 (representative micrographs are reported in Fig. S3†). A minimal variation in this metric was observed across the catalytic series, with a mean particle size between 2 and 5 nm observed for the parent AuPd, and Fe-containing trimetallic formulations. While such measurements were conducted on fresh materials (*i.e.* prior to use in the direct synthesis reaction), it is considered that they reveal no direct correlation between catalytic performance and particle size or nanoparticle dispersion. As such it may be reasonable to conclude that the improved reactivity that results from the incorporation of dopant concentrations of Fe may be attributed to the electronic modification of Pd species, as indicated by our XPS and CO-DRIFTS analysis.

The observation of a strong dependency between Fe content and catalytic performance in the H₂O₂ synthesis reaction, and the enhanced catalytic activity of key formulations compared to those previously reported in the literature (Table S3†),

Table 1 The Mössbauer fitted parameters of the AuPd⁵⁷Fe/TiO₂ samples, obtained at different temperatures

Sample	T (K)	IS (mm s ⁻¹)	QS (mm s ⁻¹)	Hyperfine field (T)	Γ (mm s ⁻¹)	Phase	Spectral contribution (%)
0.02% ⁵⁷ Fe/TiO ₂	4.2	1.09	2.08	—	0.67	Fe ²⁺ (red)	37
		1.29	2.49	—	0.71	Fe ²⁺ (blue)	63
Au–Pd–0.02% ⁵⁷ Fe/TiO ₂	4.2	0.37	0.02	31.4	0.64	Fe–Pd(Au) (red)	18
		1.32	2.62	—	1.20	Fe ²⁺ (magenta)	19
		0.59	–0.14	40.9	1.21	Fe ³⁺ (oligomers) (blue)	41
		0.49	0.93	—	0.97	Fe ³⁺ (isolated) (green)	22
Au–Pd–1% ⁵⁷ Fe/TiO ₂	4.2	0.13	0.00	34.0	0.36	Fe ⁰ (red)	6
		1.12	2.63	—	1.20	Fe ²⁺ (magenta)	14
		0.58	–0.15	37.7	1.27	Fe ³⁺ (oligomers) (blue)	35
		0.51	0.79	—	0.70	Fe ³⁺ (isolated) (green)	45
Au–Pd–1% ⁵⁷ Fe/TiO ₂	50	0.11	0.00	33.9	0.36	Fe ⁰ (red)	10
		1.10	2.51	—	0.71	Fe ²⁺ (magenta)	19
		0.50	0.78	—	0.60	Fe ³⁺ (oligomers) + Fe ³⁺ (isolated) (green)	71

Experimental uncertainties: isomer shift: I.S. ± 0.1 mm s⁻¹; quadrupole splitting: Q.S. ± 0.2 mm s⁻¹; line width: Γ ± 0.2 mm s⁻¹; hyperfine field: ± 0.2 T; spectral contribution: ± 5%.



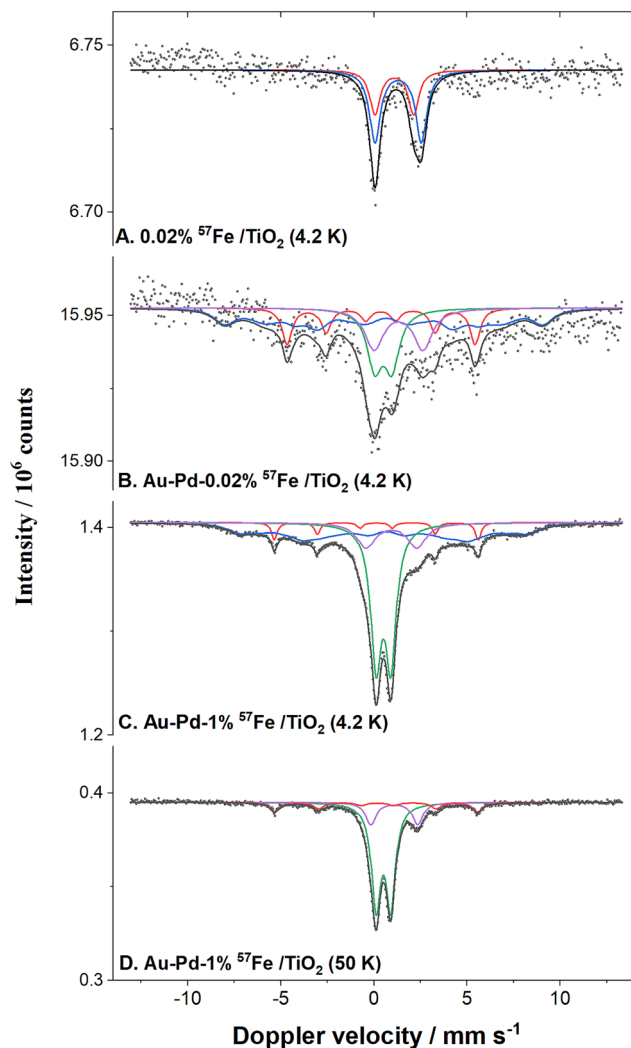


Fig. 3 Mössbauer analysis of the AuPd⁵⁷Fe/TiO₂ samples at different temperatures; (A) 0.02%⁵⁷Fe/TiO₂ (B) 0.5%Au–0.5%Pd–0.02%⁵⁷Fe/TiO₂ and (C–D) 0.5%Au–0.5%Pd–1%Fe/TiO₂. Note: analysis temperatures reported in parentheses, phase identification is reported in Table 1.

motivated us to further investigate the structure–activity relationships existing over the 0.5%Au–0.5%Pd/TiO₂, 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ and 0.5%Au–0.5%Pd–1%Fe/TiO₂ catalysts. While our initial studies (Fig. 1) indicated that the incor-

poration of Fe resulted in a loss of selectivity towards H₂O₂, it is important to highlight that the catalytic series was not compared at near-equivalent rates of H₂ conversion. Subsequent evaluation of H₂O₂ selectivity of key catalyst formulations at near iso-conversion is reported in Table S4,† from which it is clear that the incorporation of dopant concentrations of Fe (0.02 wt%) does indeed reduce catalytic selectivity (41% selectivity at 9% H₂ conversion), compared to that offered by the parent bimetallic analogue (50% selectivity at 8% H₂ conversion). However, the extent of this reduction is not as substantial as that which may be inferred from the data reported in Fig. 1. Regardless, from such comparisons and previous observations, it is possible to conclude that the enhanced performance of the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst is indeed associated with increased activity, rather than a promotion of catalytic selectivity towards H₂O₂.

Analysis of key catalyst formulations *via* STEM-HAADF imaging (Fig. 4, with additional data reported in Fig. S4†) corroborated our earlier investigation by TEM (Table 2 and Fig. S3†) which indicated the minimal variation in particle size across the wider catalyst series. Corresponding EDX mapping further revealed the intimate alloying of active metals (Fig. 4, additional data is reported in Fig. S5–7†). However, in the case of the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst, no clear signal associated with Fe was measured, which may be attributed to the low metal loading, rather than the inability of the constituent metals to form alloyed structures, which is evidenced by analysis of the 0.5%Au–0.5%Pd–1%Fe/TiO₂ catalyst and supported by Mössbauer spectroscopy (Fig. 3 and Table 1). Notably, the immobilised metal nanoparticles were found to exist as random alloys, rather than the core–shell morphologies which have previously been reported for AuPd-based catalysts prepared on oxide supports, *via* similar impregnation methodologies.³³ However, it is important to note that the formation of such core–shell structures typically results from exposure of the catalyst to an oxidative heat treatment, rather than the reductive treatment employed in this study, and the resulting formation of a Pd-oxide outer layer and Au-core.

Time-on-line studies investigating the performance of the key formulations over a reaction time of 180 minutes are reported in Fig. 5 (Fig. S8† compares the activity of the optimal AuPdFe catalyst to alternative trimetallic formulations reported in the literature, under identical reaction conditions, to a reac-

Table 2 Mean particle size, of the as-prepared AuPdFe/TiO₂ catalysts, as a function of Fe content

Catalyst	Mean particle size (nm)/(standard deviation)	Productivity/mol _{H₂O₂} kg _{cat} ⁻¹ h ⁻¹
0.5%Au–0.5%Pd/TiO ₂	4.4 (1.7)	70
0.5%Au–0.5%Pd–0.01%Fe/TiO ₂	4.6 (2.0)	78
0.5%Au–0.5%Pd–0.02%Fe/TiO ₂	2.8 (1.1)	122
0.5%Au–0.5%Pd–0.05%Fe/TiO ₂	4.0 (2.1)	110
0.5%Au–0.5%Pd–0.1%Fe/TiO ₂	3.8 (2.2)	105
0.5%Au–0.5%Pd–0.5%Fe/TiO ₂	3.2 (1.3)	94
0.5%Au–0.5%Pd–1.0%Fe/TiO ₂	3.7 (1.8)	65

H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 0.5 h, 2 °C 1200 rpm. Note: catalysts exposed to a reductive heat treatment prior to use (5%H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹).



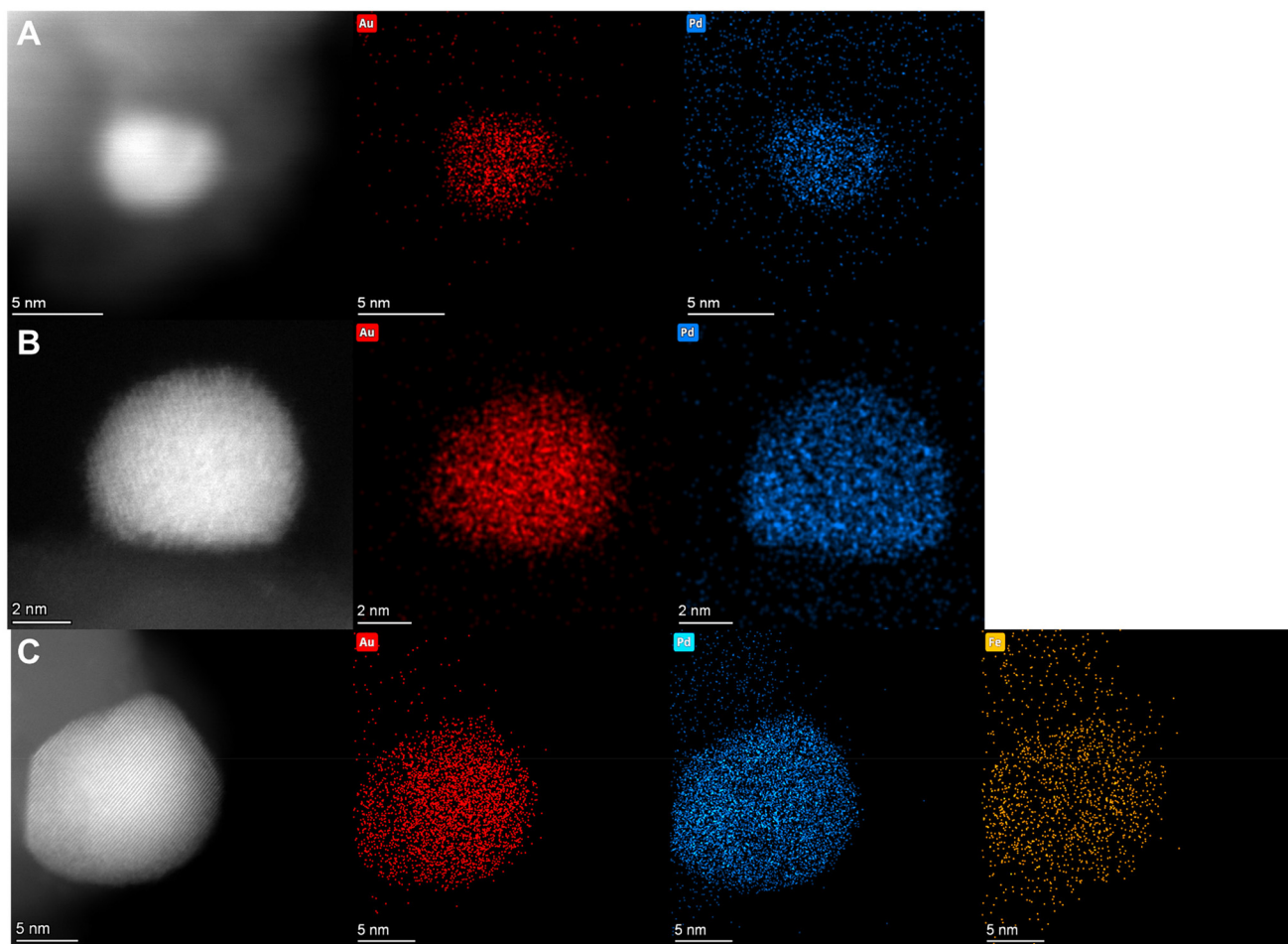


Fig. 4 Representative HAADF-STEM micrographs and complementary EDX analysis of individual alloy nanoparticles in (A) 0.5%Au–0.5%Pd/TiO₂, (B) 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ and (C) 0.5%Au–0.5%Pd–1%Fe/TiO₂. Note: catalysts exposed to a reductive heat treatment prior to use (5% H₂/Ar, 400 °C, 4 h, 10 °C min^{−1}).

tion time of 60 min). It should be noted that gaseous reagents were not continuously introduced during these experiments. An analysis of catalyst stability, as evidenced by ICP-MS analysis of post-reaction solutions is reported in Table S5† and indicates the relative stability of these materials. Notably, the inclusion of Fe, particularly at high concentrations, seems to lead to an enhancement in Pd leaching. However, in all cases, the total loss of active species is less than 0.3% of individual metal loadings.

The stark improvement in the reactivity of the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst compared to the AuPd or Fe-rich analogues is clear, achieving net concentrations of H₂O₂ between 35 and 45% greater than that offered by alternative formulations, at a reaction time of 60 minutes (Fig. 5A). Notably, at extended reaction times this metric decreases considerably, with the net H₂O₂ concentrations of all three catalysts relatively similar (approx. 0.25 wt%), at a reaction time of 180 minutes. Importantly, the extent of H₂ conversion over the catalytic series (Fig. 5B–D), reveals the near total utilisation of this reagent over the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst

(>80% H₂ conversion after 180 minutes on-line), compared to that of the alternative formulations (66 and 54% H₂ conversion after 180 minutes for the 0.5%Au–0.5%Pd/TiO₂ and 0.5%Au–0.5%Pd–1%Fe/TiO₂ catalysts, respectively), correlating well with earlier observations that revealed the improved performance of the low Fe-loaded AuPd catalyst are likely attributed to increased activity (*i.e.* a greater extent of H₂ conversion), rather than improved selectivity towards H₂O₂ (Fig. 1 and Tables S2 and S4†).

An evaluation of key catalytic formulations by XPS, over the course of a 180 minute H₂O₂ direct synthesis reaction, is reported in Fig. 6 and indicates that the Pd-speciation present within the as-prepared 0.5%Au–0.5%Pd/TiO₂ and 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalysts is maintained to a far greater extent, than over the Fe-rich analogue. Indeed, a total shift towards Pd⁰ was detected in the case of the 0.5%Au–0.5%Pd–1.0%Fe/TiO₂ catalyst at a reaction time as short as 5 minutes, revealing the ability of Fe to promote the reduction of Pd. Such observations, when coupled with the known lower selectivity of Pd⁰ species, compared to mixed Pd²⁺–Pd⁰ domains, and our



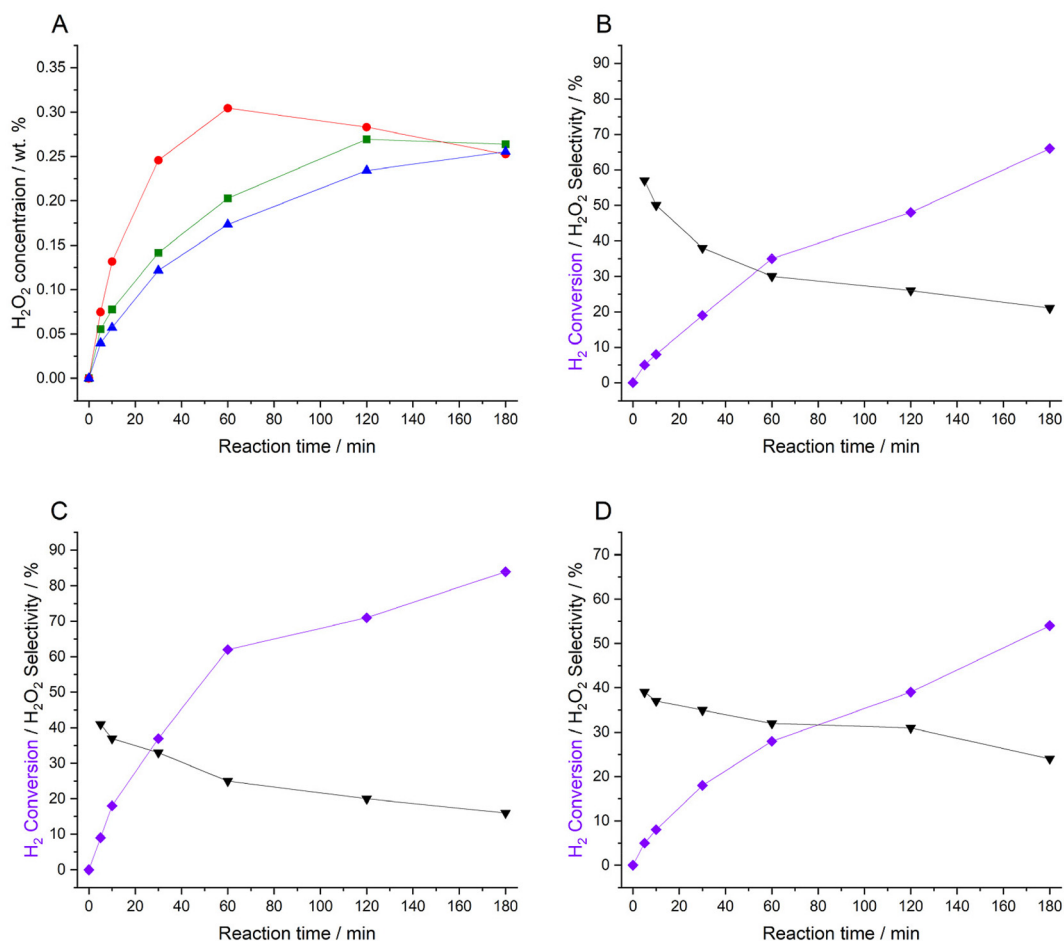


Fig. 5 Comparison of catalytic activity towards the direct synthesis of H₂O₂, as a function of reaction time. (A) Catalytic activity based on net H₂O₂ concentration. Determination of H₂ conversion and H₂O₂ selectivity for the (B) 0.5%Au–0.5%Pd/TiO₂ (C) 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ and (D) 0.5%Au–0.5%Pd–1.0%Fe/TiO₂ catalysts Key: 0.5%Au–0.5%Pd/TiO₂ (green squares), 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ (red circles), 0.5%Au–0.5%Pd–1.0%Fe/TiO₂ catalysts (blue triangles) H₂ conversion (purple diamonds), H₂O₂ selectivity (black inverted triangles). H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 2 °C, 1200 rpm.

earlier assessment of H₂ conversion rates and H₂O₂ selectivity may help rationalise the catalytic trends reported in Fig. 1.

With the high rates of H₂ conversion observed over extended reaction times, we subsequently investigated catalytic performance over sequential H₂O₂ synthesis experiments, where gaseous reagents were replaced at intervals of 0.5 h (Fig. 7). The improved performance of the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst was again clear, offering a H₂O₂ concentration of 0.76 wt% after five consecutive reactions, approximately 1.8 times greater than that achieved by the bimetallic (0.41 wt%) or Fe-rich (0.44 wt%) analogues. Indeed, the net concentration of H₂O₂ offered by the 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst is comparable to that achieved by the previously reported and highly active AuPd formulation which has been modified with Pt incorporation,³⁴ when investigated under identical reaction conditions to those utilised in this work. Indeed, the optimal Fe-containing formulation was found to offer superior activity compared to all of the alternative trimetallic catalysts reported in the literature, when evaluated under identical reaction conditions (Fig. S9†).

With the requirement to re-use a catalyst successfully at the heart of green chemistry, we next evaluated catalytic activity towards H₂O₂ synthesis and H₂O₂ degradation pathways, upon re-use (Table 3). Table S6.† reports metal leaching as determined by ICP-MS analysis of post-direct synthesis reaction solutions. It was found that for all formulations, catalytic activity toward H₂O₂ production decreased upon second use (approx. 32–42% loss of initial activity), with a corresponding loss in H₂ conversion rates. Such deactivation may be attributed to metal leaching, however, our analysis reveals negligible loss of Pd ($\leq 0.12\%$), and no detectable loss of Au or Fe after 0.5 h of reaction, indicating that alternative factors may contribute to the apparent deactivation of the catalysts upon use in the direct synthesis reaction.

Analysis of key formulations after use in the direct synthesis reaction by TEM is reported in Table 4 (with representative micrographs reported in Fig. S10†), and reveals no considerable change in particle size compared to the as-prepared catalysts (Table 2 and Fig. S3†). Additional evaluation of the spent materials by HAADF-STEM and corresponding EDX analysis



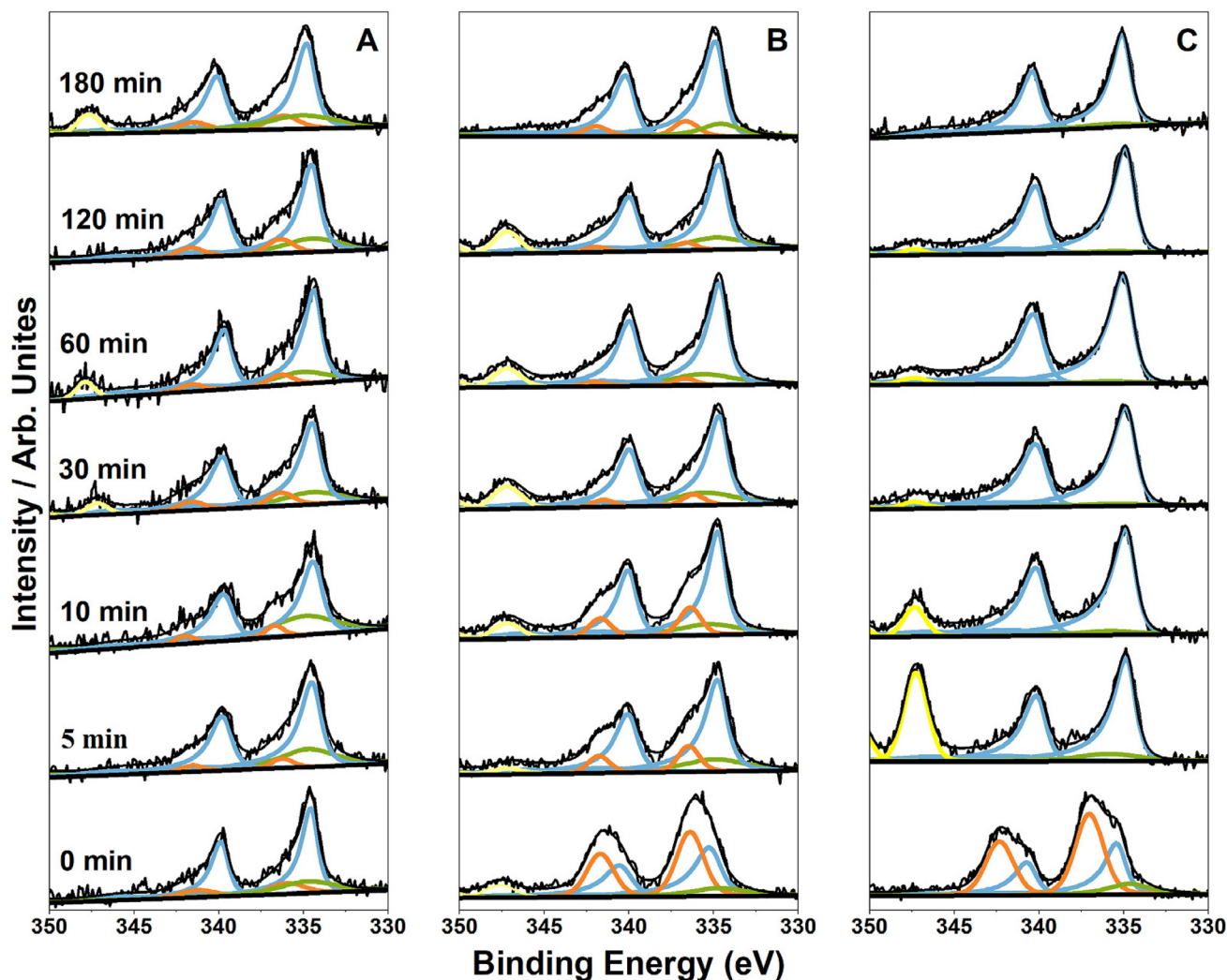


Fig. 6 XPS analysis of the AuPdFe/TiO₂ catalysts, as a function of reaction time. (A) 0.5%Au–0.5%Pd/TiO₂, (B) 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ and (C) 0.5%Au–0.5%Pd–1.0%Fe/TiO₂. Key: Au(4d) (green); Pd⁰ (blue); Pd²⁺ (orange); Ca²⁺ (yellow). Note 1: catalysts exposed to a reductive heat treatment prior to use (5% H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹). Spent catalysts were dried (30 °C, 16 h, under vacuum), prior to XPS analysis. Note 2: Ca signal associated with the washing of the spent catalyst with DI water, prior to drying and XPS analysis.

(Fig. S11–13†) corroborates these findings and further indicates that there is no discernible change in nanoparticle composition after use in the direct synthesis reaction (*i.e.* the random alloy nature of the as-prepared materials is retained upon use).

Notably, our previous evaluation of spent catalytic samples by XPS (Fig. 6), revealed the electronic modification of Pd as a result of exposure to H₂O₂ direct synthesis reaction conditions; with a discernible shift in Pd speciation towards Pd⁰. Based on this observation alone, and the known lower selectivity, but improved activity of metallic Pd species, one may not have expected the observed decrease in H₂ conversion rates or the lower rates of H₂O₂ degradation observed upon reuse. However, our analysis of spent materials by XPS also reveals a significant loss in chloride content after use in the direct synthesis reaction, (Fig. S14†). Halide ions are well-known promo-

oters for the direct synthesis reaction,^{15,35} and their use has typically been shown to result in improved catalytic performance, with this promotive effect often attributed to either the blocking of sites that promote O–O bond scission^{36,37} or a reduction in the density of states near the Fermi level, which consequently results in metal surfaces being less reactive for O–O cleavage.³⁸ More recently, Flaherty and co-workers,²² proposed that the electronic modification of the solution at the liquid–solid interface induced by the presence of counterions, is largely responsible for the improved activity observed in the presence of Cl⁻. Such propositions are indeed compelling. However, regardless of the underlying cause for catalytic promotion in the presence of Cl⁻, we can draw a direct correlation between these factors and indeed, such observations are in keeping with earlier studies into AuPd-based catalysts for H₂O₂ synthesis.¹⁵



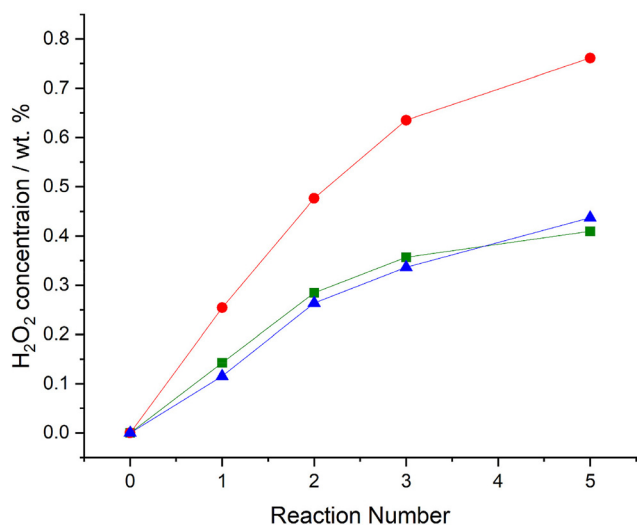


Fig. 7 Comparison of catalytic activity over sequential H₂O₂ synthesis reactions. Key: 0.5%Au–0.5%Pd/TiO₂ (green squares), 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ (red circles), and 0.5%Au–0.5%Pd–1.0%Fe/TiO₂ (blue triangles). H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 0.5 h, 2 °C, 1200 rpm.

Based on the presented catalytic data, we subsequently sought to compare the economic potential of the optimal AuPdFe-based catalyst, to other formulations widely studied within the literature, including those based on AuPd and Pd (Fig. 8, with additional data reported in Tables S7A–J†). Notably, such analysis is based on the material cost of key components in the generation of 1 ton of H₂O₂ and does not consider, for example, the additional costs associated with the separation of promoter agents (halides/acids) or the improved reactor lifetime that may result from avoiding their utilisation.³⁹ Such analysis, perhaps unsurprisingly, indicates that regardless of the catalyst composition a major contributor to cost may be associated with H₂ usage and that based on this, despite the relatively lower cost of the AuPdFe/TiO₂ catalyst (\$40.95 per kg), in comparison to a comparable AuPdPt/TiO₂ catalyst (\$45.61 per kg), further efforts are required to overcome limitations associated with H₂O₂ selectivity (*i.e.* improve-

Table 4 Mean particle size, of key AuPdFe/TiO₂ catalysts, after use in the direct synthesis of H₂O₂

Catalyst	Mean particle size (nm)/ (standard deviation)	
	Fresh	Used
0.5%Au–0.5%Pd/TiO ₂	4.4 (1.7)	5.1 (1.9)
0.5%Au–0.5%Pd–0.02%Fe/TiO ₂	2.8 (1.1)	5.1 (1.4)
0.5%Au–0.5%Pd–1.0%Fe/TiO ₂	3.7 (1.8)	3.6 (1.4)

H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 0.5 h, 2 °C 1200 rpm. Note: catalysts exposed to a reductive heat treatment prior to use (5%H₂/Ar, 400 °C, 4 h, 10 °C min⁻¹). Spent samples were dried (30 °C, 16 h, under vacuum).

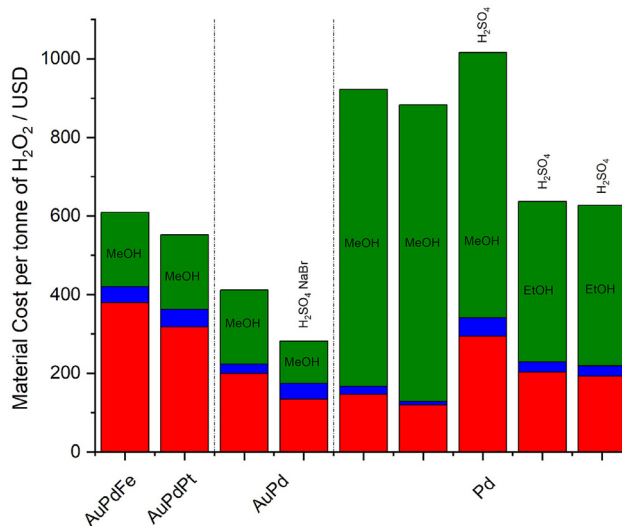


Fig. 8 Techno-economic analysis of the direct synthesis of H₂O₂ over the optimal AuPdFe/TiO₂ catalysts and comparison to alternative formulations. Key: H₂ (red bar), catalyst (blue bar) and organic component of reaction solvent (green bar, ethanol or methanol as indicated), promoters utilised as indicated. Additional data is provided in Tables S7A–J.†

ments in catalytic activity must not lead to a loss in net H₂O₂ production) if the AuPdFe/TiO₂ catalyst is to truly rival alternative formulations.

Table 3 Re-usability of AuPdFe/TiO₂ catalysts towards the direct synthesis and subsequent degradation of H₂O₂

Catalyst	Productivity/ mol _{H₂O₂} kg _{cat} ⁻¹ h ⁻¹		H ₂ conv./%		H ₂ O ₂ sel./%		Initial rate of reaction ^a / mmol _{H₂O₂} mmol _{metal} ⁻¹ min ⁻¹		Degradation/ mol _{H₂O₂} kg _{cat} ⁻¹ h ⁻¹	
	Use 1	Use 2	Use 1	Use 2	Use 1	Use 2	Use 1	Use 2	Use 1	Use 2
0.5%Au–0.5%Pd/TiO ₂	70	45	19	12	39	37	2.46 × 10 ³	9.71 × 10 ²	208	169
0.5%Au–0.5%Pd–0.02%Fe/TiO ₂	122	83	40	22	31	40	3.00 × 10 ³	1.72 × 10 ³	451	431
0.5%Au–0.5%Pd–1.0%Fe/TiO ₂	65	38	16	11	42	36	4.65 × 10 ²	1.91 × 10 ²	287	193

H₂O₂ direct synthesis reaction conditions: catalyst (0.01 g), H₂O (2.9 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 25% O₂/CO₂ (160 psi), 0.5 h, 2 °C 1200 rpm. H₂O₂ degradation reaction conditions: catalyst (0.01 g), H₂O₂ (50 wt% 0.69 g) H₂O (2.21 g), MeOH (5.6 g), 5% H₂/CO₂ (420 psi), 0.5 h, 2 °C 1200 rpm. Note: ^areaction rates are calculated based on the as-determined metal content. Spent samples were washed with DI water and dried (30 °C, 16 h, under vacuum), prior to re-use.



Conclusion

The introduction of dopant concentrations of Fe into supported AuPd nanoalloys results in a significant enhancement in catalytic activity towards the direct synthesis of H₂O₂, with the optimal 0.5%Au–0.5%Pd–0.02%Fe/TiO₂ catalyst offering rates of H₂O₂ synthesis greater than that of the parent formulation and competitive with state-of-the-art trimetallic formulations. This improvement is considered to result from the electronic modification of Pd oxidation states upon the addition of Fe, as evidenced by analysis by XPS and CO-DRIFTS. Notably, the enhanced performance of the optimal Fe-containing catalyst can be related to greater H₂ utilisation rather than an inhibition of competitive H₂O₂ degradation pathways, *i.e.* it is increased catalytic reactivity, rather than selectivity, that is responsible for the improvements offered over the parent AuPd bimetallic catalyst. While efforts are still required to overcome concerns around catalytic stability and H₂O₂ selectivity, we consider that these formulations represent a promising basis for further exploration.

Author contributions

R. L., and R. J. L. conducted testing experiments and corresponding data analysis. R. L., D. J. M., T. E. D., D. K. and A. I. D. conducted catalyst characterization and corresponding data processing. R. J. L., A. L., B. R. C. and G. J. H. contributed to the design of the study and provided technical advice and result interpretation. R. J. L. wrote the Manuscript and the ESI,† and all authors commented on and amended both documents. All authors discussed and contributed to the work.

Data availability

All the data is presented in the paper and in the detailed supplementary data.

Conflicts of interest

The authors declare no conflict of interest.

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References

- R. J. Lewis, K. Ueura, Y. Fukuta, T. E. Davies, D. J. Morgan, C. B. Paris, J. Singleton, J. K. Edwards, S. J. Freakley, Y. Yamamoto and G. J. Hutchings, *Green Chem.*, 2022, **24**, 9496–9507.
- N. O'Callaghan and J. A. Sullivan, *Appl. Catal., B*, 2014, **146**, 258–266.
- C. M. Crombie, R. J. Lewis, R. L. Taylor, D. J. Morgan, T. E. Davies, A. Folli, D. M. Murphy, J. K. Edwards, J. Qi, H. Jiang, C. J. Kiely, X. Liu, M. S. Skjøth-Rasmussen and G. J. Hutchings, *ACS Catal.*, 2021, **11**, 2701–2714.
- A. Santos, R. J. Lewis, D. J. Morgan, T. E. Davies, E. Hampton, P. Gaskin and G. J. Hutchings, *Catal. Sci. Technol.*, 2021, **11**, 7866–7874.
- S. J. Freakley, Q. He, J. H. Harrhy, L. Lu, D. A. Crole, D. J. Morgan, E. N. Ntainjua, J. K. Edwards, A. F. Carley, A. Y. Borisevich, C. J. Kiely and G. J. Hutchings, *Science*, 2016, **351**, 965.
- H. Li, Q. Wan, C. Du, J. Zhao, F. Li, Y. Zhang, Y. Zheng, M. Chen, K. H. L. Zhang, J. Huang, G. Fu, S. Lin, X. Huang and H. Xiong, *Nat. Commun.*, 2022, **13**, 6072.
- J. K. Edwards, B. Solsona, E. N. Ntainjua, A. F. Carley, A. A. Herzing, C. J. Kiely and G. J. Hutchings, *Science*, 2009, **323**, 1037–1041.
- S. Yu, X. Cheng, Y. Wang, B. Xiao, Y. Xing, J. Ren, Y. Lu, H. Li, C. Zhuang and G. Chen, *Nat. Commun.*, 2022, **13**, 4737.
- D. Kovačič, R. J. Lewis, C. M. Crombie, D. J. Morgan, T. E. Davies, Á. López-Martín, T. Qin, C. S. Allen, J. K. Edwards, L. Chen, M. S. Skjøth-Rasmussen, X. Liu and G. J. Hutchings, *Green Chem.*, 2023, **25**, 10436–10446.
- P. Tian, F. Xuan, D. Ding, Y. Sun, X. Xu, W. Li, R. Si, J. Xu and Y. Han, *J. Catal.*, 2020, **385**, 21–29.
- N. M. Wilson, J. Schröder, P. Priyadarshini, D. T. Bregante, S. Kunz and D. W. Flaherty, *J. Catal.*, 2018, **368**, 261–274.
- T. Richards, R. J. Lewis, D. J. Morgan and G. J. Hutchings, *Catal. Lett.*, 2022, **153**, 32–40.
- N. M. Wilson, P. Priyadarshini, S. Kunz and D. W. Flaherty, *J. Catal.*, 2018, **357**, 163.
- J. Li, T. Ishihara and K. Yoshizawa, *J. Phys. Chem. C*, 2011, **115**, 25359.
- J. Brehm, R. J. Lewis, D. J. Morgan, T. E. Davies and G. J. Hutchings, *Catal. Lett.*, 2022, **152**, 254–262.
- R. J. Lewis, K. Ueura, Y. Fukuta, S. J. Freakley, L. Kang, R. Wang, Q. He, J. K. Edwards, D. J. Morgan, Y. Yamamoto and G. J. Hutchings, *ChemCatChem*, 2019, **11**, 1673.
- J. K. Edwards, J. Pritchard, L. Lu, M. Piccinini, G. Shaw, A. F. Carley, D. J. Morgan, C. J. Kiely and G. J. Hutchings, *Angew. Chem., Int. Ed.*, 2014, **53**, 2381.
- A. Barnes, R. J. Lewis, D. J. Morgan, T. E. Davies and G. J. Hutchings, *Catal. Sci. Technol.*, 2022, **12**, 1986–1995.



- 19 A. Barnes, R. J. Lewis, D. J. Morgan, T. E. Davies and G. J. Hutchings, *Catalysts*, 2022, **12**, 1396.
- 20 A. Santos, R. J. Lewis, G. Malta, A. G. R. Howe, D. J. Morgan, E. Hampton, P. Gaskin and G. J. Hutchings, *Ind. Eng. Chem. Res.*, 2019, **58**, 12623–12631.
- 21 J. K. Edwards, A. Thomas, A. F. Carley, A. A. Herzing, C. J. Kiely and G. J. Hutchings, *Green Chem.*, 2008, **10**(4), 388.
- 22 N. M. Wilson and D. W. Flaherty, *J. Am. Chem. Soc.*, 2016, **138**, 574.
- 23 Z. Klencsár, *Nucl. Instrum. Methods Phys. Res., Sect. B*, 1997, **129**, 527–533.
- 24 L. Ouyang, P. Tian, G. Da, X. Xu, C. Ao, T. Chen, R. Si, J. Xu and Y. Han, *J. Catal.*, 2015, **321**, 70–80.
- 25 R. Vanleerberghe, E. de Grave, R. E. Vandenberghe and G. G. Robbrecht, *J. Phys. Colloques*, 1980, **41**, 179–180.
- 26 S. Cho, S. M. Kauzlarich, J. Olamit, K. Liu, F. Grandjean, L. Rebbouh and G. J. Long, *J. Appl. Phys.*, 2004, **95**, 6804–6806.
- 27 J. Brehm, R. J. Lewis, T. Richards, T. Qin, D. J. Morgan, T. E. Davies, L. Chen, X. Liu and G. J. Hutchings, *ACS Catal.*, 2022, **19**, 11776–11789.
- 28 J. H. Carter, S. Althahban, E. Nowicka, S. J. Freakley, D. J. Morgan, P. M. Shah, S. Golunski, C. J. Kiely and G. J. Hutchings, *ACS Catal.*, 2016, **6**, 6623–6633.
- 29 G. Cerrato, L. Marchese and C. Morterra, *Appl. Surf. Sci.*, 1993, **70–71**, 200–205.
- 30 I. X. Green, W. Tang, M. Neurock and J. T. Yates, *Science*, 2011, **333**, 736–739.
- 31 M. A. P. Dekkers, M. J. Lippits and B. E. Nieuwenhuys, *Catal. Lett.*, 1998, **56**, 195–197.
- 32 B. Zheng, G. Liu, L. Geng, J. Cui, S. Wu, P. Wu, M. Jia, W. Yan and W. Zhang, *Catal. Sci. Technol.*, 2016, **6**, 1546–1554.
- 33 J. K. Edwards, A. F. Carley, A. A. Herzing, C. J. Kiely and G. J. Hutchings, *Faraday Discuss.*, 2008, **138**, 225.
- 34 X. Gong, R. J. Lewis, S. Zhou, D. J. Morgan, T. E. Davies, X. Liu, C. J. Kiely, B. Zong and G. J. Hutchings, *Catal. Sci. Technol.*, 2020, **10**, 4635.
- 35 E. N. Ntainjua, M. Piccinini, J. C. Pritchard, Q. He, J. K. Edwards, A. F. Carley, J. A. Moulijn, C. J. Kiely and G. J. Hutchings, *ChemCatChem*, 2009, **1**, 479.
- 36 J. H. Lunsford, *J. Catal.*, 2003, **216**, 455.
- 37 V. R. Choudhary and C. J. Samanta, *J. Catal.*, 2006, **238**, 28.
- 38 M. Hohenegger, E. Bechtold and R. Schennach, *Surf. Sci.*, 1998, **412–413**, 184–191.
- 39 G. Gao, Y. Tian, X. Gong, Z. Pan, K. Yang and B. Zong, *Chin. J. Catal.*, 2020, **41**(7), 1039–1047.

