Introduction

Significant environmental benefits have been achieved by the introduction of three-way catalysts, which convert pollutants emitted by the car engine into not-harmful gases. Palladium, which has been recognized as a critical material,1 is a crucial, expensive catalytic component of TWCs2 and has limited and geographically localized natural availability. Data from Johnson Matthey show that the use of palladium for autocatalysts represents about 70% of the total demand for the metal.3

Due to the lifetime of TWCs (approximately 160,000 km, corresponding to an average of 8–10 years of use), an accumulation of noble-metals4 (NMs) rich wastes has been growing over the last few years. Palladium recovery has therefore economic and environmental relevance, in particular recovery from exhaust TWCs, especially given the introduction in the 2000s of the so-called Pd-only technology.‡ Despite this interest in NMs recovery, also encouraged by recent EU directives on end-of-life vehicles management,4 currently they are recycled at only a low extent (Pd: 26%; Pt: 25%; Rh: 31%; in 2014),3 primarily by non-selective and unattractive methods, such as pyrometallurgical chlorination5 or dissolution with strong oxidising acids.6,7 As an alternative to these polluting and/or harmful methods, over the last decade we have thoroughly investigated the leaching properties of a new class of reagents – namely dihalogen mixtures with donors bearing two vicinal thionic acid groups, such as ecyclic-dithioxamides e.g. N,N′-dimethylperhydrodiazepine-2,3-dithione (Me₂dazdt) and N,N′-dimethylpiperazine-2,3-dithione (Me₂pipdt) – that show a peculiar capability to dissolve noble and toxic metals effectively and in very mild conditions, as well as their applicability in different fields.8 In particular, a safe methodology for the effective and selective Pd dissolution and extraction from model spent TWCs, based on the use of the Me₂dazdt-2L molecular adduct (Chart 1a), have been pointed out and patented (Scheme 1).9

The use of this non-cytotoxic leaching reagent, capable of combining with oxidizing properties in the same

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‡ Pd, Pt and Rh were in a tunable molar ratio 2:4:1 in 1997, 28:1:1 in 2000. The NMs content of catalysts depends closely from the market price of these metals. In the last years, an increased use of Pt in car catalysts has been observed, due to the jump of the Pd price in 2001.
molecule, allows almost quantitative palladium recovery under mild conditions (temperature: 80 °C and at atmospheric pressure without protection from air or moisture) and provides the \([\text{Pd(Me}_2\text{dazdt})_2][\text{I}_3]\) complex (Chart 1b) as the leaching product.

This product, which should be destroyed in order to recover Pd-metal, has instead shown itself to be a very valuable catalyst precursor and useful for designing a sustainable palladium “recovery and re-employment” method, as described herein. Specifically, the growing interest in the photo-catalytic activity of palladium-based materials in the reforming of alcohols and carbohydrates to produce \(\text{H}_2\) prompted us to study the potential of this complex as a metal precursor for the preparation of photo-catalysts and also as a reference TiO\(_2\) Degussa P25 as the supporting semiconductor.

Results and discussion

Preparation of the precursor

The \([\text{Pd(Me}_2\text{dazdt})_2][\text{I}_3]\) complex was obtained in the form of a crystalline product from the extraction solution recovered at the end of the palladium recovering process from model exhausted TWCs, as summarized in Scheme 1 and in the Experimental section. In particular, a model Pd(TiO\(_2\))-based photo-catalyst by a Pd photo-deposition process using [Pd(Me\(_2\)dazdt)]\(\text{I}_3\) obtained through a one-step palladium oxidation/extraction from a model spent TWC, and the commercial reference TiO\(_2\) Degussa P25 as the supporting semiconductor.

In this respect, the use of largely available organic species in the so-called photo-reforming processes has been increasingly considered. Many oxygenate molecules, mostly derived from biomasses (e.g. sugar, starch, vegetable oils, lignocellulosic crops, algae fuels), have been tested for more sustainable \(\text{H}_2\) production by these routes. In this context, we investigated the production of a Pd-TiO\(_2\)-based photo-catalyst by a Pd photo-deposition process using [Pd(Me\(_2\)dazdt)]\(\text{I}_3\), obtained through a one-step palladium oxidation/extraction from a model spent TWC, and the commercial reference TiO\(_2\) Degussa P25 as the supporting semiconductor.

The addition of sacrificial agents, which can irreversibly react with photo-generated holes (or OH\(^+\) radicals derived from the \(\text{H}^+\) reaction with \(\text{H}_2\text{O}\) and undergo an easier oxidation than water, has also been proven to enhance the performance. In this respect, the use of largely available organic species in the so-called photo-reforming processes has been increasingly considered. Many oxygenate molecules, mostly derived from biomasses (e.g. sugar, starch, vegetable oils, lignocellulosic crops, algae fuels), have been tested for more sustainable \(\text{H}_2\) production by these routes.

While methanol is a commonly used sacrificial agent for testing the efficiency of photo-catalysts in hydrogen evolution, \(\text{glycerol is a more challenging and sustainable substrate as it represent a 10 wt% by-product of biodiesel synthesis. Furthermore, the oxidative dehydrogenation of the glycerol and the subsequent catalytic and photo-catalytic reactions might lead also to the simultaneous and sustainable production of hydrogen and valuable products, such as 1,3-dihydroxypropanone or hydroxyacetaldehyde. In particular, 1,3-dihydroxypropanone is a promising compound for the preparation of skincare products and also a building block for the synthesis of biodegradable polymers.}

\(\text{Results and discussion}
\)

\(\text{Preparation of the precursor}
\)

The \([\text{Pd(Me}_2\text{dazdt})_2][\text{I}_3]\) complex was obtained in the form of a crystalline product from the extraction solution recovered at the end of the palladium recovering process from model exhausted TWCs, as summarized in Scheme 1 and in the Experimental section. In particular, a model Pd(2.8%-CeO\(_2\)-ZrO\(_2\)/Al\(_2\)O\(_3\)) catalyst was submitted to a severe ageing protocol (1050 °C/200 h) in order to simulate the thermal deactivation of what occurs on a real TWC. Subsequently, palladium was leached by reacting the catalyst (250 mg) with 50 mL of a 2.5 ×
10⁻³ M methyl ethyl ketone (MEK) solution of Me₂dazdt·2I₂ for 168 h under reflux. The Pd-containing solution, separated from the remaining ceramic material by means of a glass microfibre thimble in a Soxhlet apparatus, was concentrated and crystallized by the slow diffusion of Et₂O to form [Pd(Me₂dazdt)₂]I₃ complex in a quantitative way.

**Palladium photo-deposition on TiO₂**

In order to investigate the capability of [Pd(Me₂dazdt)₂]I₃ to work as a suitable and sustainable precursor for the preparation of photo-catalysts and to evaluate its activity in the photo-reforming of methanol and glycerol, a series of Pd-TiO₂ photo-catalysts were prepared by impregnation of metal precursors followed by metal photo-reduction in the presence of methanol as an additional reductant, as summarized in Chart 2.

The catalysts were prepared by the impregnation of Degussa P25 TiO₂ (54 m² g⁻¹, average pore size distribution of about 50 nm, and total pore volume 0.23 ml g⁻¹) with a proper amount of the selected metal precursor solution to obtain a 0.5% w/w Pd-loading, followed by irradiation in the UV range of the suspension obtained by dispersion of the dry material in a 1 : 1 methanol/water solution in Ar flow (see details in the Experimental section). After metal deposition, only marginal decreases of surface area, average pore size distribution and total pore volume were measured consistently under the mild reaction conditions employed and with the low metal loadings. Fig. 1 shows the hydrogen evolution during the Pd photo-reduction process on varying the metal precursor. During this step, the concomitant presence of UV electrons and methanol as an additional reductant, 18 as summarized in Chart 2.

![Fig. 1 H₂ production rates during Pd photo-deposition in methanol aqueous solutions by irradiation in the UV-vis region.](Image)

Fig. 1. H₂ production rates during Pd photo-deposition in methanol aqueous solutions by irradiation in the UV-vis region.

The performances of 2 were investigated in order to assess the role of I₂/I⁻. In fact, the improved photo-catalytic activity of TiO₂ upon sensitization with iodine is documented in the literature and is attributed to an extended absorption edge up to around 800 nm, resulting in visible light photo-catalytic activity beyond 600 nm and/or beneficial effects for enhancing e⁻⁻h⁺ lifetime. The hydrogen evolution from 2 slowly increases with time, reaching after 6 h a constant rate similar to that of 3 and only slightly lower than that of 4. By using Pd(NO₃)₂ and I₂/I⁻ solution, producing 5, a transient hydrogen evolution behaviour very similar to that observed in the case of 3 was obtained. This may suggest the formation of similar metal-halogenides in solution. Vice versa, 1 shows a progressive increase of photo-catalytic activity, leading to a H₂ production that is 80% higher than that of all the other samples. All these findings clearly indicate that not only is [Pd(Me₂dazdt)₂]I₃ suitable for the preparation of an effective photo-catalyst but it is also able to be incorporated into the TiO₂ I₂/I⁻ and/or other species from the complex as sensitizers or dopants in a more effective manner. Consistently, the diffuse reflectance spectra of 1 and 1-used show an underlying broad band in the UV-Vis region (Fig. S1, ESI†) which may be the result of this incorporation, as observed for N- or I-doped TiO₂ samples. 22 ICP-AES analysis of the samples confirmed that the real metal loading was closed to the nominal one for all the photo-catalysts (Table 1). This highlights that the deposition process was almost quantitative.

<table>
<thead>
<tr>
<th>Metal precursor</th>
<th>Support</th>
<th>Catalyst n.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Pd(Me₂dazdt)₂]I₃</td>
<td>TiO₂</td>
<td>1</td>
</tr>
<tr>
<td><a href="BF%E2%82%84">Pd(Me₂dazdt)₂</a>₂</td>
<td>TiO₂</td>
<td>2</td>
</tr>
<tr>
<td>PdCl₂</td>
<td>TiO₂</td>
<td>3</td>
</tr>
<tr>
<td>Pd(NO₃)₂</td>
<td>TiO₂</td>
<td>4</td>
</tr>
<tr>
<td>Pd(NO₃)₂ + I₂/I⁻</td>
<td>TiO₂</td>
<td>5</td>
</tr>
</tbody>
</table>

Chart 2. Nomenclature of the photo-catalysts used in this work.
CO chemisorption experiments performed on 1, 3 and 4 show high metal dispersion, from which it was possible to estimate an average metal particle size of about 1.3 nm for 3 and slightly higher for 1 and 4 (Table 1).

### Photo-catalytic activity

Catalysts 1–4 were then applied to the glycerol photo-reforming process through the same procedure followed in the photo-deposition process. Fig. 2 shows the hydrogen evolution from a 1 M aqueous solution of glycerol using UV-Vis light irradiation over each Pd/TiO2 photo-catalyst as a function of reaction time. All the Pd/TiO2 photo-catalysts showed relatively high hydrogen formation rates. Photo-activation of the relatively more complex glycerol molecule with respect to commonly used sacrificial alcohols, such as methanol and ethanol, is difficult and leads to lower H2 yields.19 Notably, under the same experimental conditions, the reference bare TiO2 Degussa P25 is practically inactive. As shown, significant differences in the photo-catalytic H2 production depending on the used metal precursor were observed.

In particular, 2 and 4 are significantly less active than 3 and 1. For all the studied photo-catalysts, the analyses of the gaseous products indicate the formation of H2 and CO2 only. In addition, 1,3-dihydroxypropanone and hydroxyacetaldehyde were detected in the liquid phase as the main by-products of the photo-oxidation of glycerol, as previously observed.17 A small amount of acetaldehyde, 1,2-ethanediol and 1,3-propanediol as well as traces of formic acid, acetic acid and 2,3-dihydroxypropanal (see Fig. S2, ESI†) were detected. These latter compounds derive from subsequent dehydrogenation occurring on the main products.17 The photo-activity of the present metalized TiO2 samples is related to the generation and utilization of photo-carriers (electrons/holes). To reach a high photo-catalytic activity, the Pd-TiO2 photo-catalyst must have a high light absorption capacity and/or a low electron/hole recombination.

Using the same TiO2 semiconductor as the metal support for all the samples, it is reasonable to consider that most of the differences observed in the samples are related to the palladium dispersion, metal crystallinity or surface morphology and/or to the presence of residuals of the synthesis (chlorides, iodine, sulphur, etc.) either as sensitzers or poisons. Therefore, in order to understand the reason for the improved photo-catalytic performances of the material obtained from [Pd(Me4dazdt)2][I3]2, we carefully investigated its metal dispersion before (sample 1) and after (sample 1-used) use.

It is interesting to note that the presence of hydrogen atoms in the alpha position to the alcoholic function has been indicated as an important pre-requirement for efficient hydrogen evolution, with tertiary alcohols showing worse H2 productivity.24,19b However, these investigations were performed under very diluted solutions. Vice versa, as in the present case, when the concentration of the sacrificial agent significantly increases, a different reactivity order is reported in the literature,25 due to the establishment of complex adsorption equilibria. In fact, the number of reaction by-products increases significantly with the increase in the sacrificial agent complexity.

The XRD analyses (Fig. S3, ESI†) of 1 and 1-used samples show similar patterns. Peaks related to a rutile/anatase mix are present but there is no evidence of Pd, due to its low loading in the catalyst. The similarity between the pre- and post-catalysis sample patterns indicates that the rutile/anatase ratio and the crystalline grain dimensions are preserved. This confirms that the TiO2 support is stable under the reaction conditions.§ Conventional TEM images of samples 1, 3 and 4 were collected in order to detect the presence and size of the Pd nanoparticles. TEM investigation highlighted the presence of Pd nanoparticles with an average size of ~3 nm on sample 4 (Fig. S4, ESI†), while no TEM evidence of Pd particles was observed on samples 1 and 3. The comparison between 1 and 4 suggests that the higher activity of 1 could be at least partially explained by invoking its higher metal dispersion and

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**Table 1.** Results from chemical analyses (ICP-AES) and CO chemisorption

<table>
<thead>
<tr>
<th>Sample</th>
<th>Metal loading (wt%)</th>
<th>CO/Pd</th>
<th>Pd Surface area (m² g⁻¹)</th>
<th>Pd NPs mean particle size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.47 ± 0.01</td>
<td>0.620</td>
<td>1.38</td>
<td>1.81</td>
</tr>
<tr>
<td>2</td>
<td>0.41 ± 0.03</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>3</td>
<td>0.38 ± 0.01</td>
<td>0.875</td>
<td>1.72</td>
<td>1.28</td>
</tr>
<tr>
<td>4</td>
<td>0.50 ± 0.04</td>
<td>0.583</td>
<td>1.30</td>
<td>1.92</td>
</tr>
</tbody>
</table>

*Mean particle size calculated from CO chemisorption assuming a spherical geometry and CO : Pd = 1 : 1 stoichiometry. Not determined.

†Similar results have been obtained for samples 3 and 4.
reduced nanoparticle size. To detect metal palladium on 1 and to compare it with 3, more sensitive high angle annular dark field (HAADF) STEM measurements were performed. Fig. 3a shows the HAADF STEM imaging and STEM-EDX analysis of 1. The presence of the Ti-phase composition (~40 nm) was assessed by the chemical analysis carried out on the single nanoparticles and was consistent with the XRD analysis. Pd particles were barely observable due to the low metal loading and likely due to the high dispersion of the metal, which, during the photo-deposition process, forms sub-nanometre particles with the amorphous/paracrystalline structure. On the other hand, HAADF STEM imaging and STEM-EDX characterizations of the 1-used (Fig. 3b) show indeed small (~3 nm) Pd particles grown over the Ti-particles, as confirmed by the chemical analysis.

For comparison, 3 shows no TEM evidences of the presence of Pd particles in the pre- and post-catalysis samples, likely due to higher metal dispersion. As a consequence, the highest activity of 1 may be relatable both to the metal particles sizes and/or the presence of sensitizers or dopants as residues of the complex.

XPS analysis of 1 reveals a complex situation, with the presence of multiple contributions arising from the partial photo-decomposition of the complex. Indeed, as shown in Fig. 4, traces of I, S and N are present in the sample, together with Pd. The Pd : S : N : I atomic ratio is 1 : 4 : 2 : 0.2, as obtained via quantitative analysis of the XPS spectra. The obtained values clearly differ from the stoichiometry of the complex, where a 1 : 4 : 4 : 6 atomic ratio is expected. Also, while the position of the 1 3d peaks (with 1 3d_{5/2} peak at 619.3 eV) is consistent with the presence of tri-iodide moieties, the S 2p and N 1s spectra are symptomatic of chemical states different from those expected for the [Pd(Me_2dazdt)_2][I_3]_2 complex. Indeed, the S 2p profile can be deconvoluted into at least 3 different components, centred at positions typical for thiols (S 2p_{3/2} at 162.5 eV), disulfides (S 2p_{3/2} at 164.5 eV) and sulfates (S 2p_{3/2} at 169 eV), while the N 1s profile can be deconvoluted into two components, centred at 400 and 402 eV and respectively ascribable to N coordinated in an organic ring and to an oxidized state of N as NO or NO_2 resulting from the decomposition of the molecule chemically adsorbed on the surface of TiO_2. The data clearly highlight that while a significant fraction of the complex is eliminated during the Pd reduction/deposition process, some species interact with the TiO_2 and remain attached to the surface, modifying its properties. Obviously, this process strongly depends on the ageing time, and is influenced by the vicinity of the various species in the complex. As cited above, literature data indicate that the TiO_2 photo-catalytic activity may be improved by encapsulated I_2 or also by the presence of sulphur and nitrogen as sensitizers or dopants. In catalyst 1 under discussion, it is not so easy to discriminate the different contribution of each component that may furthermore work individually or combined with enhanced activity.

Concerning the Pd 3d spectrum, it clearly indicates the presence of two different oxidation states. Indeed, the best fitting of the experimental profile was obtained with two components, ascribable to Pd(0) (Pd 3d_{5/2} centred at 335 eV) and Pd(II) (Pd 3d_{5/2} centred at 336.5 eV). For comparison, the XPS analysis of 1-used reveals a similar scenario, the main differences being a decrease in the intensity of the sulfate component, the disappearance of the oxidized N and an increase in the intensity of the Pd(0) component with respect to the intensity of the Pd(II) one, as shown in Fig. 4.
We estimated moreover the \( \text{Pd}(0) \) to \( \text{Pd}(\text{II}) \) fraction for all the considered photo-catalysts before and after \( \text{H}_2 \) photo-reforming from glycerol solution (Table 2 and Fig. S5, ESI†).

In order to avoid misunderstanding of the data, it is essential to recall the fact that the XPS were recorded ex situ, after exposing the photo-catalysts to air. Consequently, the information cannot be immediately translated into consideration on the status of the photo-catalyst during operational conditions, which are indeed reducing (as indicated by the UV irradiation and the presence of alcohols). With these remarks in mind, the presence of some oxidized Pd species is not surprising and can be related to both an only partial reduction of the metal precursors in the reducing operational conditions and to the exposure of the photo-catalyst to air before XPS analysis. The consequent extent of the partial oxidation/passivation of Pd should be related to the different redox stability of the starting metal precursors and to the final metal particle size, as small Pd nanoparticles are more easily passivated with respect to larger ones. From the data of the fresh samples (Table 2) it appears that palladium nitrate is easily reduced to metal Pd, which eventually is subjected to a different radiation power on the photo-catalyst was 129 mW. The incident time, while methanol was added in order to obtain a 1 : 1 by volume solution with water. Immediately after methanol addition, the suspension was irradiated for 6 h with a 125 W medium pressure Hg lamp (Helios Italquartz). The photon flux was measured by using a DeltaOHM radiometer HD2302.0. Accordingly to Lianos et al., the approximate average incident radiation power on the photo-catalyst was 129 mW. The samples were finally filtered, washed with acetone and dried. All the samples showed a stable evolution of \( \text{H}_2 \) during the catalysts preparation.

The photo-catalytic activity was evaluated for hydrogen production from aqueous solutions of 1 M glycerol. For the UV-Vis experiments, 500 mg of catalyst were suspended in 240 mL of solution and the suspension was irradiated with the same 125 W medium pressure Hg lamp described above. Ar flow (15 mL min\(^{-1}\)) was employed to remove air from the reactor and as a carrier for the reaction products. As the hydrogen production can depend on the sacrificial agent concentration, the duration of the long term experiments was optimized to prevent significant alteration of the concentration of the glycerol due to the conversion.

Gaseous products were analyzed by GC analysis using a TCD for the quantification of \( \text{H}_2 \) and a FID, coupled with a methanator, for the quantification of the C-containing compounds (CO, CO\(_2\), CH\(_4\), etc.).

**Characterization of the catalysts**

Inductively coupled plasma atomic emission spectroscopy (ICP-AES) measurements were performed on fresh catalysts for palladium quantitative determination. The palladium contents for samples 1–4 are summarized in Table 1. Experimental details on the samples’ digestion and analysis are described in the ESI†.

Fresh and used catalysts were characterized by XRD and TEM, as detailed in the ESI†.

X-ray diffraction (XRD) patterns were recorded on a Panalytical Empyrean diffractometer equipped with a graphite mono-

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**Table 2** XPS evaluation of the \( \text{Pd}(0) \) and \( \text{Pd}(\text{II}) \) atomic percentages in the fresh and used photo-catalysts, obtained from data in Fig. S5

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \text{Pd}(0) ) Fresh</th>
<th>( \text{Pd}(\text{II}) ) Fresh</th>
<th>( \text{Pd}(0) ) Used</th>
<th>( \text{Pd}(\text{II}) ) Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0%</td>
<td>75.0%</td>
<td>43.8%</td>
<td>56.2%</td>
</tr>
<tr>
<td>2</td>
<td>6.7%</td>
<td>93.3%</td>
<td>57.5%</td>
<td>42.5%</td>
</tr>
<tr>
<td>3</td>
<td>17.5%</td>
<td>82.5%</td>
<td>73.3%</td>
<td>26.7%</td>
</tr>
<tr>
<td>4</td>
<td>90.3%</td>
<td>9.7%</td>
<td>91.8%</td>
<td>8.2%</td>
</tr>
</tbody>
</table>
Conclusions

In this study, the capability of [Pd(Me₂dazdt)₂][I₃]₂, the leaching product of a sustainable Pd-recovering method from TWCs, to act as a suitable metal precursor for a photo-reforming catalyst was demonstrated. The prepared photo-catalyst showed an 80% enhanced activity in H₂ production from methanol and glycerol with respect to other catalysts prepared starting from commercially available Pd-salts. This amazing application of [Pd(Me₂dazdt)₂][I₃]₂ allowed us to design a virtuous “recovery and re-employment” process based on the green leaching of palladium from TWCs and allowed further valorization of the obtained product in the challenging renewable energy field.

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Notes and references


