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Ultrasound assisted synthesis of Ag-decorated TiO₂ active in visible light

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Abstract

Titanium dioxide is the most popular photocatalyst to degrade organic pollutants in air, as well as in water. The principal drawback preventing its commercial application lies in its limited absorption of the visible light (400-700 nm), while it is active under UV irradiation (≤ 387 nm). Supporting noble metals in the form of nanoparticles on TiO₂ increases its activity in the visible range. However, both the synthesis of noble metal nanoparticles and their deposition on TiO₂ are multi-step processes that often require organic solvents. Here, we deposit Ag nanoparticles from AgNO₃ on the surface of micrometric TiO₂ with H₂O as a solvent and under ultrasound irradiation at 30 Wcm⁻². Ultrasound increases the surface amount of Ag on TiO₂ with heterogeneous size distribution of Ag nanoparticles, which are bigger and overlaid (1-20 nm vs. 0.5-3 nm) compared to the sample obtained in traditional conditions (TEM images). While this change in morphology had no effect on acetone photodegradation under UV light, the 5 %, 10 %, and 20 % Ag-TiO₂ degraded 17 %, 20 % and 24 % acetone under visible light, respectively. The 10 % by weight Ag-TiO₂ sample obtained in absence of ultrasound only degraded 14 % acetone in 6 h, while the bare TiO₂ was not active.

Keywords

Ag-TiO₂; ultrasound; One-step deposition; Ag nanoparticles; Visible light photocatalysis; micrometric TiO₂;

1. Introduction

Titanium dioxide photocatalysis emerged in the 80' as an approach to degrade water and air pollutants exploiting sunlight as a free energy source [1]. Light with energy greater than the band-gap of TiO_2 excites electrons from the valence band to the conduction band (e_{CB}^-), generating a positive hole in the valence band (h_{VB}^+). Part of these charged species migrate to the semiconductor surface and react with water to produce $\cdot\text{OH}$ radicals [2], which oxidize organic pollutant to degradation intermediates, or, in the best scenario, they mineralize them [3]. Volatile organic compounds (VOCs) include hydrocarbons, ethers, ketons, aldehydes and, chloro-containing molecules among others. VOCs concentration is from 2 to 5 times higher in indoor environments compared to outdoors and may reach 1000 times the concentration at the background level outdoor after use of VOCs containing products, i.e. paints, cleansers, disinfectants, etc. [4].

The band gap of TiO_2 (3.2 eV) is such that only UV light (≤ 387 nm) provides sufficient energy for the electron transfer to the conduction band. Since ultraviolet light makes up only 4–5 % of the solar spectrum and lighting in indoor environments emits in the visible range, the wide adoption of TiO_2 for photocatalytic applications is limited. Beside this aspect, electron-hole charge recombination is a major weakness as it reduces the overall quantum efficiency [5]. Noble metals like Ag, Au, Pt and Pd deposited on TiO_2 surface act as an electron trap [6], thus stabilizing the interfacial charge transfer [7], lowering the chances of e^-/h^+ recombination [8]. For example, Mohite et al. [9] prepared Au doped TiO_2 thin films by spray pyrolysis, decreasing the band gap and increasing the photoelectrocatalytic degradation of benzoic acid under UV light illumination of 49 %. Even metal oxides such as WO_3 improve the photocatalytic activity of TiO_2 under solar light, as recently reported by Hunge et al. [10, 11].

Seery and co-authors report Ag modified TiO_2 with increased visible light activity compared to bare TiO_2 [12] due to the surface plasmon band of Ag, which absorbs in the visible spectrum [13]. The scientific literature is rich of procedures and data on the synthesis of Ag NPs supported on TiO_2 . Examples include impregnation from Ag colloidal dispersions [14] or from Ag inorganic salts [15, 16], electrostatic self-assembly [17], and photo-reduction of Ag salts [18]. Only few manuscripts deal with the ultrasound-aided synthesis of supported Ag particles. Liu et al. synthesized nanofiber-supported Ag particles in the presence of different reducing agents, including short-chain alcohols and nitrogen compounds [19]. Ye at al. deposited Ag seeds on the surface of $\text{SiO}_2/\text{TiO}_2$ core-shell composites in a multi-step process, growing them to the structure of Ag shells with formaldehyde as a solvent [20]. However, none of them specify the ultrasound (US) operating conditions (e.g. power and frequency). Moreover, they both deposit Ag in the presence of organic solvents.

Sakkas et al. report the decoration of M- or MO-NPs by means of US in aqueous or organic solution containing dispersed ceramics or polymers in powder form [21].

US has a potential to impact every stage of the preparation of a material in liquid phase. US produces nanomaterials in amorphous state (due to the very high cooling rates) [22], or stabilizes crystalline phases [23] which is relevant to fields such as catalysis, magnetism and coating processes. US generates shock waves that facilitate coating and insertion/intercalation processes and improves the distribution of the active phase on a support [24]. The mechanical waves increase nucleation production rate (i.e., in the sol-gel process) and develop defects and deformations of solid surfaces, creating additional surface area and exposing active and selective catalytic sites [25]. Despite its undisputable advantages, US is a technique that is still unexplored in the synthesis of an enormous number of materials. Ultrasonic-synthesis may refer the manufacture of inorganic and organic materials or their deposition on supports, including metal oxides [21], and metallorganic compounds [26]. Other US-aided techniques comprise the modification of the structure and/or the morphology of already formed materials, for instance through the re-dispersion of the supported phase [27].

We recently made the choice to adopt micro-particles [28] because nanopowders exhibit potential risks in terms of dispersibility [29], ecotoxicity [30], persistency [31], and bioaccumulation [32]. The International Agency for Research on Cancer (IARC) classified ultrafine TiO_2 as possible carcinogenic to humans (IARC, 2010). Papers reporting synthesis of micrometric particles of TiO_2 are still few. Liu et al. reported the synthesis of porous TiO_2 microsphere [33]. However all the other data refer to sub-micrometric powders [34, 35]. We first pioneered the photocatalytic application of commercial micrometric TiO_2 and proved that is as efficient as the nanometric TiO_2 [36, 37]. Finally, in a recent work, we synthesized Cu NPs supported over micrometric TiO_2 : while the bare micro-metric TiO_2 is inactive under visible light, the 40 % by weight Cu- TiO_2 sample degrades 28 % acetone in 6 h [38].

Here, we report the one-step US-assisted synthesis of Ag NPs. Our work is innovative for the following aspects: i) We are the first to report the ultrasonic synthesis of Ag- TiO_2 and we explicit US operating conditions; ii) Water is the solvent, which eliminates organic solvent disposal issues; iii) The support are micro-sized TiO_2 spheres as an alternative to nano-sized TiO_2 , differently from the quasi-totality of the reported data .

The data reported in this manuscript show how the photocatalytic activity under visible light increases for the samples obtained with ultrasound.

2. Experimental

2.1 Materials

The support was TiO₂ (1077, KRONOS Worldwide, Inc.), which is pure anatase as of its crystallographic structure. We characterized it in a previous work [37], and here we summarized the main features (Tab. 1).

BET surface area (m ² g ⁻¹)	Particle size range (nm)	XPS Ti 2p _{3/2} (eV)	XPS OH/O _{tot}	Band gap (eV)
12 ± 2 m ² g ⁻¹	110 - 130	458.4	0.32	3.15

Tab. 1 TiO₂ (1077, KRONOS Worldwide, Inc.) features.

Silver nitrate (AgNO₃, ACS Reagent, ≥ 99 %) was the metal precursor. The other reagents were polyvinylpyrrolidone (PVP40, average mol wt 40,000) and sodium borohydride (NaBH₄, ≥ 99 %). The model compound for the photocatalytic degradation tests was acetone (CHROMASOLV® Plus, for HPLC, ≥ 99.9 %).

2.2 Synthesis of Ag-TiO₂

We followed the synthesis reported by Goharshadi et al. [39] to decorate the micro-sized TiO₂ with Ag nanoparticles (NPs). The precursor solutions were two: the first solution contained AgNO₃, polyvinyl pyrrolidone (PVP40, surfactant) in the amount of 0.02 g, TiO₂ 1077, while the second was a NaBH₄ 0.1 M. aqueous solution. AgNO₃ ranged from 0.02 g to 0.4 g, depending on the sample. The amount of TiO₂ was fixed at 2 g.

Ultrasound (US) irradiated the first solution for 10 minutes before the NaBH₄ solution was added in 2 min. Afterwards, the sonication was maintained for 60 minutes at the same power. Ag⁽⁰⁾ forms with the following reaction: $\text{AgNO}_3 + \text{NaBH}_4 + 3\text{H}_2\text{O} \rightarrow \text{Ag} + \text{H}_3\text{BO}_3 + \text{NaNO}_3 + 7/2 \text{H}_2$.

The finished powder was washed with distilled water 3 times, dried at 100 °C for 24 h, and calcined in static air at 400 °C, for 2 h.

We recently published a work on the ultrasound synthesis of Cu NPs supported on TiO₂, whereby Cu ranged from 1 % to 20 % [38]. In the present work, we made the choice of optimizing the Ag loading in the same range.

The US processor was a Bandelin SONOPLUS HD 3200 ultrasound generator with a nominal power of 200 W, equipped with a sonication horn (fixed frequency: 20kHz). The horn tip diameter was 13 mm, thus resulting in a power of 30 W cm⁻².

2.2 Catalyst characterization

The surface area of all the catalysts was measured by conventional N₂ adsorption (BET) at 77 K using a Sorptometer (Costech Mod. 1042).

A PW 3830/3020 X' Pert Diffractometer from PANalytical working Bragg-Brentano with the Cu K α 1 radiation ($k = 1.5406 \text{ \AA}$) analyzed the crystallographic composition. High-resolution transmission electron microscopy (HR-TEM, JEOL 3010-UHR Instrument, acceleration potential 300 kV, LaB6 filament) surveyed the surface of the particles. A Thermo Scientific Evolution 600 spectrophotometer equipped with a diffuse reflectance accessory Praying-Mantis sampling kit measured the absorbance, (Harrick Scientific Products, USA). The reference material was a Spectralon1 disk. The Kubelka–Munk function originated the plot of the experimental absorption versus the wavelength [40]. A M- probe spectrophotometer (Surface Science Instruments) measured the X-ray photoelectron spectra (XPS) absorbance. The source was a monochromatic Al K α radiation (1486.6 eV). The accuracy of the reported binding energy (BE) can be estimated at ± 0.2 eV. A Perkin Elmer Optima 8300 instrument carried out the ICP/OES analysis. The samples were first mineralized by nitric acid followed by microwave treatment.

2.3 Reactor design and photocatalytic tests

UV and visible light irradiated the samples to promote the degradation of acetone as a model compound. The setup for the photocatalytic tests consisted of a PIREX glass reactor (5 L volume), connected to a micro-gaschromatograph (Agilent 3000 A microGC), which quantified the acetone in the gas phase.

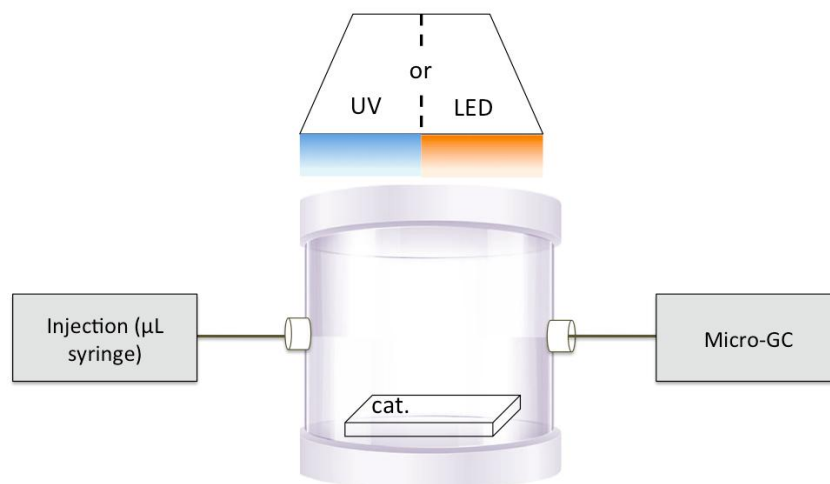


Fig. 1. Setup scheme.

The catalyst **was in the form of a thin film deposited** on a 100 cm² glass slab [41].

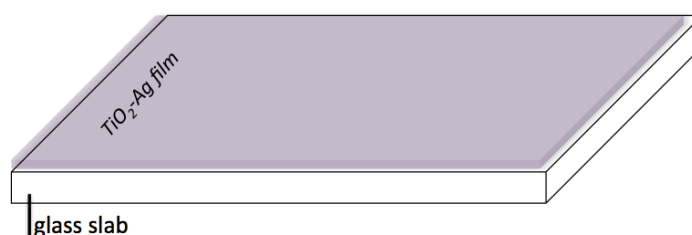


Fig. 2. TiO₂ catalyst deposited on glass slab.

The film was deposited as follows: 50 mg of powder **were suspended** in 10 ml of isopropanol. **Three layers of the suspension were deposited on the glass slab before each test and let dry.** The source of light was a UV lamp (Jelosil–Model HG-500, 500 W, $\lambda = 315\text{--}400$ nm) or LED (MW mean well, 350 mA rated current, 9–48 V DC voltage range, 16.8 W rated power) with light emission between 400 nm and 700 nm. **A radiometer measured** the irradiation power at the catalyst surface, so as to position the lamps at a distance resulting in an emission of 30 W cm⁻² for UV and 15000 lux for LED.

3. Results and discussion

3.1 Surface area and HR- TEM imaging

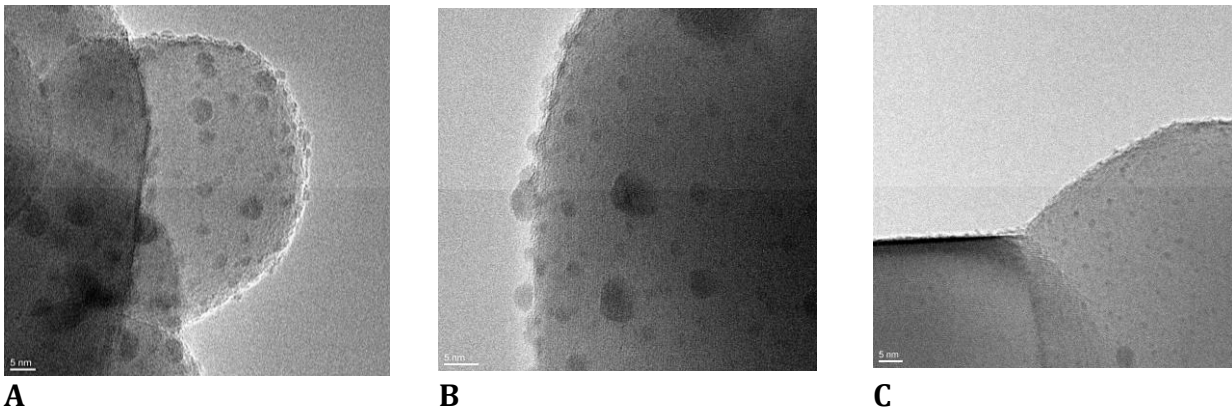


Fig. 3. HR- TEM images of TiO₂ decorated with Ag NPs (10 %) with (A, B) and without (C) US.

Surface area of bare TiO₂ was $12 \pm 2 \text{ m}^2 \text{ g}^{-1}$ and this value remained unchanged for all the samples decorated with Ag.

The HR-TEM imaging provides information on the particle size and distribution of Ag over TiO₂. The micro-sized dimension of TiO₂ is unchanged after ultrasound (US) treatment (Fig. 3). US does not therefore affect the morphology of the support, without significant surface erosion. However, US does modify the silver NPs morphology on the TiO₂ surface. Deposition of Ag by the traditional method (Fig. 3 C) resulted in a fine distribution of nano-disperse particles, ranging from 0.5 to 3 nm. Instead of increasing the dispersion, US had rather an effect on the amount of Ag loaded. US provoked the growth of Ag crystallites over the surface of TiO₂ in the form of aggregates. The overlapped Ag NPs, thus expanded in different dimensional ranges, from 1 to 20 nm (Fig. 3 A and 3 B). This is ascribable to the increased diffusion rate of the solute [23, 42]. The improved mass transfer between PVP and silver under the action of the mechanical waves facilitates the adsorption of Ag NPs onto the TiO₂ surface, resulting in the heterogeneity of the Ag NPs distribution on TiO₂ [43].

3.2 Crystallographic phase composition and XPS analysis

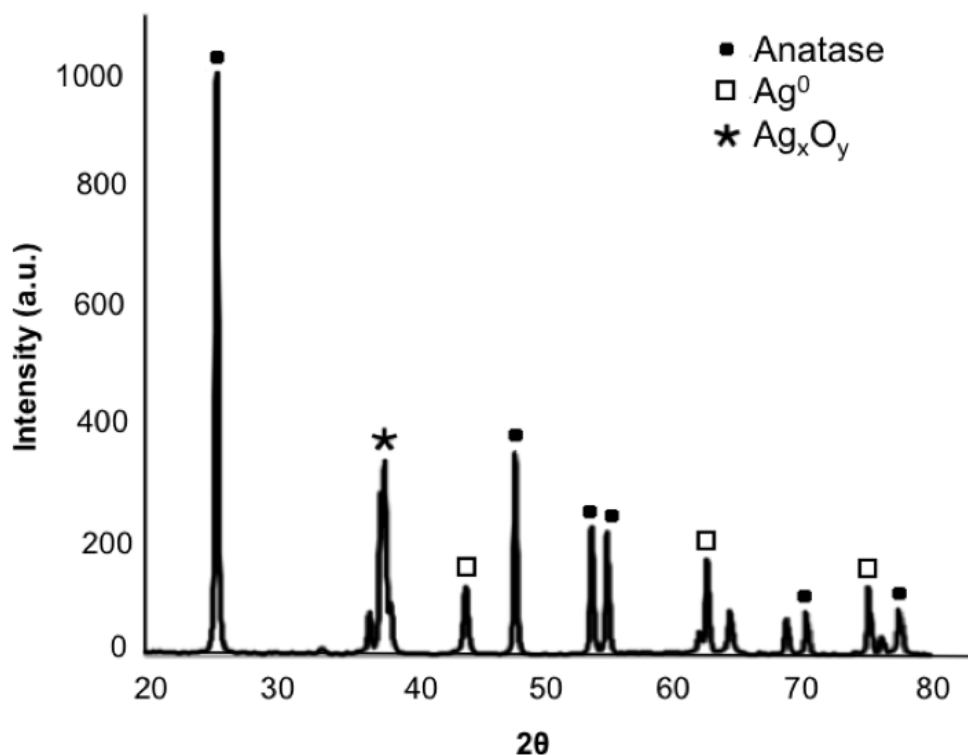


Fig. 4. XRD spectrum of Ag-TiO₂ 10 % synthesized by ultrasound.

We reported the spectrum of 10 % by weight Ag-TiO₂ as a representative for the Ag-TiO₂ samples. If decorated on the surface with Ag, the sample maintains the typical crystallographic phase composition of TiO₂ anatase, as reported by Bianchi et al. [36]. Peaks at 25 ° and 48° 2θ correspond to TiO₂ in the anatase phase (JCPDS no.: 88-1175 and 84-1286). Peaks at 2θ of 65°, 78°, 45° confirm the presence of metallic Ag, while the peak at a 2θ of 38 ° reveals the presence of Ag₂O, ascribable to the oxidation of Ag during the calcination.

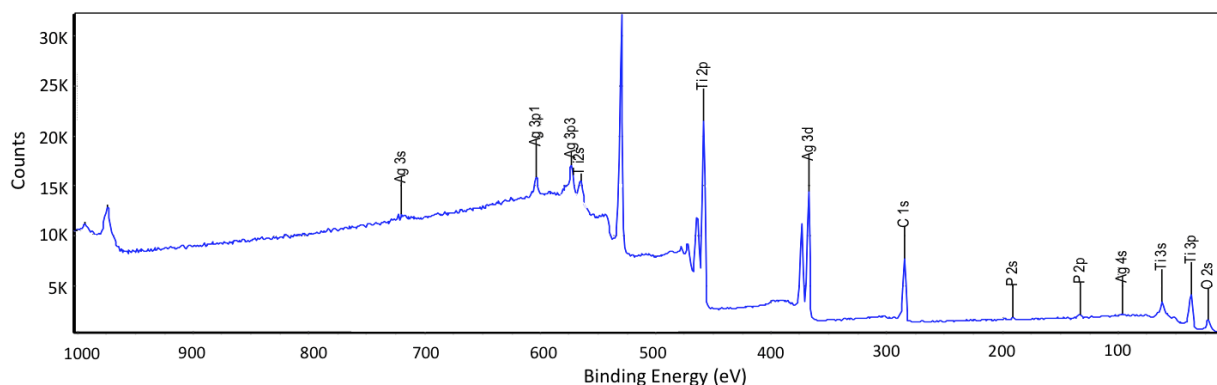


Fig. 5. XPS Survey analysis of Ag decorated TiO₂.

Silver - Ag		
$3d_{5/2} = 368.2 \text{ eV}$		
$\Delta = 6.0 \text{ eV}$		
	Oxidation state	Binding energy (eV)
Ag-TiO₂	Ag ²⁺ (AgO); Ag ⁺ (Ag ₂ O)	367.6 (± 0.8) eV

Tab. 2 XPS binding energy (eV) of metal and metal-oxides Ag from Handbook [44].

For Ag₂O and AgO the shifts are approximately -0.3 eV and -0.8 eV due to initial-state factors of ionic charge and lattice potential [45]. Thus, both binding energies for Ag₂O and AgO are similar. XPS survey analysis (Fig. 5) confirmed the presence of both Ag in metal and metal-oxide form, as expected after the calcination. Mostly Ag₂O contributes to increase the visible light absorption [46].

ICP analysis confirmed the % of Ag amount with an error <2 %.

3.3 UV-Vis absorption and band gap quantification

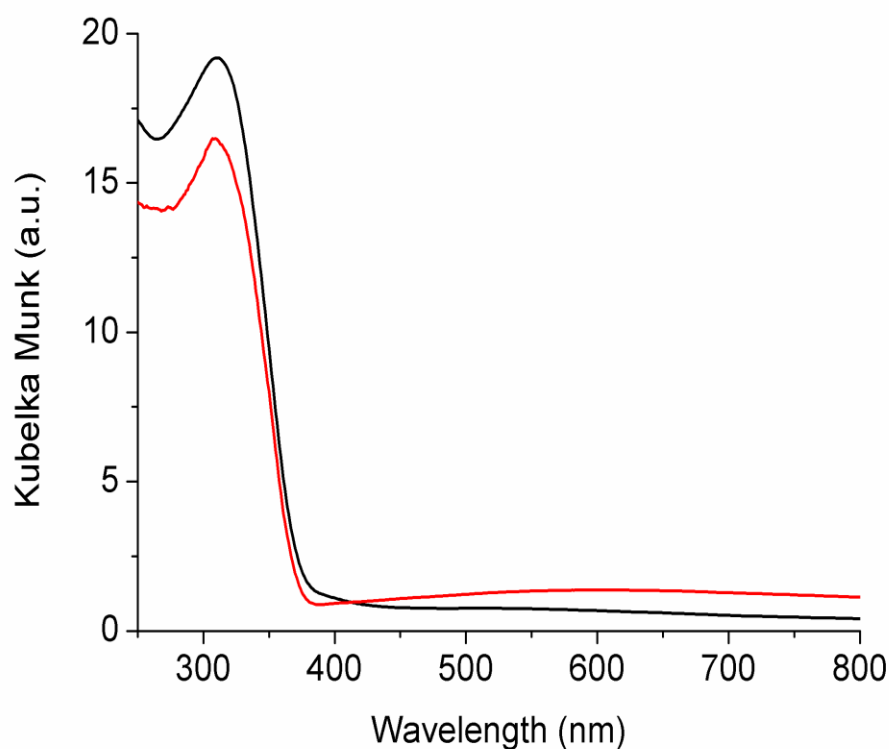


Fig. 6. Absorbance spectra in UV–VIS region of TiO₂ decorated with Ag NPs (10 %) with (red line) and without (black line) US.

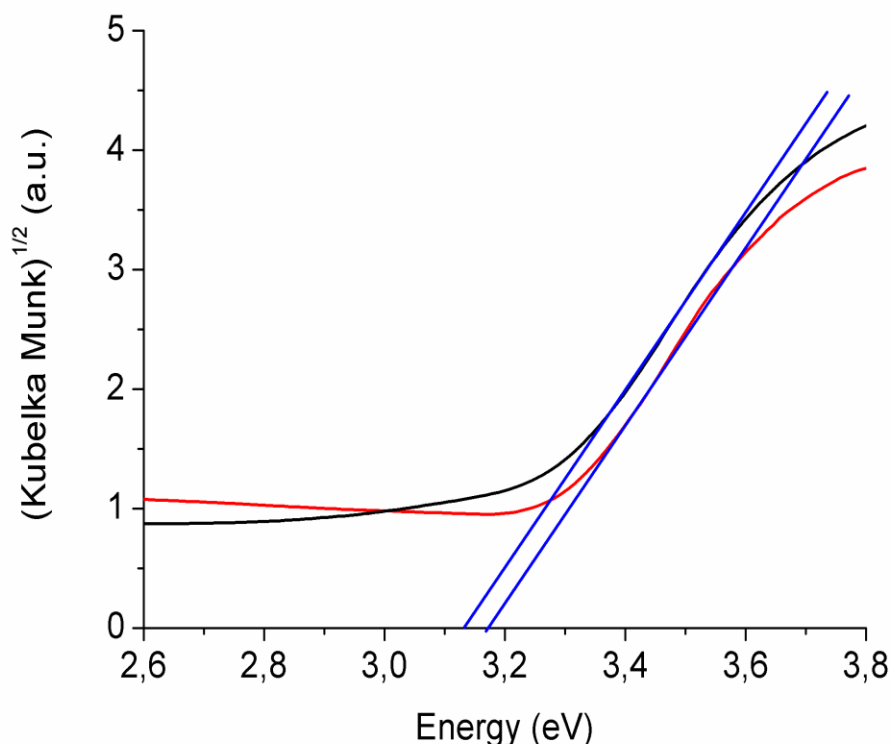


Fig. 7. KM^{1/2} vs. photon energy (eV) of TiO₂ decorated with Ag NPs (10 %) with (red line) and without (black line) US. Tangent lines (blue) intercept the band gap values on x-axis.

US mainly affected the size of Ag nanoparticles on TiO₂ surface (Fig. 3). UV-Vis spectra proved that this is the crucial feature to increase the adsorption at wavelengths in the visible range of 400 nm and 700 nm (Fig. 6).

Generally, noble metal nanostructures exhibit strong light absorption behavior due to the surface plasmon resonance (SPR) derived from the collective oscillation of surface electrons [47]. Several papers report the effect of Ag NPs on the Vis range light absorption [48], the improvement of the efficiency of thin film C-Si solar cell [49], or the light absorption enhancement of polymeric films [50], confirming that localized plasmonic resonances can be used as efficient light trapping region of Ag-TiO₂.

We observed a slight, but still significant reduction of the band gap. The UV-VIS absorption spectra were e-elaborated with the Kubelka Munk function (Fig. 7). Tangent line crosses x-axis at the band gap values, at 3.1 eV to 3.2 eV. The band gap decreases mainly because of the electronic defects introduced by Ag. Ag nanoparticles on TiO₂ are able to capture the electrons of the visible light, making them usable in the redox reactions that occur upon the surface.

Both metal and metal oxides are able to act as an electron trap, reducing the electron-hole recombination rate [51].

The so-called “antenna mechanism” refers to the electrons or holes transfer between some particles in contact; the particle on the semiconductor surface can act as much as electrons trap as holes trap, and the immediate effect is a better electron-hole separation [52].

This passage of electrons, assumed in the M-TiO₂ systems that are described in this paper, takes place thanks to the differences between the valence and conduction bands of the respective elements [53, 54]. The band gap of Ag_xO_y species ranges from 1.69 to 1.71 eV [55]. According to relative energy band positions between TiO₂ and visible-light-absorbing semiconductors, the coupling between Ag and TiO₂ formed an heterojunction.

3.4 Photocatalytic activity

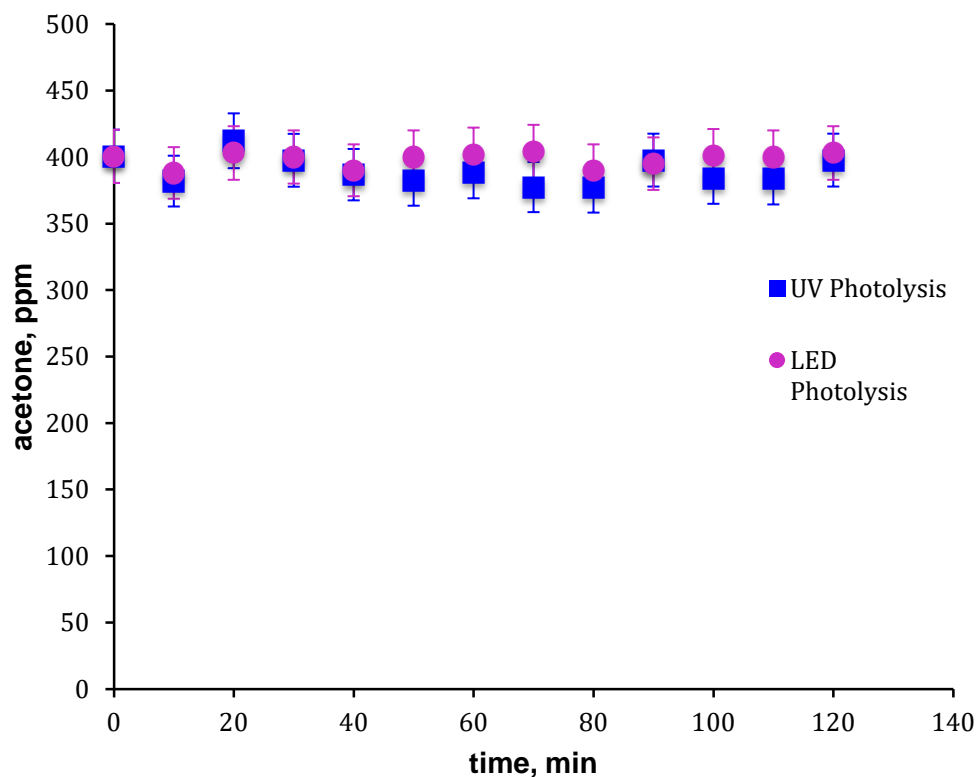


Fig. 8. UV and LED photolysis of acetone.

Photolysis is negligible being acetone concentration constant in time. Error bars ($\pm 5\%$) refer to the instrument resolution and their overlap is consistent with the oscillation of the concentrations.

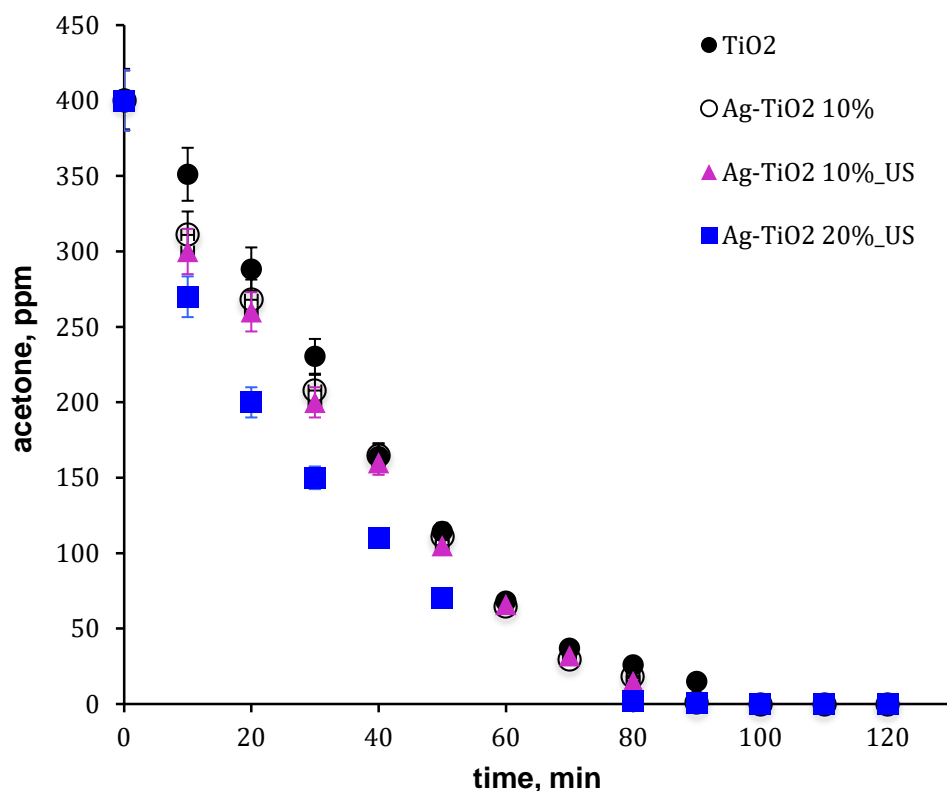


Fig. 9. Acetone photodegradation under UV-A irradiation (30 W cm^{-2}). Comparison between bare TiO_2 (black dots) and TiO_2 decorated with Ag NPs without US (empty dots) or by US (10-20 Ag %). Error bars refer to instrument resolution.

The commercial TiO_2 (Kronos) degrades acetone when irradiated by UV light according to the following oxidation pathway:



After 90 min, 100 % acetone was mineralized [37].

Sample	Acetone degradation rate ($\text{mg m}^{-3} \text{ min}^{-1}$) - UV irradiation	Acetone degradation rate ($\text{mg m}^{-3} \text{ min}^{-1}$) - LED irradiation
TiO2	$7.92 \text{ mg m}^{-3} \text{ min}^{-1}$	$0 \text{ mg m}^{-3} \text{ min}^{-1}$
Ag-TiO2 10 %	$7.92 \text{ mg m}^{-3} \text{ min}^{-1}$	$0.23 \text{ mg m}^{-3} \text{ min}^{-1}$
Ag-TiO2 5 %	--	$0.29 \text{ mg m}^{-3} \text{ min}^{-1}$
Ag-TiO2 10 %_US	$9.50 \text{ mg m}^{-3} \text{ min}^{-1}$	$0.36 \text{ mg m}^{-3} \text{ min}^{-1}$
Ag-TiO2 20 %_US	$10.56 \text{ mg m}^{-3} \text{ min}^{-1}$	$0.57 \text{ mg m}^{-3} \text{ min}^{-1}$

Tab. 3 Acetone degradation rates for photocatalytic reactions by UV (first column) and LED (second column).

In this case, we did not observe any photocatalytic activity under visible light up to 5 % of Ag loading (Table 3). The modification of Ag NPs morphology due to US application (see TEM, Fig. 3) does not have an impact on the degradation rate of acetone: the 10 % by weight sample synthesized with US degrades acetone at the same rate as the sample obtained with traditional impregnation (Fig. 9). Differently, the 20 % by weight Ag-TiO₂ sample completely degrades acetone in 20 min. This is ascribable to higher loading of Ag. The presence of Ag on the surface decreases the band gap (Fig. 7), thus the number of electrons that can be potentially promoted from the valence to the conduction band increases. On the other hand, a shorter band gap increases the e⁻/h⁺ recombination rate, which is unfavorable. However, according to our experimental data, the increased electron absorption seems not only to annul, but to overcome this drawback. For what concerns UV photodegradation the improvement in the photodegradation of organics is evident in terms of the reduced time to achieve the complete mineralization (Fig. 9).

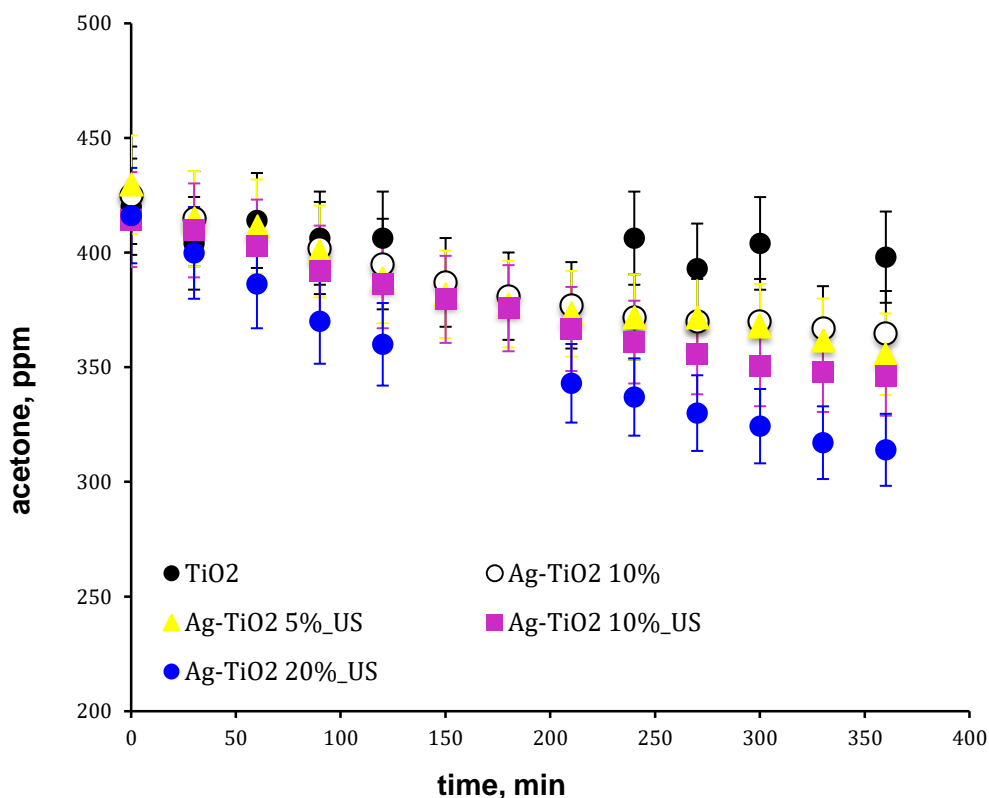


Fig. 10. Acetone photodegradation under LED irradiation using bare TiO₂ (black dots) or TiO₂ decorated with Ag NPs without US (white dots) or with US in the range 5 – 20 %.

Photodegradation under LED as the only source of light is in line with the characterization results. The almost absent activity of naked TiO₂ is indeed ascribable to its wide band gap of 3.2 eV. Visible light is in this case insufficient to excite electrons from the valence band to the conduction band (Fig. 10). Ag decoration introduces a tremendous improvement. Ag nanoparticles absorb visible light due to the plasmonic resonance; moreover, by settling on the TiO₂ surface they create a junction permitting the electron transfer from Ag to TiO₂. The number of electrons available at the surfaces therefore increases. As a consequence, the concentration of photo-generated species ($\cdot\text{OH}$ and $\text{O}_2\cdot^-$) at the TiO₂ surfaces is higher and the oxidation and reduction more likely to occur. Ag-TiO₂ absorbs beyond 400 nm (black line, Fig. 3), hence also the electrons of TiO₂ gain photo-energy because of the accumulative higher light absorption capacity. Moreover, Ag acts also as an electron sink, and this is the reason why the wider dimensions range of Ag nanoparticles play a crucial role, together with the Ag amount (Fig. 10).

4. Conclusion

We deposited 1 to 20 % by weight of Ag on micro-metric TiO₂ in one step either in presence of ultrasound or by traditional impregnation. We tested the photocatalysts in the degradation of acetone as a model compound under UV and visible light.

Under the tested conditions of 30 W cm⁻² for 70 min, ultrasound increases the Ag surface loading on TiO₂ by acting on the size of Ag crystallites, which are heterogeneous compared to the traditional impregnation: Ag aggregates ranged from 1 to 2 nm vs. 0.3 to 3 nm.

Ultrasound increases the Ag surface loading on TiO₂ by acting on the size of Ag crystallites, which are heterogeneous compared to the traditional impregnation: Ag aggregates ranged from 1 to 2 nm vs. 0.3 to 3 nm.

While the degradation of acetone under UV light only depended on the Ag loading and was the highest for the 20 % by weight Ag-TiO₂ sample, under visible light the samples obtained with ultrasound were more active. In 6h they degraded 3 to 11 % more acetone compared to the samples synthesized with traditional impregnation in 6 h

The advantages of micro-metric TiO₂ over nano-metric TiO₂ are several. Micro-metric TiO₂ (e.g. Kronos TiO₂) costs 10 times less than the nano-metric P25. Moreover, micro-metric TiO₂ is safer than nano-metric powders, because it eliminates the health risks related to inhalation.

Therefore, Ag deposited over micrometric TiO₂ is a viable and safer alternative to the nanometric TiO₂ as a photocatalyst. Moreover, Ag makes it active under visible light.

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Graphical Abstract

