Photocatalytic Selective Reduction by TiO$_2$ of 5-Nitrosalicylic Acid Ethyl Ester: A Mild Route to Mesalazine

A. Molinari[1] · M. Mazzanti[1] · M. Fogagnolo[1]

Abstract

Photoexcited TiO$_2$ dispersed in a de-aerated acetonitrile/2-propanol (CH$_3$CN/2-PrOH) reaction mixture catalyzes the quick and selective reduction of 5-nitrosalicylic acid methyl ester to the corresponding aniline, an immediate precursor of the drug mesalazine. The transformation is selective also when the starting concentration of nitro compound is increased by orders of magnitude and occurs at room temperature and atmospheric pressure. The photocatalyst can be reused. The photocatalytic reaction can be carried out also under aerated conditions without any loss in selectivity and efficiency. All these factors point out the feasibility of this important synthesis under mild conditions.

Graphic Abstract

photocatalysis in greener conditions than
catalytic hydrogenation with noble metals
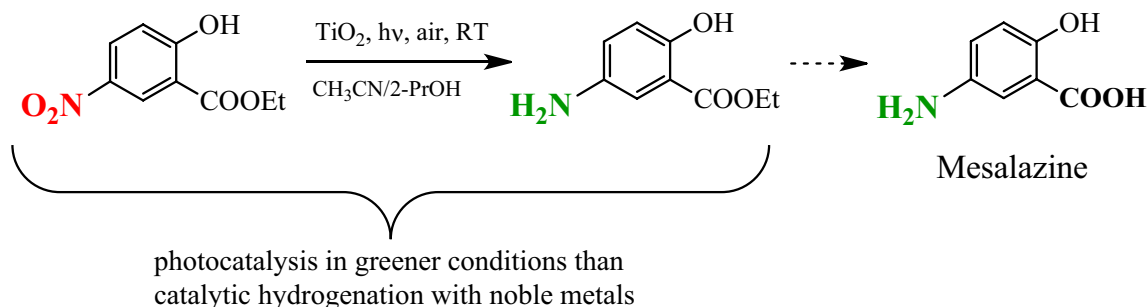
Keywords Heterogeneous photocatalysis · TiO$_2$ · Mesalazine · Nitrosalicylic acid · Mild conditions

✉ A. Molinari
  Alessandra.molinari@unife.it

  M. Mazzanti
  michele.mazzanti@unife.it

  M. Fogagnolo
  marco.fogagnolo@unife.it

[1] Dipartimento di Scienze Chimiche e Farmaceutiche, Università degli Studi di Ferrara, Via Luigi Borsari 46, 44121 Ferrara, Italy

1 Introduction

Mesalazine (5-aminosalicylic acid) is an important building block in dye industry. In fact, this molecule can be used to make a variety of reactive dyes with good quality because of three functional groups present on the aromatic ring. Most importantly, 5-aminosalicylic acid is one of the preferred drugs for the clinical treatment of inflammatory bowel diseases, such as Crohn disease. For the pharmaceutical industry alone, the needs are up to several hundred tons/year [1–3].

For this reason, it is of particular significance to improve the preparation method of this drug lowering environmental impact and costs. At present, a main manufacturing technique for 5-aminosalicylic acid includes

2 Experimental

2.1 Materials

TiO$_2$ P25 (Evonik) employed throughout this work is a commercial photocatalyst. Solvents, such as acetonitrile (CH$_3$CN) and 2-propanol (2-PrOH), were purchased from Sigma and used without further treatments. 5-nitrosalicylic acid is commercial from Fluka. Ethyl 5-nitrosalicylate and ethyl 5-aminosalicylate are synthesized as described in the following.
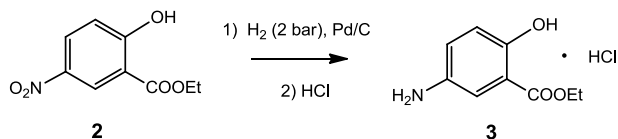
2.2 Methods

Mass spectra were recorded using a LCQ Duo (Thermo-Quest, San Jose, CA, USA), equipped with an electrospray ionization (ESI) source. Irradiation was carried out by using a Helios Italquartz Q400 medium pressure mercury lamp (400 W) selecting wavelengths higher than 360 nm with a cut off filter (15 mW/cm^2). The incident flux was 2.75×10^{16} photons s^{-1} cm^{-2}, calculated from the measured radiant power density in mW cm^{-2} [20]. UV–vis spectra were recorded by a spectrophotometer Jasco V-630. ^{1}H NMR spectrum was recorded on 400 MHz spectrometer at room temperature. Chemical shifts are given in parts per million (ppm); J values are given in hertz (Hz). Infrared spectra were obtained with a Nicolet 510P FTIR instrument in KBr, fitted with a Spectra-Tech collector diffuse reflectance accessory (range 4000 to 200 cm^{-1}).

2.3 Synthesis of Ethyl 5-Nitrosalicylate
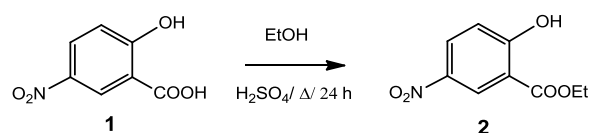
Synthesis of compound (**2**) is mandatory because of the strong adsorption of (**1**) on TiO$_2$ surface as explained below in Sect. 3. For the preparation of ethyl 5-nitrosalicylate (**2**), concentrated H$_2$SO$_4$ (0.5 mL) is added to a solution of (**1**) (1.5 g, 8.2 mmol) dissolved in absolute ethanol (20 mL) and the reaction mixture is refluxed for 24 h. The mixture is then cooled to ambient temperature and a solid is recovered by filtration and washed (3 × 2 mL cold ethanol). The amount of (**2**) obtained is 1.34 g (83% yield). ^{1}H-NMR (400 MHz, CDCl$_3$) δ: 11.57 (s, 1H), 8.79 (d, J = 2.8 Hz, 1H), 8.32 (dd, J = 9.2, 2.8 Hz, 1H), 7.08 (d, J = 9.2 Hz, 1H), 4.48 (q, J = 7.1 Hz, 2H), 1.47 (t, J = 7.1 Hz, 3H). See Supplementary Information (Fig. 1S).

catalyzed Kolbe–Schmidt reaction, starting from p-aminophenol or p-acetaminophenol. A gas phase catalytic carboxylation reaction in the presence of a basic compound under conditions of high temperature (493 K) and pressure (0.5–5.0 MPa) has been recently patented [2]. Other proposed pathways include electrochemical reduction of an azo compound obtained from the reaction between salicylic and sulphanilic acid [4, 5]. However, all of the above processes suffer from certain limitations, including high energy consumption, long reaction times, low yields, complicated operation and pollution-causing tendencies. Therefore, they haven't been implemented so far. Catalytic hydrogenation represents an important improvement, but conventional systems require high H$_2$ pressure (> 5 bar), high reaction temperature (> 373 K), noble metal catalyst. Moreover, the shown chemoselectivity is usually poor.

It is well known that heterogeneous photocatalysis often offers an alternative green route for replacing hazardous processes with pathways of low environmental impact and allows the synthesis of valuable compounds by shorter reaction sequences than conventional routes [6–8]. On this account, and in view of the above mentioned drawbacks concerning mesalazine synthesis, we are interested here in demonstrating the feasibility of a mild method of synthesizing 5-aminosalicylic acid that does not need the presence of any metal. Our project stems from the possibility of reducing nitroaromatic compounds to the corresponding anilines by photoexcited TiO$_2$. It has been reported in literature that this transformation can be accomplished in organic media by the UV excitation of the semiconducting oxide dispersed in the reaction mixture containing an alcohol as sacrificial reducing agent for photogenerated holes [6–12]. The additional presence of a sulfonic acid group allows to perform the reaction in an aqueous environment with low pH, using formic acid as holes scavenger [13]. When other reducible functionalities are present in the nitroaromatic compound [14, 15], chemoselectivity can be reached by a controlled tailoring of the energetics of TiO$_2$ [12, 13, 16–19]. Among all the investigated nitroaromatic compounds, results about photocatalytic reduction of 5-nitrosalicylic acid have never been reported in literature.

Herein, for the first time we report that photoexcited TiO$_2$ dispersed in a de-aerated reaction mixture made of an organic solvent and 2-propanol as sacrificial reagent catalyzes the quick and selective reduction of 5-nitrosalicylic acid methyl ester to the corresponding aniline. The product obtained by the photocatalytic process has been compared with that prepared by conventional synthesis and fully characterized by ESI–MS and ^{1}H NMR. Effect of the presence of O$_2$ is also reported. The selectivity is maintained also when the starting concentration of nitro compound is increased up to two orders of magnitude.

2.4 Conventional Synthesis of Ethyl 5-Aminosalicylate

The solid catalyst Pd/C (10%, 20 mg) is added to a THF/MeOH (2/1) solution (20 mL) containing (**2**) (0.5 g, 2.5 mmol). The reaction mixture is put in an autoclave under pressure of H$_2$ (2 atm) for 12 h at T = 318 K. Then the mixture is filtrated and concentrated under reduced pressure. The solid is re-dissolved in diethyl ether and treated with gaseous HCl. Product (**3**) is recovered as hydrochloride (0.37 g, 90%). ^{1}H-NMR (400 MHz, CD$_3$OD); δ: 7.80 (d, J = 2.8, 1H), 7.43 (dd, J = 8.8, 2.8 Hz, 1H), 7.07 (d, J = 8.8 Hz, 1H), 4.45 (q, J = 7.2 Hz, 2H), 1.42 (t, J = 7.2 Hz, 3H). See Supplementary Information (Fig. 2S).

2.5 Photocatalytic Experiment

Typically, commercial P25-TiO$_2$ (10 mg) is suspended in the mixture CH$_3$CN/2-PrOH (4/1, 3 mL) containing (**2**) (1×10^{-4} M), prepared as described above. The suspension is put in a spectrophotometric cell (with an optical path of 1 cm) together with a magnetic bar. Then the cuvette is closed with a septum and degassed by N$_2$ bubbling (20 min) and irradiated under magnetic stirring by using a medium pressure mercury lamp equipped with a cut off filter (λ > 360 nm).

At the end of the irradiation, the solid photocatalyst is separated from the solution by centrifugation and the solution has been analyzed by UV–vis spectrophotometry and ESI–MS. When requested, starting concentration of (**2**) was 1×10^{-3} M or 1×10^{-2} M. In addition, analogous experiments have been carried out under air atmosphere. Concentrations of (**2**) and (**3**) are calculated from absorbance variations at 300 nm and 360 nm respectively. Determination of ε_{300} and of ε_{360} values has been obtained from calibration curves built by using the synthesized compounds (**2**) and (**3**).

The employed amount of P25 TiO$_2$ (3 g/L) warrants the absorption of more than 90% of the impinging radiation. Text experiments on the reuse of the photocatalyst were performed washing twice TiO$_2$ P25 with the solvent mixture, calcining (500 °C, 30 min) and using in a photocatalytic experiment. At the end of irradiation, TiO$_2$ is recovered by centrifugation, washed, calcined and reused in a subsequent photocatalytic experiment.

Yield of the process has been evaluated as follows: the photocatalytic experiment with a starting concentration of (**2**) of 1×10^{-3} M has been repeated ten times. In each repetition the irradiation time was 1200 s. Irradiated organic mixtures were put together and the solvents evaporated. A solid mass was recovered, and the yield of the process has been estimated. The identity and purity of the crude product was established using ^{1}H NMR spectroscopy.

2.6 Infrared Measurements

The samples were prepared using an aliquot (10 mg) of TiO$_2$-P25, which was put in contact with a CH$_3$CN/2-PrOH (4/1) solution of 5-nitrosalicylic acid (or 5-nitrosalicylic acid ethyl ester, 1×10^{-4} M). The suspensions were stirred at room temperature until the evaporation of the solvent was complete. Then the powder impregnated with the nitrocompound was dried overnight in an oven. In the case of the irradiated experiments, TiO$_2$ (10 mg) was suspended in CH$_3$CN/2-PrOH (4/1, 3 mL) containing 5-nitrosalicylic acid or 5-nitrosalicylic acid ethyl ester (1×10^{-4} M). The suspension was degassed and irradiated (300 s, λ > 360 nm). After irradiation, the powder was recovered and dried in the oven overnight. For the sake of comparison, pure 5-nitrosalicylic acid and 5-nitrosalicylic acid ethyl ester have been also examined by IR technique.

3 Results and Discussion

3.1 Adsorption of Nitro-compounds (1) and (2) on TiO$_2$

Earlier (Sect. 2.3) we mentioned that the use of the nitrosalycilate derivative (**2**) is essential for the reduction of the –NO$_2$ functionality. The parent compound (**1**) is strongly adsorbed on TiO$_2$ as proved by both UV–vis (Fig. 3S) and FTIR spectra (Fig. 4S). The latter clearly reveal that adsorption occurs through both carboxyl and hydroxyl groups, confirming previous studies [e.g. 21, 22]. The –NO$_2$ group is not involved in adsorption (Fig. 4S) and, accordingly, no photoreduction of (**1**) to mesalazine takes place.

In contrast, IR measurements confirm that (**2**) interacts with TiO$_2$ surface through both OH and NO$_2$ group (Fig. 5S), as evidenced from the disappearance of the band relative to OH and from the shift of the asymmetric vibration wavenumber of the N–O bond from 1525 to 1518 cm^{-1}, in accordance with previous data on nitrobenzene adsorption on TiO$_2$ [11, 12, 22]. Photoreduction of (**2**) to ester form of mesalazine (**3**) does take place (vide infra), and the subsequent recover of the -COOH group from the ethyl ester is a routinary reaction.

3.2 Photocatalysis with TiO$_2$ in the Absence of O$_2$

Irradiation of TiO$_2$ dispersed in a degassed CH$_3$CN/2-PrOH (4/1) mixture containing the nitroester (**2**) leads to the
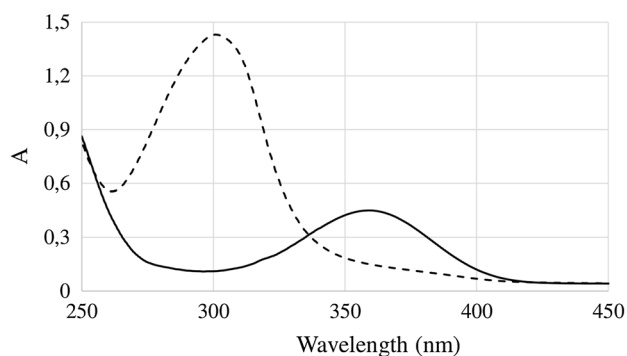
Fig. 1 Spectral variations obtained upon irradiation ($\lambda > 360$ nm) of TiO$_2$ (10 mg) suspended in a CH$_3$CN/2-PrOH (4/1, 3 mL) deaerated solution containing (**2**) (1×10^{-4} M). Dashed line is before irradiation and solid line is after irradiation
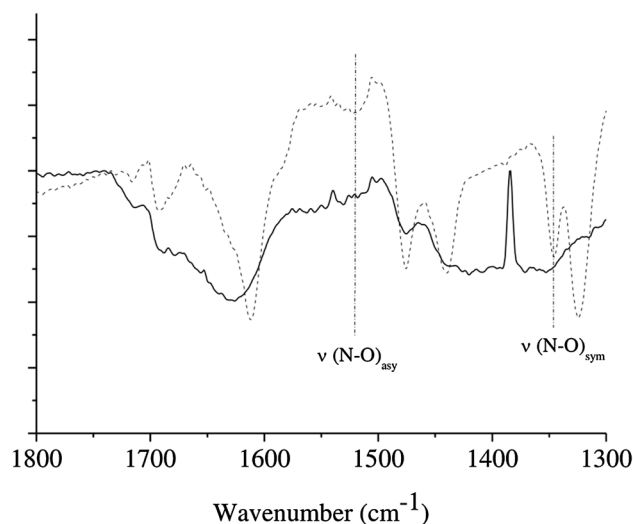

Fig. 2 Infrared spectra of 5-nitrosalicylic acid ethyl ester (**2**) adsorbed on TiO$_2$ before (dashed line) and after irradiation (solid line) respectively

spectral variations reported in Fig. 1: the starting electronic spectrum relative to compound (**2**) is disappeared and a new absorption band with a maximum at 360 nm is present after irradiation. These variations are in agreement with the conversion of (**2**) into a new species. Moreover, the addition of one drop of CF$_3$SO$_3$H causes a blue shift of the maximum to 305 nm and the subsequent addition of ammonia restores the old position of the absorption maximum at 360 nm. These variations can be tentatively ascribed to the acid/base behavior of a –NH$_2$ group present in the molecule. This acid/base response is suggestive of a reduction of the original –NO$_2$ group to –NH$_2$. Indeed, identical shifts are observed upon acid and base addition to a solution containing ethyl 5-aminosalycilate (**3**) prepared by the conventional reduction method that uses H$_2$ (data not shown).

The infrared spectra of 5-nitrosalicylic acid ethyl ester on TiO$_2$ before irradiation and after irradiation are reported in Fig. 2. It is observed that the stretchings assigned to N–O vibrations (1518 cm^{-1} and 1347 cm^{-1}) [11] are completely disappeared after irradiation, confirming that a reaction involving the nitro group occurred [21].

Positive ion mode ESI–MS spectrum of the sample after irradiation is reported in Fig. 3. A base peak at m/z 182 corresponds to protonated compound (**3**), definitely demonstrating that ethyl 5-nitrosalicylate undergoes reduction to the corresponding amino derivative by photoexcited TiO$_2$. The lowest-intensity peak at m/z 242 was assigned to the $[(\mathbf{3}) + 2\text{-PrOH} + \text{H}]^+$ species.

Figure 4 reports the concentration values of (**2**) and (**3**) as a function of time obtained upon irradiation of TiO$_2$ suspended in a de-aerated CH$_3$CN/2-PrOH (4/1) solution containing (**2**) (1.3×10^{-4} M). Under our experimental conditions, about 85% of the starting nitro compound (**2**) is transformed after 5 min irradiation. The decay curve of (**2**) is characteristic of first-order kinetics and the corresponding apparent rate constant is 0.011 s^{-1}. At the same time, the only photoreduction product accumulated in the liquid phase is species (**3**): in fact, the mass balance is higher than 90% at the end of irradiation. The photoprocess is quite fast because it implies an interaction of the nitro group with the surface in agreement with IR measurements and also with literature data concerning 4-nitrobenzaldehyde and nitrobenzene on TiO$_2$ [11, 16, 21, 23].

Similarly to what previously observed with TiO$_2$ and 4-nitrobenzaldehyde dissolved in the same reaction medium employed in this work [10, 19, 20], no reaction intermediates are detected during the multielectronic reduction process, implying that the reaction is fast and occurs on the surface of the semiconductor, inhibiting the accumulation of intermediate compounds in the reaction medium. Since, however, in some literature [10, 21] nitroso- and N-phenylhydroxylamine derivatives have been detected, one can expect that reduction of 5-nitrosalicylic acid ethyl ester likely occurs through the subsequent steps schematized in reaction sequence below:
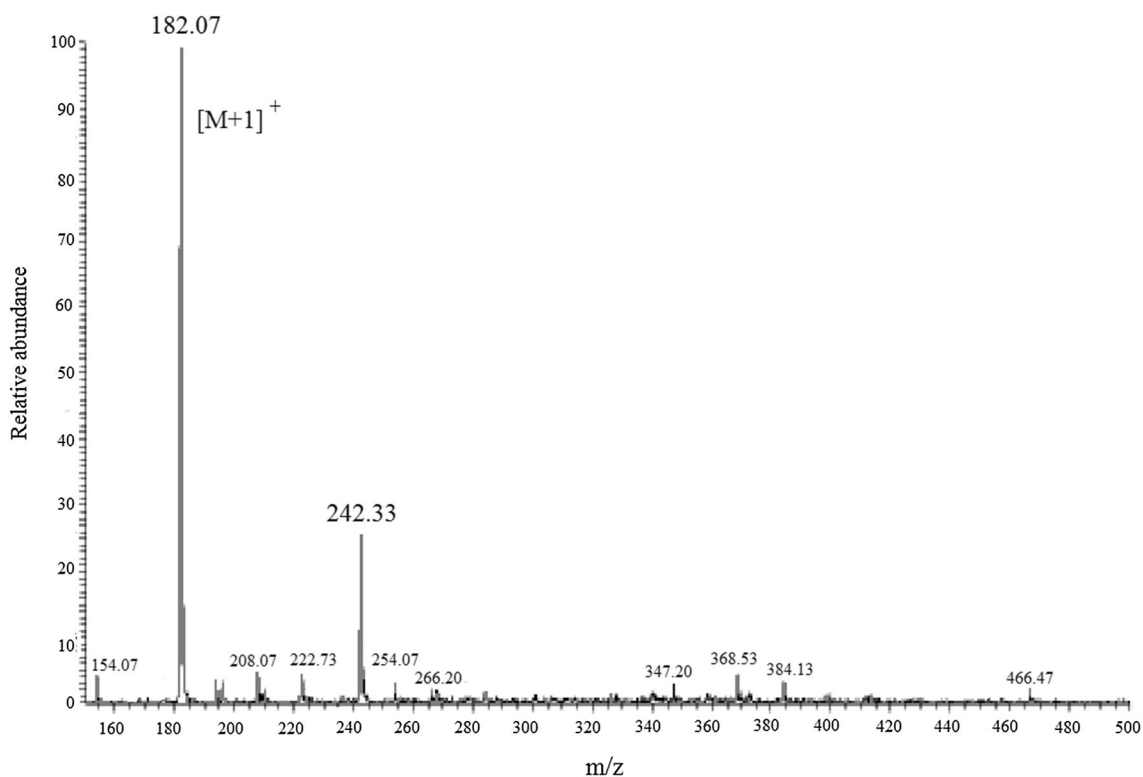

reaction intermediates

(1)
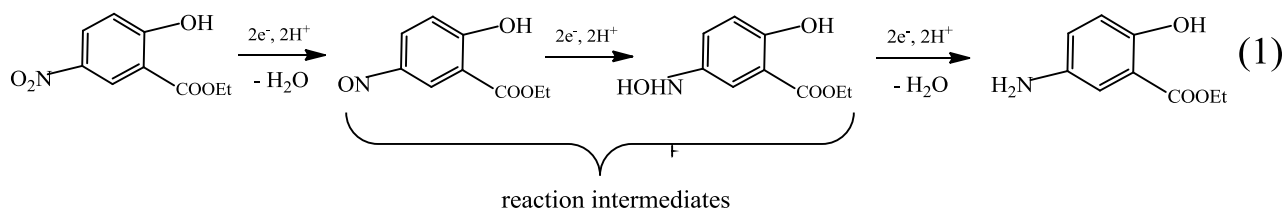
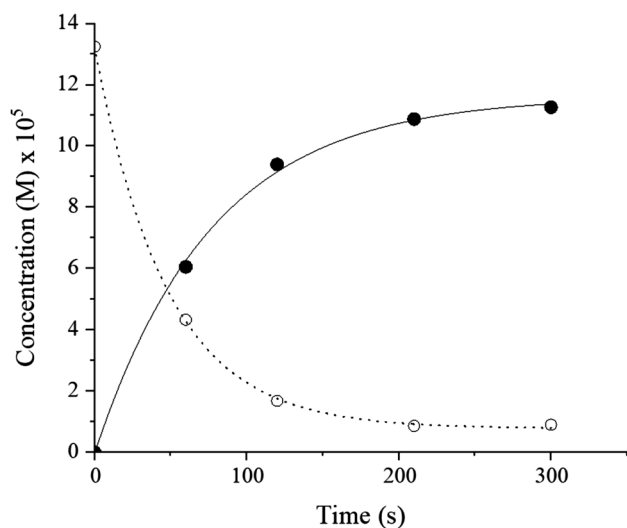**Fig. 3** ESI-MS spectrum of the solution after irradiation with TiO$_2$

Fig. 4 Time courses of the amounts of ethyl 5-nitrosalicylate (**2**) (1.3×10^{-4} M, empty circles) and of ethyl 5-aminosalicylate (**3**) (full circles) during irradiation (λ > 360 nm, 25 °C) of TiO$_2$-P25 (3.5 g L^{-1}) suspended in a degassed CH$_3$CN/2-PrOH (4/1) reaction mixture

Electrons and protons needed for the reduction of (**2**) to (**3**) are provided by the overall photocatalytic mechanism reported in Scheme 1. In fact, electrons are promoted in the conduction band of TiO$_2$ upon photoexcitation, while photogenerated holes are reduced by 2-PrOH [10, 19] which, in turn, undergoes oxidation to acetone via a radicalic process with the concomitant formation of protons.

Considering that the photoreduction of (**2**) is almost quantitative and that the alcohol is in large excess, two photocatalytic experiments were carried out in which the starting concentrations of (**2**) was 1x10^{-3} M and 1 × 10^{-2} M respectively. The courses of the reaction, i.e. the decrease of (**2**) and the increase of (**3**) during irradiation time, are reported in Fig. 5 (parts a and b respectively).

Likely due to the excess of holes scavenger, the increase of the starting concentration of nitroaromatic compound (**2**) does not alter the overall reaction mechanism, and the unique product observed is (**3**). The mass balance is almost complete demonstrating that conversion of (**2**) into (**3**) is still the only process that takes place. The main difference resides in the lengthening of irradiation times: in fact, when initial concentration of (**2**) is 1x10^{-3} M, a conversion of about 80% occurs after 1200 s. Moreover, with initial concentration of (**2**) of 1 × 10^{-2} M, after 6000 s of irradiation the observed conversion is low (19%).

The slowing down of the reaction could be ascribed to the decrease of the ratio between the mass of TiO$_2$ (3 g/L), constant in all these experiments, and starting concentration of (**2**). Since the reduction of nitro compound is a surface

Scheme 1 Representation of the photocatalytic processes
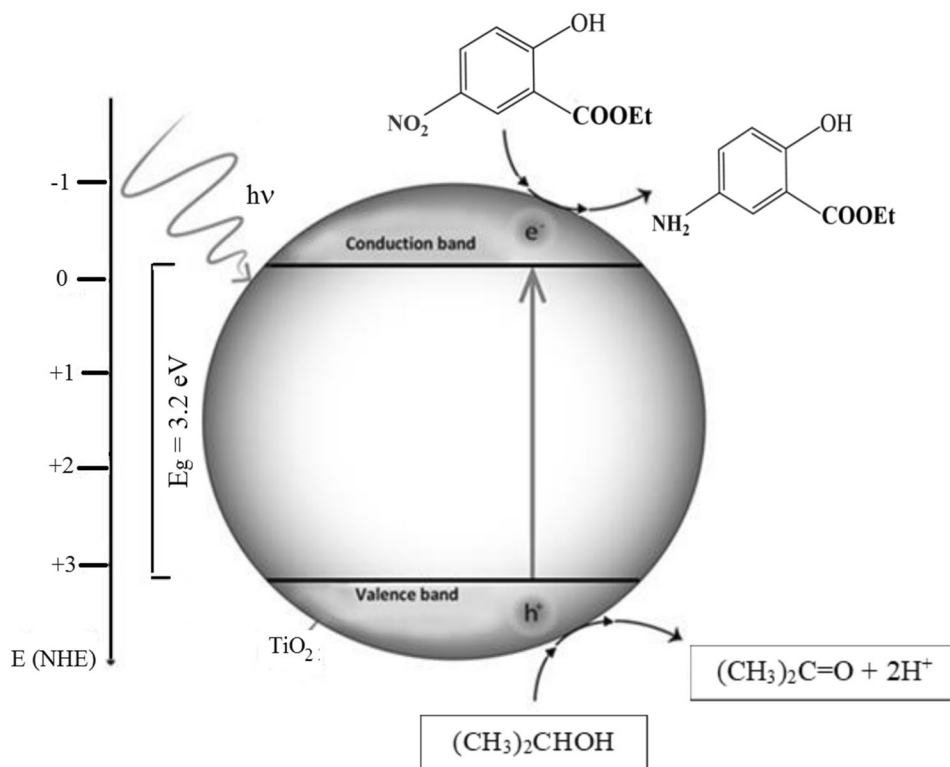
reaction and, as recently reported by Shiraishi et al. as well as by our group [11, 12], it occurs through surface defects, conspicuous accumulation of (**3**), slowly desorbing from the surface, prevents adsorption of new reactant molecules.

Although we are aware that a semiconductor suspended in a reaction environment does not represent the better way to scale up a reaction, these results clearly indicate that photoexcited TiO_2 is a very promising photocatalyst for the selective production of the drug mesalazine. Interestingly enough, following the procedure reported in Sect. 2.5, we estimate that reaction yield is almost quantitative. ^{1}H NMR spectrum of the crude product obtained after evaporation of the solvent (Fig. 6S), confirms that ethyl 5-amino-salicylate is produced. Its purity is high, because no evidence of both the starting nitro compound and some intermediates are present. Moreover, the ^{1}H NMR spectrum of the purified 5-amino-salicylate (see Sect. 2.3) contains the same signals of the spectrum of Fig. 2S, relative to 5-aminosalicylate hydrochloride obtained from conventional synthesis.

3.3 Photocatalysis with TiO₂ in the Presence of O₂

Some researchers previously reported a photocatalytic reduction of nitrobenzenes at TiO_2 occurring even under aerobic conditions [16].

If oxygen is present, formation of superoxide can occur

$$O_2 + e_{cb}^- \rightarrow O_2^{\cdot -} \tag{2}$$

at a potential of about -0.9 V vs. SCE for a metallic electrode in dry acetonitrile [24]. In these conditions, the potential for the one-electron reduction of some complex nitro-compounds is about -1 V [25]. In contrast to the case of metallic surfaces, we note that a comparable wealth of studies on the electrochemical O_2 reduction is not available for TiO_2; it is generally known that it is a good electron scavenger [26] and, in principle, O_2 might compete with the reduction of the nitroaromatic compound.

If protons are present, potentials are expected to be somewhat lower [27, 28], but more generally the process can be influenced by a number of other factors among which the nature of the catalyst material is important as it controls adsorption of the species.

Experimentally, we see (Fig. 6a) that O_2 does not affect greatly the formation of (**3**) when the starting concentration of (**2**) is 1×10^{-4} M. For a possible explanation, we remark that (**2**), strongly interacting with the surface, can more efficiently intercept protons generated at the surface by the alcohol oxidation (Scheme 1) than does the weakly physisorbed O_2 [26, 27]. Consequently, reduction of the latter to give adsorbed $HO_2^{\cdot}$ is negligible.
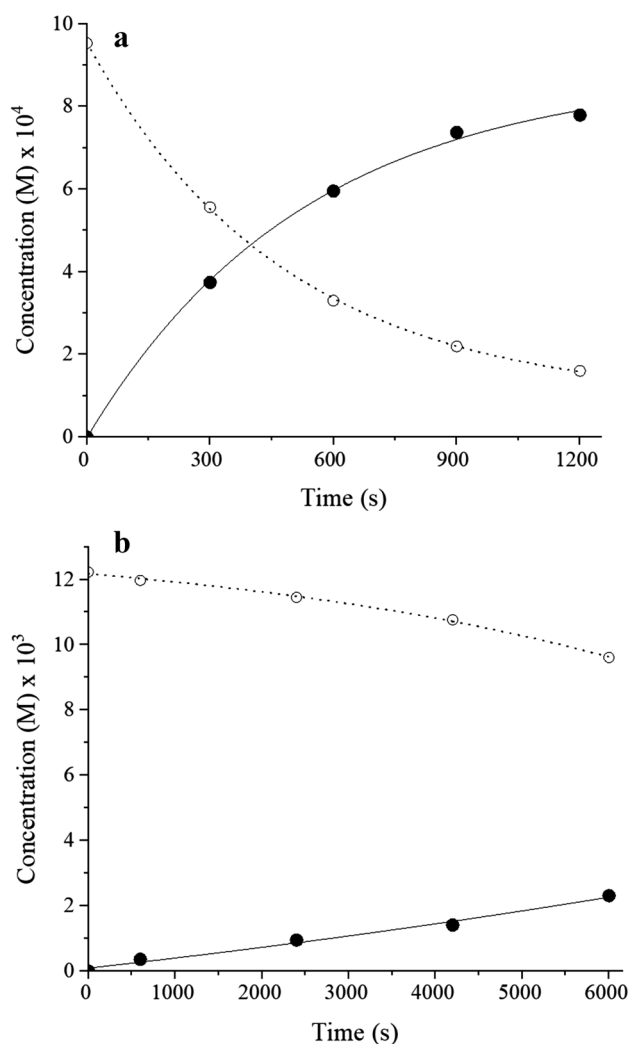
Fig. 5 Time courses of the amounts of ethyl 5-nitrosalicylate (**2**) (empty circles) and of ethyl 5-aminosalicylate (**3**) (full circles) during irradiation ($\lambda > 360$ nm, 25 °C) of TiO₂-P25 (3.5 g L^{-1}) suspended in a degassed CH₃CN/2-PrOH (4/1) reaction mixture. **a** Starting concentration of (**2**) is 0.95×10^{-3} M. **b** Starting concentration of (**2**) is 1.22×10^{-2} M

Fig. 6 Time courses of ethyl 5-aminosalicylate (**3**) during irradiation ($\lambda > 360$ nm, 25 °C) of TiO₂-P25 (3.5 g L^{-1}) suspended in CH₃CN/2-PrOH (4/1) reaction mixture in deaerated (full circles) or aerated (empty circles) conditions. **a** Starting concentration of (**2**) is 1.3×10^{-4} M. **b** Starting concentration of (**2**) is 0.95×10^{-3} M

On the contrary, when the concentration of (**2**) is increased up to 1×10^{-3} M, the presence of dioxygen slows down the formation rate of (**3**) and after 1200 s of irradiation the conversion is significantly decreased (Fig. 6b). A possible explanation in this case could lie in the fact that a high concentration of nitro compound leads to a noticeable accumulation of adsorbed amino derivative. Its slow desorption process would prevent a surface interaction of new reactant molecules thereby favouring the competing reduction of O₂. Reaction selectivity is maintained also in aerated conditions since there are no traces of either intermediates accumulation or parallel reactions between superoxide (or HO₂ radicals) and aminoderivative (**3**). Therefore, it is possible to state that selective photocatalytic reduction of (**2**)
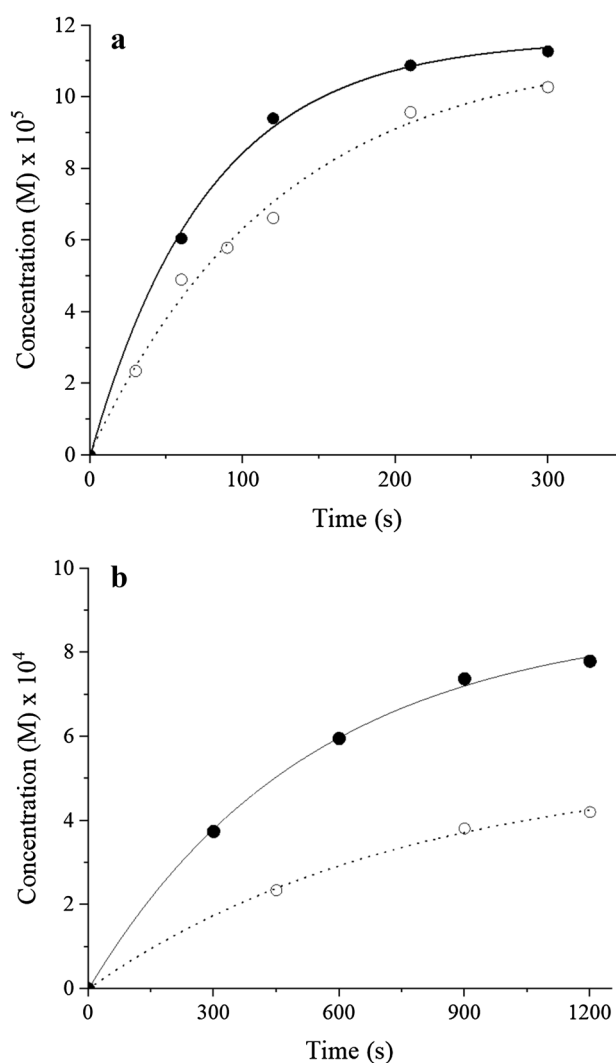
can be accomplished also under aerated conditions, opening a new mild route for the synthesis of mesalazine.

3.4 Stability of TiO₂

The recyclability of TiO₂ powder is evaluated following the procedure described below: the semiconductor powder is washed with the solvent mixture, calcined (500 °C, 30 min) and then used in a photocatalytic experiment. The treated TiO₂ is, in fact, suspended in a CH₃CN/2-PrOH (4/1) solution containing (**2**) (starting concentration is 1×10^{-3} M): the suspension is deaerated and illuminated (20 min, $\lambda > 360$ nm). At the end of the irradiation the photocatalyst is recovered by centrifugation from the reaction environment,
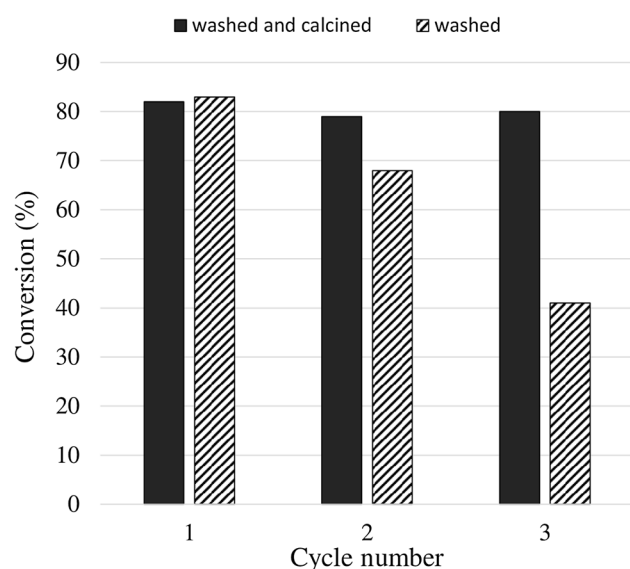
Fig. 7 Percentage of conversion of (**2**) after irradiation (20', λ > 360 nm) of TiO$_2$ P25 during consecutive runs. Starting samples are de-aerated CH$_3$CN/2-PrOH (4/1) solutions containing (**2**) (1 × 10^{-3} M)

washed two times with aliquots of CH$_3$CN/2-PrOH (4/1), calcined and reused in a subsequent photocatalytic experiment. Figure 7 shows that conversion efficiency of TiO$_2$ is maintained during the three runs investigated. Results obtained in parallel experiments where used TiO$_2$ is simply washed and not calcined point out a significant decrease in efficiency from one run to the following one. Considering that the transformation of nitro group into amino functionality is a multielectronic reaction, this decrease in efficiency can be tentatively ascribed to the formation of intermediates that remain adsorbed on the surface and that the washing is not able to remove. Interestingly enough, calcination is an efficient step to clean the TiO$_2$ surface making the photocatalyst reusable for several times without loss of activity.

4 Conclusions

In this work, we have demonstrated that photocatalysis by TiO$_2$ has a great potential for the selective reduction of nitrosalicylic acid ethyl ester to the corresponding amino derivative, immediate precursor of the mesalazine drug. An alcohol (2-PrOH) is used both as sacrificial hole scavenger and a proton source. Interestingly, the photocatalytic process is selective, mass balance is almost complete and although reduction of the nitro compound is a multielectronic process, the intermediates do not accumulate in the solution and remain on the TiO$_2$ surface. For this, the reaction is also fast. Moreover, the photocatalytic process can be carried out also

in the presence of O$_2$ without any decrease in the selectivity to the amino derivative.

The possibility of working under atmospheric aerated conditions underscores even more the greener nature of this important synthesis. In fact, the photocatalytic method requires operative conditions that are milder than those needed during catalytic hydrogenation, entails lower costs (no noble metals) and uses a commercial low cost, non-toxic and stable photocatalyst.

All these aspects highlight the potential of photocatalysis with TiO$_2$ in reduction processes for the synthesis of intermediates of pharmaceutical interest. Future perspectives will be addressed to a better exploitation of the solar light and to the possibility of using aqueous environment.

References

1. Lu H, Liu J, Xing C, Tan M, Gao F (2011) Asian J Chem 23:3819–3823
2. Lu G, Li J, Zhu D, Jiang Q, Cai L, Xie Y, Gan L, (2013) US Patent, #0281730A1
3. Breviglieri G, Giacomo B, Contrini S, Assanelli C, Campana E, Panunzio M (2001) Molecules 6:M260–M261
4. Sanchez-Cano G (2004) US Patent, #6,808,616B2
5. Sjostrand U (1988) US Patent, #4,788,331
6. Palmisano G, Garcia-Lopez E, Marcì G, Loddo V, Yurdakal S, Augugliaro V, Palmisano L (2010) Chem Commun 46:7074–7089
7. Lang X, Chen X, Zhao J (2014) Chem Soc Rev 43:473–489
8. Kou J, Lu C, Wang J, Chen Y, Xu Z, Varma RS (2017) Chem Rev 117:1445–1514
9. Ferry JL, Glaze WH (1998) Langmuir 14:3551–3555
10. Shiraishi Y, Togawa Y, Tsukamoto D, Tanaka S, Hirai T (2012) ACS Catal 2:2475–2481
11. Shiraishi Y, Hirakawa H, Togawa Y, Sugano Y, Ichikawa S, Hirai T (2013) ACS Catal. 3:2318–2326
12. Molinari A, Maldotti A, Amadelli R (2014) Chem Eur J 20:7759–7765
13. Imamura K, Yoshikawa T, Hashimoto K, Kominami H (2013) Appl Catal B: Environ 134–135:193–197
14. Tanaka A, Nishino Y, Sakaguchi S, Yoshikawa T, Imamura K, Hashimoto K, Kominami H (2013) Chem Commun 49:2551–2553
15. Hakki A, Dillert R, Bahnemann DW (2013) Phys Chem Chem Phys 15:2992–3002
16. Imamura K, Iwasaki S, Maeda T, Hashimoto K, Ohtani B, Kominami H (2011) Phys Chem Chem Phys 13:5114–5119
17. Imamura K, Hashimoto K, Kominami H (2012) Chem Commun 48:4356–4358
18. Imamura K, Nakanishi K, Hashimoto K, Kominami H (2014) Tetrahedron 70:6134–6139
19. Molinari A, Maldotti A, Amadelli R (2015) J Electroanal Chem 755:143–150
20. Molinari A, Maldotti A, Amadelli R (2017) Catal Today 281:71–77

21. Makarova OV, Rajh T, Thurnauer MC, Martin A, Kemme PA, Cropek D (2000) Environ Sci Technol 34:4797–4803

22. Amadelli R, Maldotti A, Samiolo L (2009) Catal Today 144:149–153

23. Boronat M, Concepcion P, Corma A, Gonzales S, Illas F, Serna P (2007) J Am Chem Soc 129:16230–16237

24. Vasudevan D, Wendt H (1995) J Electroanal Chem 192:69–74

25. da Silva AF, da Silva Filho AJ, Vasconcellos MLAA, de Santana OL (2018) Molecules 23:2129–2141

26. Henderson MA (2011) Surf Sci Rep 66:185–297

27. Pegis ML, Roberts JAS, Wasylenko DJ, Mader EA, Appel AM, Mayer JM (2015) Inorg Chem 54:11883–11888

28. Ishida T, Masatake H (2017) In: Sels B, Van de Voorde M (eds) Nanotechnology in catalysis. Wiley, Weinheim