Review

Photo-Induced Degradation of Priority Air Pollutants on TiO$_2$-Based Coatings in Indoor and Outdoor Environments—A Mechanistic View of the Processes at the Air/Catalyst Interface

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Abstract: In recent decades, numerous studies have indicated the substantial role semiconductors could play in photocatalytic processes for environmental applications. Materials that contain a semiconductor as a photocatalyst have a semi-permanent capacity for removing harmful gases from the ambient air. In this paper, the focus is on TiO$_2$. Heterogeneous photocatalysis using TiO$_2$ leads to the degradation of NO/NO$_2$, benzene, toluene, and other priority air pollutants once in contact with the semiconductor surface. Preliminary evidence indicates that TiO$_2$-containing construction materials and paints efficiently destroy the ozone precursors NO and NO$_2$ by up to 80% and 30%, respectively. Therefore, the development of innovative coatings containing TiO$_2$ as a photocatalyst was in the foreground of research activities. The aim of this was for coatings to be used as building and construction materials, mainly outdoors, e.g., on building façades on high-traffic roads for the degradation of priority air pollutants (NOx and volatile organic compounds) in the polluted urban atmosphere. Though there are advantages connected with the application of TiO$_2$, due to its band gap of 3.2 eV, these are limited. TiO$_2$ is effective only in the UV region (ca. 5%) of the solar spectrum with wavelengths $\lambda < 380$ nm. Hence, efforts are made here, as in many research studies, to dope TiO$_2$ with transition metals to increase its activity using visible light, which will extend its application to indoor environments. In our studies, experiments were conducted with 0.1% (w/w) and 1% (w/w) Mn-TiO$_2$ admixtures, and the ability of the modified photocatalysts to degrade NO by both solar and indoor illumination was evaluated. The surface chemistry at the air/catalyst interface, governed by the photoelectric characteristics of TiO$_2$ and the formation of reactive oxygen species with co-occurring redox reactions, is reviewed in this paper. The factors affecting the application of TiO$_2$ for the degradation of priority air pollutants as single compounds or mixtures are discussed. We investigated, particularly, the degradation of mixtures of priority compounds at typical concentrations in ambient air and confined spaces. This is a realistic approach, because pollutants are present as mixtures, rather than as individual compounds in ambient and indoor air. Moreover, organic polymers as paint constituents were found to be the primary source for carbonyl formation, e.g., formaldehyde, acetaldehyde, etc., during the heterogeneous photocatalytic processes conducted on TiO$_2$-enriched coatings.

Keywords: TiO$_2$; heterogeneous photocatalysis; air pollutants; visible light; byproducts

1. Introduction

After the pioneering work of Fujishima and Honda (1972) [1] on the photocatalytic properties of TiO$_2$, numerous studies were carried out to elucidate the principles, mechanisms, and mode of action of TiO$_2$ for environmental remediation purposes. The development of innovative coatings containing TiO$_2$ as a photocatalyst was at the forefront of research activities, with the aim for these coatings to be used as building and construction materials, mainly outdoors, e.g., on building façades on high-traffic roads for the degradation of priority air pollutants (NOx and volatile organic compounds) in the urban atmosphere.
Research in recent decades has clearly documented that heterogeneous photocatalysis leads to the degradation of inorganic and organic pollutants under various environmental conditions. Photo-induced reactions in the heterogeneous phase proceed differently from those in the homogeneous phase. Due to the interaction between the functional groups of the adsorbed chemical compounds and the adsorbent surfaces, bond lengths and bond angles between individual atoms of the adsorbed compounds are altered. This leads to changes in the light absorption behaviour of the compounds. Changes in the absorption behaviour are generally of a bathochromic nature (redshift). In addition to this, changes in the relative intensities of the individual bands (hyper-chromic effects) might also be very important. As a consequence, compounds which practically do not absorb tropospheric light (λ > 290 nm), once adsorbed on various surfaces, e.g., soil, might be transformed or degraded by atmospheric conditions due to changes in the absorption behaviour, and the reaction with reactive species formed on the surface.

Numerous studies in the literature report photo-induced degradation of compounds of different chemical classes, e.g., aromatics, insecticides, and herbicides adsorbed onto silica gel or soil after irradiation with UV light (λ > 290 nm) of the solar spectrum, indicating a total degradation of the organic compounds (photo-mineralization). In some of these studies, an attempt was made to correlate the rates of the heterogeneous photo-oxidation (photo-mineralization, % of CO₂ production) of chemicals adsorbed onto a substance such as silica gel, with their ionization potential [2,3]. This correlation suggests that the photochemical oxidative degradation of environmental chemicals can be estimated merely by measuring their ionization potential.

Unlike the heterogeneous photocatalysis with solar or UV light and the degradation of substances adsorbed onto soil, particulate matter, or SiO₂ surfaces, the photo-induced degradation of chemicals with semiconductors, e.g., TiO₂ proceeds in another way. It is an energetically interesting process, because it operates near ambient temperature, basically using solar energy/UV to initiate photocatalytic reactions. The impact of solar or UV light on TiO₂ leads to the separation of charges, through the movement of an electron from the valence band (VB) of TiO₂ to the conduction band (CB), leaving a positive hole behind (Figure 1). TiO₂ is considered to be the most used photocatalyst for the removal of pollutants, due to its strong oxidative ability even at low UV irradiation. The best photocatalytic performance with the maximum quantum yield, which represents the number of reactions per absorbed photon, is achieved by TiO₂. Moreover, TiO₂ is a chemically stable material (with no photo-corrosion), and it is very common and relatively cheap.

![Figure 1. Basic processes on TiO₂ surface in the presence of water molecules and oxygen [4].](image)

The positive hole (h+) and the free electron (e−) can recombine very fast (in femtoseconds) if no other molecules are present in the photochemical system. Recombination is inhibited when water molecules, oxygen, or other compounds are present. In this case, positive holes in the valence band and the electrons in the conduction band may react at the air/catalyst interface. The formation of reactive oxygen species and co-occurring
redox reactions are reported. The photocatalytic effectiveness of a semiconductor surface is measured by its ability to generate positive holes in the valence and promote electrons to the conduction band, initiating redox reactions of charge carriers with other molecules present in the photochemical system [4–6].

Building materials modified/enriched with TiO$_2$ have gained an increasing importance in recent years, given the full range of possible applications. TiO$_2$-based photocatalytic materials (e.g., paints) are initially developed and used as outer coatings on the façades of buildings to clean polluted air using only solar energy. Since we spend around 85–90% of our time indoors (Figure 2), substantial efforts were made to further investigate the photocatalytic activity of materials containing TiO$_2$, or modified (doped) TiO$_2$, towards priority air pollutants, e.g., NO, NO$_2$, and VOCs frequently accumulated in indoor environments.

![Figure 2. Questionnaire responses of exposed individuals (AIRMEX project).](image)

The use of a number of transition metals, such as V, Cr, Fe, Mn, Ni, Co, Cu, and Zn, as well as non-metals (N) has been explored to reduce the energy gap, facilitating the movement of electrons and, thus expanding the absorption spectral range of modified TiO$_2$ towards the visible light [7,8].

Experiments conducted with manganese (Mn)-doped TiO$_2$ indicate the total degradation of NO at indoor-like irradiation conditions [9].

In the present paper, the focus is on heterogeneous photocatalysis using TiO$_2$ for the degradation of NO/NO$_2$, benzene and toluene (at typical indoor/outdoor concentration levels) once in contact with the semiconductor surface. The surface chemistry at the air/catalyst interface and the formation of reactive oxygen species with co-occurring redox reactions were investigated. Factors affecting the application of TiO$_2$ in relation to the degradation of air contaminants as individual compounds and mixtures are discussed. The photocatalytic activity of Mn-doped TiO$_2$ on the degradation of NO under indoor-like illumination was evaluated. Moreover, the formation of byproducts, particularly carbonyls, by the irradiation of TiO$_2$-enriched building materials was investigated.

2. Adsorption of Volatile Organic Compounds on the TiO$_2$ Surface

Adsorption of pollutants, such as benzene, toluene, and aldehydes, onto a photocatalyst surface plays an important role in the efficacy of the photocatalytic oxidation (PCO) technology for air purification applications. TiO$_2$ has three main allotropic forms: rutile,
anatase and brookite. The principal forms employed as photocatalysts are anatase and rutile. The use of brookite is limited due to its photoelectric properties, e.g., its higher band gap. In addition to this, pure brookite, without rutile or anatase, is rather difficult to prepare to the extent that, until recently, its photocatalytic properties had not been extensively studied.

Generally, the affinity for the adsorption of organic compounds on anatase is higher than on rutile, and the adsorption capacity of O\(_2\) on rutile is lower than on anatase. This also leads to an increased recombination rate of e\(^-\) and h\(^+\). In a study on the adsorption performance of P25 (70% anatase and 30% rutile), it was shown that alcohols possess higher adsorption efficiency compared to ketones, aromatics, and alkanes. Boulamanti et al. examined the adsorption of aromatic VOCs on P25, and reported that the adsorption constants calculated from a Langmuir-Hinshelwood model adhere to the following order: ethyl-benzene < benzene < o-xylene < p-xylene~m-xylene~toluene. The low adsorption of ethyl-benzene and o-xylene was partly ascribed to their molecular structures, which give rise to bigger stereo-chemical hindrance during adsorption [10].

3. Formation of Singlet Oxygen \((^1\text{O}_2)\) during the Photocatalytic Processes

The formation of singlet oxygen during the photocatalytic processes with various oxides, e.g., TiO\(_2\), vanadium (V\(_2\)O\(_5\)) and molybdenum oxides (MoO\(_3\)), was reported [11]. Singlet oxygen can react with and degrade organic compounds, leading to the production of CO\(_2\) and water. Singlet oxygen is formed through the reaction of superoxide anion with positive holes (O\(_2\)\(^{•-}\) + h\(^+\) \rightarrow ^1\text{O}_2 or O\(_2\)).

According to M.V. Vishnetskaya and I.S. Tomskiy, the reaction between singlet oxygen and toluene leads to various intermediates (maleic acid and maleic anhydride) that finally degrade to the end products CO\(_2\) and H\(_2\)O [11]. The photocatalysis in relation to organic compounds is mainly an oxidative process; usually, only the molecular oxygen is reduced. It is possible that a molecule initially oxidized by positive holes can then be reduced again by conduction-band electrons. This can be seen as a special case of recombination that possibly leads to the formation of singlet oxygen \((^1\text{O}_2)\).

4. Degradation of Benzene, Toluene, and NO as Model Compounds on TiO\(_2\)-Enriched Materials

In numerous studies, the photocatalytic behaviour of TiO\(_2\)-enriched materials and the removal of benzene and toluene have been studied. The vast majority of experiments in relation to the heterogeneous photocatalysis of pollutants were carried out at ppmv concentration levels, much higher than those typically found in the real environment [12–16].

In our studies, two types of experiments were carried out:

(a) Experiments were carried out in a 30 m\(^3\) environmental chamber (INDOORTRON facility at the EC-Joint research Centre, Ispra, Italy) to estimate the degradation of NO and NO\(_2\) on panels covered with a mineral silicate paint enriched with 10% and 5% TiO\(_2\), respectively (Table 1). The initial concentration of NO was 220 ppbv, the temperature was set at 23 °C and the humidity level at 50%. After six hours of irradiation with UV light (S1), NO was degraded to more than 80%, while the degradation of NO\(_2\) reached values of up to 60%. The paint materials (without UV) had an insignificant effect on NO removal (5.9%), while the corresponding value for NO\(_2\) was 26.2%.

<table>
<thead>
<tr>
<th>Component</th>
<th>Content (Percentage by Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (containing TiO(_2))</td>
<td>43</td>
</tr>
<tr>
<td>Fine sand</td>
<td>52.6</td>
</tr>
<tr>
<td>Cohesion agents (Methyl-hydroxy-ethylcellulose)</td>
<td>0.65</td>
</tr>
<tr>
<td>Super-plasticizer (sulphonated melamin)</td>
<td>1.4</td>
</tr>
<tr>
<td>Defoaming agent (fatty alcohols, polyacrylate)</td>
<td>0.47</td>
</tr>
<tr>
<td>Re-dispersible resin (vinyl copolymer)</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Table 1. Composition of the investigated mineral silicate paint.
Higher NO\textsubscript{2} than NO adsorption phenomena on the surface of the sample (mineral silicate paint) was the main reason for the higher amount of NO\textsubscript{2} removal on the blank sample. An experiment with the same type of mineral silicate paint, containing 5\% of TiO\textsubscript{2} (S3), resulted in 29.6\% removal of NO. This rate was significantly lower than that of the same paint containing 10\% of TiO\textsubscript{2}, with which reduction of NO\textsubscript{2} was about 33.6\%. Also, in this experiment, higher NO\textsubscript{2} than NO adsorption on the surface of the sample was the main reason for the NO\textsubscript{2} removal (Table 2) [17].

Table 2. Photocatalytic degradation of NO\textsubscript{x} on mineral silicate paints with different content of TiO\textsubscript{2} (220 ppbv NO, 220 ppbv NO\textsubscript{2}) [modified].

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>%NO Reduction With UV</th>
<th>%NO Reduction Without UV</th>
<th>%NO\textsubscript{2} Reduction With UV</th>
<th>%NO\textsubscript{2} Reduction Without UV</th>
<th>%NO\textsubscript{2} Reduction Due to TiO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>82.4</td>
<td>5.9</td>
<td>73.9</td>
<td>60.5</td>
<td>26.2</td>
</tr>
<tr>
<td>S2</td>
<td>8.5</td>
<td>5.0</td>
<td>0</td>
<td>32.9</td>
<td>37.9</td>
</tr>
<tr>
<td>S3</td>
<td>29.6</td>
<td>4.5</td>
<td>21.1</td>
<td>33.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

S1: mineral silicate paint containing 10\% TiO\textsubscript{2}, S2: mineral silicate paint containing 0\% TiO\textsubscript{2}, S3: mineral silicate paint containing 5\% TiO\textsubscript{2}.

As an intermediate of the NO degradation, NO\textsubscript{2} is formed and is further oxidized to nitrate, the end-product of the NO degradation (Scheme 1). The mass spectrometric analysis (TOF-SIMS (Time of Flight–Secondary Ion Mass Spectrometry)) shows the presence of NO\textsubscript{2}, NO\textsubscript{3} on the surface of TiO\textsubscript{2}-containing materials as the products of NO after UV irradiation (Figure 3). It should be mentioned that the degradation of NO proceeds not only heterogeneously on the TiO\textsubscript{2} surface, but also in the gas phase via oxidation with oxygen (2NO + O\textsubscript{2} \rightarrow 2NO\textsubscript{2}) to form NO\textsubscript{2}. Elimination of NO\textsubscript{2} from the gas phase through adsorption on the TiO\textsubscript{2}-containing materials is the speed-determining step for the oxidation of NO to NO\textsubscript{2}.

Scheme 1. Reactions of NO at the air/catalyst interface.
Experiments conducted with low concentrations of benzene/toluene (7–8 ppbv) and NO (40 ppbv) in environmental (glass) chambers of a volume of 0.45 m³. At low concentration levels the degradation of benzene and toluene at 23 °C and at humidity levels of 60 and 20%, reaches up levels for benzene between 25%–77%, and for toluene under the same conditions between 75 and 90%, after six hours of irradiation, respectively. The photocatalytic degradation of NO on TiO₂-enriched surfaces (gypsum board) is not influenced at any humidity level under the conditions in our study. After three hours of irradiation, NO is almost quantitatively degraded. According to the data obtained, oxidation of NO to NO₂ and the subsequent conversion to nitrate (Scheme 1), seems to be, under these conditions, the key process leading to the elimination of NO at both humidity levels (20 and 60%). The addition of toluene or benzene to NO does not have a measurable impact on NO degradation at 20% or 60% relative humidity. The photo-induced degradation of NO on the plaster surface strongly differs from that reported with other photocatalytic materials, where changes in relative humidity result in changes in the photodegradation of NO [18].

Most studies with priority pollutants were carried out with single compounds, with either toluene, benzene, or NO present in the photochemical system. In a few studies, the compounds were mixed and subjected to irradiation with UV in the presence of TiO₂. This was carried out to simulate and evaluate the photo-induced degradation of mixtures of these chemicals on TiO₂-enriched surfaces, because in real environments, both indoors and outdoors, toluene, benzene, and NO/NO₂ are mostly present as mixtures. Experiments were carried out with distinct mixtures of volatile organic compounds at low concentrations (7 to 8 ppbv for benzene/toluene, and 40 ppbv for NO), and at humidity levels of 20 and 60% under the same experimental conditions as with the degradation of the individual compounds. The photocatalytic degradation of toluene (in mixtures with NO or benzene) was strongly influenced by the presence of benzene and/or nitrogen oxide at 20% relative humidity. After four hours of UV irradiation, toluene as an individual compound was degraded to 77%, while in a mixture with NO or benzene the photo-induced degradation of toluene after four hours was 92–93% (Figure 4). After six hours of UV irradiation, toluene as an individual compound was degraded to 91%, while in a mixture with NO or benzene the photo-induced degradation of toluene within the same amount of time was 100% (Figure 3). At humidity levels of 60%, the degradation of toluene in mixture with NO and benzene...
reached levels between 70 and 80%. Hence, the impact of nitrogen oxide and benzene on the degradation of toluene at the 60% humidity level was found to be negligible.

![Graph showing the conversion of toluene over time.](image)

**Figure 4.** Photocatalytic degradation of toluene as a single compound and in the presence of NO and benzene at RH 20% [18].

The presence of benzene strongly influenced the photo-induced degradation of toluene (at RH 20%) in the first two to three hours of irradiation. This cannot only be explained through the generation of OH radicals following the interaction of water molecules with positive holes. The substantial impact of benzene on the degradation of toluene is explained via a classical electrophilic substitution, according to Figure 5 and Scheme 2. Positive holes react as electrophiles towards benzene. The degradation of toluene also proceeds through reactive oxygen species like HO₂ and H₂O₂, formed due to the release of H⁺ from the aromatic ring. The products are benzyl alcohol, benzaldehyde, and benzoic acid.

![Chemical structures](image)

**Figure 5.** The electrophilic mingling of a positive hole (h⁺) with the benzene ring. Step 2 represents the mesomeric/resonance forms in the benzene ring.

\[
\begin{align*}
H^+ + e^- + O_2 &\rightarrow HO_2 \quad (1) \\
2HO_2 &\rightarrow H_2O_2 + O_2 \quad (2) \\
2e^- + O_2 + 2H^+ &\rightarrow H_2O_2 \quad (3)
\end{align*}
\]

**Scheme 2.** Electrophilic substitution.

Through reactions 1, 2, and 3 (Scheme 2) the proton (H⁺) from the benzene ring initiates the formation of radicals (HO₂) that attack toluene, leading to the creation of products like benzyl alcohol, benzaldehyde, and benzoic acid (Figure 6).
5. Heterogeneous Photocatalysis of NO under Indoor-like Illumination Conditions/Doping

The advantages connected with the application of TiO$_2$ are limited due to its band gap of 3.2 eV. Hence, efforts are being made to increase the area of activity of TiO$_2$ using visible light, which will extend its application to indoor environments. The activity of TiO$_2$ depends on the lifetime of charge carriers—positive holes and electrons—produced on its surface. Recombination of positive holes and electrons occurs in an extremely short timeframe before redox reactions take place.

Therefore, the primary challenge for an efficient photocatalytic process is to reduce or inhibit the recombination of charge carriers to maintain the photocatalyst activity at a high level.

One way to reduce or inhibit recombination is to blend/dope TiO$_2$ with transition metals, which create traps for electrons and block the charge carriers by reducing the recombination rate and facilitating the promotion of electrons to the conduction band. Doping (change/modification of the crystalline structure of TiO$_2$) causes a bathochromic (red) shift, which results in a reduction in the energy gap, leading to increased absorption in the visible light region.

\textit{Doping: Preparation of Two Admixtures—Mn and TiO$_2$(0.1 and 1%- Mn-TiO$_2$)}

In our experiments, 0.1% (w/w) and 1% (w/w) Mn-TiO$_2$ admixtures were prepared, and the ability of the modified photocatalysts to degrade NO by both solar and indoor-like illumination was evaluated \cite{9}. Mn-doped TiO$_2$ photocatalyst powders containing 0.1% and 1% Mn (w/w) were tested for the oxidation of NO (200 ppb) under solar and indoor-like illumination conditions. Only the catalyst containing 0.1% Mn was able to degrade NO efficiently upon irradiation with the indoor-like source (visible light), whereas the one containing 1% Mn was active only under solar-like irradiation. Mn$^{2+}$ has the electronic configuration of 3d$^5$. When it traps electrons, the electronic configuration changes to d$^9$, and if it traps holes its electronic configuration changes to d$^4$; both configurations are highly unstable. To restore its stable electronic configuration, the trapped electron will be transferred to oxygen molecules, and the trapped hole transferred to surface-adsorbed water molecules to generate superoxide (\textbullet{O}_2^-) radicals and hydroxyl (OH\textbullet) radicals in line with the reactions shown in Figure 7.

The results of our experiments clearly show that the photocatalyst doped with 0.1% Mn was able to degrade NO by up to 95% in six hours under indoor-like illumination, whereas TiO$_2$ doped with 1% Mn did not have an impact on the degradation of NO under indoor illumination conditions. When considering these results, it was observed that adding a small amount of foreign ions (in our case, 0.1% manganese) to TiO$_2$ extended its activity to

![Figure 6. Degradation of toluene (with OH and HO$_2$ radicals) on TiO$_2$-enriched materials.](image-url)
visible light, while the addition of higher concentrations of manganese (1% Mn-TiO\(_2\)) did not have an effect on the degradation of NO, even under solar irradiation conditions.

![Figure 7](image-url). Doping with Mn (0.1%) causes activation of TiO\(_2\) at longer wavelengths (bathochromic effect–redshift).

The resulting optimal concentration used in our experiments was 0.1%. The doping atoms/cations represent catching points (traps) for electrons and/or holes. These catching points immobilize the charge carriers and reduce the recombination rate. Immobilized charge carriers can also recombine through tunnel processes in the crystal lattice, as when a dopant atom is in direct neighbourhood to another dopant atom it can be regarded as a recombination centre [19]. Partial inactivation (around 10% per cycle) of the 0.1% manganese-doped photocatalyst was observed after consecutive photocatalytic cycles. This can be attributed to the adsorption of H\(_2\)O\(_3\) formed during the photocatalysis of NO onto the catalyst occupying active photocatalyst centres [9]. This effect had already been observed by Ohko et al. for photocatalysis of NO and NO\(_2\) using pure anatase TiO\(_2\) [20].


The development of TiO\(_2\)-containing paints that are activated by UV and visible light opens up a wide range of air-purifying applications in indoor environments.

However, the degradation of organic additives (Table 3) used in TiO\(_2\)-enriched paints, when irradiated with UV light, lead to the formation of carbonyl compounds like formaldehyde, acetaldehyde, acetone, and other low-molecular-weight carbonyls that are formed and emitted into the air (Figure 8).

The formation and emission of these compounds, particularly into the indoor atmosphere, might substantially affect human health and wellbeing.

Photocatalytic paints, especially for indoor environments, need (regarding the ingredients/paint components) to be optimized in order to reduce or eliminate the emission of harmful substances.

<table>
<thead>
<tr>
<th>Table 3. Chemical substances as common additives in paints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cohesion agents (Methyl-hydroxy-ethylcellulose)</td>
</tr>
<tr>
<td>• Super-plasticizer (sulphonated melamine)</td>
</tr>
<tr>
<td>• De-foaming agent (fatty alcohols, polyacrylate)</td>
</tr>
<tr>
<td>• Re-dispersible resin (vinyl copolymer)</td>
</tr>
</tbody>
</table>
7. Conclusions

The removal of NOx and VOCs at typical urban/indoor air levels, using photocatalytic (TiO$_2$-based) technology, is feasible. Humidity affects VOC photodegradation. An increase in humidity inhibits photo-oxidation, due to the competition of water molecules with pollutant molecules for adsorption sites. The mixtures of VOCs and NO behave differently than the individual compounds following UV irradiation. This is an important fact for the evaluation of the efficiency of building materials (e.g., paints) for the removal of harmful air contaminants in ambient air and confined spaces. For NO degradation at low concentrations, humidity does not play a significant role.

The hypothesis on the role of aromatic compounds as possible inhibitors of the recombination process (h$^+$ and e$^-$) should be further tested to clarify whether organic compounds with electrophilic/nucleophilic characteristics could act analogously to water molecules and oxygen as a source for radicals and other oxidizing compounds.

The development of TiO$_2$ photocatalytic paints to be applied indoors needs to be optimized to minimize the formation and emission of harmful substances.

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References


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