Visible-Light-Assisted Selective Catalytic Reduction of NO with NH₃ over Dye-Modified TiO₂ Photocatalysts

Akira Yamamoto,[a] Kentaro Teramura,[a, b, c] Saburo Hosokawa,[a, b] Tetsuya Shishido,[b, d] and Tsunehiro Tanaka*[a, b]

Abstract: Dye-modified TiO₂ photocatalysts showed high photocatalytic activity for the selective catalytic reduction of NO with NH₃ in the presence of O₂ under visible-light irradiation. Among the 15 dyes investigated, the maximum conversion was achieved using a Ru(2,2′-bipyridyl-4,4′-dicarboxylic acid)₃(NCS)₃ complex (N3-dye) for the modification of TiO₂ (NO conversion > 99%, N₂ selectivity > 99%). Diffuse reflectance infrared Fourier transform (DRIFT) investigation showed that nitrite (NO₂⁻) and nitrate (NO₃⁻) species were generated on the N3-TiO₂ surface under visible-light irradiation. In gas switch reactions, NO₂⁻ on the N3-TiO₂ surface became N₂ by a reaction with adsorbed NH₃ under visible-light irradiation, although NO₂⁻ reacted with NH₃ to form N₂ and N₂O. Based on the relativity with NH₃, we concluded that the NO₂⁻ species is an intermediate in photo-SCR and reacts with NH₃ adsorbed on the surface of N3-TiO₂ under visible-light irradiation to selectively form N₂.

Introduction

Nitrogen oxides (NOₓ) are air pollutants and cause serious environmental problems, including acid rain and town smog. The removal of NOₓ in exhaust gases that contain excess O₂ is an important process in air purification. Typically, NOₓ are decomposed to harmless N₂ using selective catalytic reduction with ammonia (NHₓSCR) over vanadium oxide-based catalysts[15] and Fe- or Cu-zeolite catalysts,[5] according to eq. 1.

\[
4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} \quad (1)
\]

These catalysts, however, cannot efficiently remove NOₓ from diesel engines during cold start condition (< 473 K).[9] Therefore, novel catalysts that can perform NHₓ-SCR at low temperatures are strongly required.

We have reported photocatalysts that show activity for NHₓ-SCR at low temperatures in the presence of excess O₂ (referred to as photo-SCR).[9] The reaction mechanism of photo-SCR has been investigated by us and other groups using spectroscopic,[5] kinetic,[10, 11] and theoretical[7] methods. Over TiO₂ photocatalyst, the conversion of NO and the selectivity to N₂ becomes 90% and 99%, respectively, at a gas hourly space velocity (GHSV) of 8000 h⁻¹, which is sufficient for the De-NOₓ process in typical stationary sources such as power plants, blast furnaces, and incinerators. However, higher GHSV values (>50000 h⁻¹) are required in diesel engines owing to the limited installation space of the De-NOₓ process and a high flow rate of the exhaust gas.

Recently, we reported that porphyrin-sensitized TiO₂ functions as a visible-light-sensitive photocatalyst for NHₓ-SCR. This reaction proceeds via electron injection from photo-excited dyes into the conduction band of TiO₂ (dye-sensitization mechanism),[15] although a detailed mechanism of the reaction is unclear. The electron injection process from photo-excited dyes into the conduction band of a semiconductor is an important step in dye-sensitized solar cells (DSSCs)[9] and dye-sensitized photocatalysts,[15] and has been previously investigated.[11] Many researchers have tested various dyes, including Ru complexes,[11] porphyrins,[9] phthalocyanines,[14] and other dyes,[8c, 10c, 15] to improve the performance of DSSCs and dye-sensitized photocatalysts. The type of dye used for the modification of semiconductors has a great impact on the performance of DSSCs and dye-sensitized photocatalysts, and thus, should have a significant effect on the activity in photo-SCR under visible-light irradiation. A major problem of the dye-sensitization system is the stability of the dyes; moreover, optimization of the dye is essential to evaluate and improve the performance of photo-SCR over dye-modified TiO₂ photocatalysts. Herein, we investigated photo-SCR under visible-light irradiation using TiO₂ photocatalysts modified with 15 different dyes (Fig. 1). The reactivity of the adsorbed intermediates generated over the dye-modified TiO₂ photocatalyst were also investigated by means of in situ diffuse reflectance infrared Fourier transform (DRIFT) and UV–Vis diffuse reflectance (DR) spectroscopies to elucidate the reaction mechanism.

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Results and Discussion

Screening of dyes. Fig. 2 shows the results of photo-SCR over dye-modified TiO₂ photocatalysts. The reaction proceeded to some extent (ca. 5%) over a bare TiO₂ photocatalyst under visible-light irradiation, as reported in the previous paper.[16] Modification of TiO₂ with various dyes greatly enhanced photo-SCR activities. The maximum conversion of NO (>99%) was obtained using an N3-dye (1 in Fig. 1)-modified TiO₂ photocatalyst (N3-TiO₂) after 30 min. The conversion of NO was significantly higher than those of other photocatalysts (e.g., UV-light irradiated TiO₂)[4d, 8] and conventional catalysts (e.g., Fe- and Cu-zeolite catalysts)[17] at low temperatures. N₂O was not detected in all reactions shown in Fig. 2. The high selectively to N₂ is consistent with our previous reports of photo-SCR over porphyrin-modified TiO₂ photocatalysts under visible-light irradiation.[8] The order of activities is discussed in the last section.

The conversion of NO was almost stable over 180 min of visible-light irradiation over the TiO₂ photocatalysts modified with Ru(bpy)₃Cl₂ 4, TCPP 7, phthalocyanines 9 and 11, and RhCl₃ 12. A relatively high stability was observed in the case of N3-dye (1), and the N3-TiO₂ photocatalyst showed the highest conversion of NO even at 180 min (95%). When xanthene dyes were used, relatively high conversions of NO were obtained after 30 min; rose bengal 2 (81%), eosin Y 3 (80%), and rhodamine B 5 (63%). However, as shown by the time course of photo-SCR (Fig. 3), conversions gradually decreased over 180 min of the reaction. Bleaching of the catalyst colors was observed after the reaction, which suggests that the decrease in the activity was due to dye decomposition. The low stability of xanthene dyes was consistent with previously reported DSSCs.[9b, 18] Thus, the xanthene dyes were deemed unsuitable for photo-SCR.

![Figure 1. Schematic representation of dyes.](image1)

![Figure 2. Conversion of NO in photo-SCR over the dye-modified TiO₂ photocatalysts under visible-light irradiation. Dye loading: 12.5 μmol g⁻¹. GHSV: 100000 h⁻¹. The numbers in the bottom axis correspond to those in Fig.1.](image2)
Reactivity of adsorbed species of NH$_3$ and NO. Table 1 lists the results of reactions under various conditions. Efficient N$_2$ formation was observed over N3-TiO$_2$ in the presence of NO, NH$_3$, and O$_2$ under visible-light irradiation (640 ppm, entry 2). The activity of N3-TiO$_2$ was significantly higher than that of a bare TiO$_2$ photocatalyst under UV and visible light irradiation (290 ppm, entry 1). Product formation was greatly diminished without NO, NH$_3$, or O$_2$ (entries 3, 4, and 5), which indicated that all the gases are involved in the formation of N$_2$. Furthermore, visible-light irradiation drastically promoted photo-SCR over N3-TiO$_2$ (entry 6).

A couple of gas switch experiments were carried out to investigate the reactivity of the adsorbed species of NH$_3$ and NO on the N3-TiO$_2$ surface. In the first experiment, NH$_3$/He gas was flowed in the first 120 min in the dark (Fig. 4(A)), and no product was observed. Subsequently, the feed gas was switched to NO/O$_2$/He gas and visible-light irradiation was started. Selective formation of N$_2$ (910 ppm, selectivity to N$_2$ > 99%) was observed after 5 min of visible-light irradiation. The concentration of N$_2$ in the outlet gas gradually decreased with increasing visible-light irradiation time and dropped to 24 ppm after 270 min. This formation of N$_2$ presumably derived from the reaction between the initially adsorbed NH$_3$ and NO in the gas phase, because low amounts of N$_2$ were formed via a reaction between NO and O$_2$ under visible-light irradiation (Table 1, entry 4).

In the second experiment, NO/O$_2$/He gas was flowed under visible-light irradiation for 90 min, and then the feed gas was switched to NH$_3$/He gas in the dark (Fig. 4(B)). During this period, a small amount of N$_2$ was formed and N$_2$O was not detected. After 120 min of the NH$_3$/He gas flow in the dark, visible-light irradiation was started and N$_2$ (780 ppm) and N$_2$O (130 ppm) were observed (selectivity to N$_2$: 86%) after 5 min; the concentrations gradually decreased as the irradiation time was increased. The blank test results showed that NH$_3$ did not decompose to N$_2$ over N3-TiO$_2$ under visible-light irradiation (Table 1, entry 3). Accordingly, this formation of N$_2$ and N$_2$O was due to the reaction between the adsorbed NH$_3$ and the surface NO$_x$ species formed by the addition of NO/O$_2$/He gas under visible-light irradiation. The NO$_x$ species on the surface of N3-TiO$_2$ did not react with NH$_3$ without visible-light irradiation, which indicated that visible-light was essential for this surface reaction. Based on the gas switch experiment, we concluded that surface NO$_x$ species became N$_2$ and N$_2$O by a reaction with adsorbed NH$_3$ on the N3-TiO$_2$ surface under visible-light irradiation (Langmuir-Hinshelwood mechanism).

### Table 1. Result of photo-SCR under various reaction conditions.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Inlet ppm</th>
<th>Lamp</th>
<th>Outlet ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TiO$_2$</td>
<td>0.1 0.1</td>
<td>2</td>
<td>UV+Vis. 290 4</td>
</tr>
<tr>
<td>2</td>
<td>N3-TiO$_2$</td>
<td>0.1 0.1</td>
<td>2</td>
<td>Vis. 640 n.d.</td>
</tr>
<tr>
<td>3</td>
<td>N3-TiO$_2$</td>
<td>0 0.1</td>
<td>2</td>
<td>Vis. 14 n.d.</td>
</tr>
<tr>
<td>4</td>
<td>N3-TiO$_2$</td>
<td>0.1 0</td>
<td>2</td>
<td>Vis. 10 n.d.</td>
</tr>
<tr>
<td>5</td>
<td>N3-TiO$_2$</td>
<td>0.1 0.1</td>
<td>0</td>
<td>Vis. 35 7</td>
</tr>
<tr>
<td>6</td>
<td>N3-TiO$_2$</td>
<td>0.1 0.1</td>
<td>2</td>
<td>OFF 15 n.d.</td>
</tr>
<tr>
<td>7</td>
<td>N3-TiO$_2$</td>
<td>0.1 0.1</td>
<td>2</td>
<td>Vis. 16 n.d.</td>
</tr>
</tbody>
</table>

[a] Concentration of N$_2$ and N$_2$O in the inlet gas. [b] Light source, UV+Vis: 300 W Xe lamp without cut-off filter. [c] Vis: 300 W Xe lamp with L42 cut-off filter. [d] Concentration of N$_2$ and N$_2$O in the outlet gas. GHSV: 250000 h$^{-1}$, total flow rate: 500 ml min$^{-1}$, catalyst amount: 110 mg. [e] Loading of N3-dye: 37.5 μmol g$^{-1}$.

### Figure 4. Time course of concentration of N$_2$ and N$_2$O in the gas switch reactions. Catalyst: 37.5 μmol g$^{-1}$ N3-TiO$_2$. NO: 1000 ppm, NH$_3$: 1000 ppm, O$_2$: 2%, He: balance. GHSV: 8000 h$^{-1}$, Light source: 300 W Xe lamp equipped with a L42 cut-off filter.

DRIFT investigations of surface NO$_x$ species. Fig. 5 represents the DRIFT spectra before and after the addition of NO/O$_2$/He gas in the dark. The spectrum before the addition was used as the baseline. Two peaks, at 1478 and 1198 cm$^{-1}$, gradually increased with increasing the exposure time (Fig. 5(A)). The peak at 1478 cm$^{-1}$ was assigned to a ν$_1$ vibration of monodentate NO$_2^-$ adsorbed on the surface of N3-TiO$_2$. This species is also expected to have a ν$_1$ vibration band between 1065 and 1050 cm$^{-1}$.[19] In the DRIFT experiment, a shoulder band was observed around that region, which supports its
proposed generation. The peak at 1198 cm\(^{-1}\) was assigned to a bridged bidentate NO\(_2\) in a previous paper\(^{[19]}\). Three negative peaks at 3697, 3659, and 3631 cm\(^{-1}\), and a broad positive peak around 3500 cm\(^{-1}\) appeared after the addition of NO/O\(_2\)/He gas (Fig. 5(B)). The negative peaks were assigned to isolated OH groups in different surroundings (e.g., number of coordinated Ti atom, valence of coordinated Ti atom, surface sites of TiO\(_2\))\(^{[20]}\) and the broad positive peak was attributed to a hydrogen-bonded OH group. We did not observe a characteristic band of deformation vibration of water molecules around 1640 cm\(^{-1}\), which indicated that the amount of adsorbed water did not change by the co-adsorption of NO and O\(_2\). Thus, the increase of the band intensity centered at 3500 cm\(^{-1}\) is not due to the adsorption of water molecules generated. The change in the OH region suggests that the adsorbed NO\(_2\)– species interacted with the isolated OH groups through hydrogen bonding, thus reducing the band intensities of the isolated OH groups and increasing the hydrogen-bond-related band intensity. Both NO\(_2\)– species (monodentate and bridged bidentate) were generated on the surface of N3-TiO\(_2\) by the co-adsorption of NO and O\(_2\) in the dark.

After 30 min of NO/O\(_2\) gas flow, O\(_2\)/He gas was introduced to the DRIFT cell, and then visible-light irradiation was started across the KBr window. As shown in Fig. 6(A), the band at 1478 cm\(^{-1}\) decreased with visible-light irradiation, which indicated that the NO\(_2\)– species were consumed by the reaction with O\(_2\) under visible-light irradiation. New bands at 1605, 1583, 1297, and 1253 cm\(^{-1}\) increased with increasing irradiation time. Bands at 1605 and 1253 cm\(^{-1}\) were attributed to a \(v_3\) vibration of the bridging bidentate nitrate (NO\(_3\)–\(\cdot\)), and a set of bands at 1583 and 1297 cm\(^{-1}\) was assigned to the chelating bidentate NO\(_3\)–\(\cdot\)\(^{[19]}\). Thus, the NO\(_2\)– species was oxidized into the NO\(_3\)– species under visible-light irradiation. In the OH region (Fig. 6(B)), the isolated OH bands at 3697, 3659, and 3631 cm\(^{-1}\) decreased with visible-light irradiation, suggesting that the surface OH groups reacted with the adsorbed NO\(_2\)– to form NO\(_3\)–. The DRIFT investigation revealed that the NO\(_2\)– species appeared after the co-adsorption of NO and O\(_2\) in the dark, and were oxidized into NO\(_3\)– by O\(_2\) under visible-light irradiation (Scheme 1).

**Figure 5.** DRIFT spectra of N3-TiO\(_2\) in the dark before addition of NO/O\(_2\)/He gas (blue line), and after 5, 10, 15, 20, 25 (grey lines), and 30 min (red line).

**Figure 6.** DRIFT spectra of N3-TiO\(_2\) in O\(_2\)/He gas before visible-light irradiation (blue line), and after 20 min, 40 min (grey lines), and 60 min (red line) from the start of visible-light irradiation.

**Reactivity of the NO\(_2\)– and NO\(_3\)– species with NH\(_3\) under visible-light irradiation.** Either NaNO\(_2\) or NaNO\(_3\) was impregnated over N3-TiO\(_2\) in order to investigate the reactivity of NO\(_2\)– and NO\(_3\)– on the surface of N3-TiO\(_2\). NH\(_3\) was flowed into the reactor filled with the NaNO\(_2\)– or NaNO\(_3\)–-impregnated catalysts (Fig. 7). In the dark, N\(_2\) and N\(_2\)O were not detected in an NH\(_3\)/He gas flow for both catalysts. For the NaNO\(_2\)-impregnated N3-TiO\(_2\), N\(_2\) (2020 ppm) and N\(_2\)O (1420 ppm) were observed after 5 min of visible-light irradiation. Not much N\(_2\) was observed in the NH\(_3\)/He gas flow under visible-light irradiation in the blank tests (Table 1, entry 3). Thus, the generated N\(_2\) shown in Fig. 7(A) is derived from a reaction between NH\(_3\) in the gas phase and NO\(_3\)– species on the surface of N3-TiO\(_2\). Surprisingly, a large amount of N\(_2\)O was detected in this experiment (selectivity to N\(_2\) = 59%). In contrast, selective formation of N\(_2\) was observed from the NaNO\(_3\)-impregnated N3-TiO\(_2\) under visible-light irradiation (Fig. 7(B), selectivity to N\(_2\) = 94%), which suggested that NO\(_3\)– became N\(_2\) on reacting with NH\(_3\). As shown above, the reactivity of NO\(_2\)– with NH\(_3\) was significantly different from that of NO\(_3\)– in terms of selectivity to N\(_2\) (Scheme 1), which could explain the relatively low selectivity to N\(_2\) (selectivity to N\(_2\) = 86%) in the gas switch reaction shown in Fig. 4(B); both the NO\(_2\)– and NO\(_3\)– species were formed in NO/O\(_2\)/He gas under visible-light irradiation on the surface of N3-TiO\(_2\) and reacted with NH\(_3\). High selectivity to N\(_2\) (>99%) in photo-SCR in the presence of NO, NH\(_3\), and O\(_2\) (Table 1, entry 1) over N3-TiO\(_2\) strongly indicated that an intermediate in photo-SCR was NO\(_3\)– was adsorbed on the surface of N3-TiO\(_2\) on the based of the difference in their reactivity.
adsorption band at 455 nm was observed (spectrum (a) in Fig. 8) and attributed to an MLCT band of Ru(II)(bpy)₃. After the addition of Cl₂, the catalyst color changed from light orange to slightly greyish orange and the adsorption at 600–800 nm increased (spectra (b)), which was assigned to an LMCT band of Ru(II)(bpy)₃.[21] As previously mentioned, Ru(II)(bpy)₃ was successfully prepared on the TiO₂ surface by using Cl₂ as an oxidant. Subsequent introduction of NH₃ to the cell resulted in a decrease in the adsorption at 600–800 nm (spectra (c)), which clearly showed the reaction of Ru(II)(bpy)₃ with NH₃ and reduction to the initial Ru(II)(bpy)₃ species. The UV–Vis spectroscopic result shows that Ru(II)(bpy)₃ has the potential to oxidize NH₃. We concluded that Ru(II)(bpy)₃ generated after the electron injection, activates NH₃ to an NH₃ radical (eq. 3),[16] which reacts with NO₂⁻ to form N₂ selectively.

\[
\text{Ru}^{2+}(\text{bpy})_3 + \text{NH}_3 \rightarrow \text{Ru}^{3+}(\text{bpy})_3 + \text{NH}_2 \text{ radical} + \text{H}^+ \tag{3}
\]

Figure 8. UV–Vis DR spectra of the TiO₂ photocatalyst modified with Ru(bpy)Cl₃ after evacuation (a), after addition of Cl₂, and after addition of NH₃. Dye loading: 37.5 μmol g⁻¹.

Proposed reaction mechanism and effects of dyes on the activity. Based on the results obtained thus far, we proposed the reaction mechanism of photo-SCR over Ru-dye-modified TiO₂ photocatalysts under visible-light irradiation (Scheme 2). The mechanism is composed of five steps: (1) adsorption of NO and NH₃ on the catalyst surface, (2) electron injection from photo-excited Ru dyes into the conduction band of TiO₂, (3) activation of NH₃ by oxidized Ru dyes, (4) surface reaction between an NH₂ radical and NO₂⁻, and (5) re-oxidation of Ti²⁺ sites by O₂.

In DSSCs, Ru complexes have shown the best photovoltaic properties among a huge number of dyes,[96] and N₃-dye was known to be an effective Ru dye for DSSCs due to 1) the wide adsorption range to 800 nm, 2) strong adsorption on the semiconductor surface due to binding with up to four carboxyl groups, and 3) sufficiently long excited state life-time (~20 ns).[96]

In our research, N₃-dye showed the highest activity in photo-SCR under visible-light irradiation among the 15 dyes studied. The adsorption of N₃-dye was not larger than other dyes as shown in Fig. 9 (UV–Vis adsorption spectra of other dyes studied are shown in Fig. S2). This result indicated that the highest activity was not due to the adsorption amount in the

Role of dyes. As shown in Table 1, the activity of N₃-SiO₂ catalyst was very low (conversion of NO: 1.6%, entry 7), which indicated that the N₃-dye did not function independently of the support (i.e., TiO₂). Thus, the reaction over N₃-TiO₂ proceeds via a dye-sensitization mechanism: visible-light irradiation induces the electron injection from photo-excited dyes to the conduction band of TiO₂. A similar result was obtained in porphyrin-modified TiO₂ photocatalysts.[85] After the electron injection, the oxidation product of N₃-dye and an electron in the conduction band of TiO₂ should be generated as shown in eq. 2:

\[
\text{N₃-dye} + hν \rightarrow \text{N₃-dye}^* + 6e^- \tag{2}
\]

Based on eq. 2, we investigated the reactivity of the oxidation product of N₃-dye with NH₃. In a previous report,[21] the one-electron oxidation product of Ru(II)(bpy)₃ (i.e., Ru(II)(bpy)₃) in zeolite was prepared using Cl₂ as an oxidant, and we attempted the corresponding oxidation of N₃-dye. However, N₃-dye* could not be prepared because of its instability, although an oxidized N₃-dye species, which underwent further transformations from N₃-dye*, reacted with NH₃ and returned to the initial state (for details, see ESI). Therefore, we used the TiO₂ photocatalyst modified with Ru(II)(bpy)₃Cl₃ (4 in Fig. 1) in the UV–Vis spectroscopic study and investigated the reactivity of Ru(II)(bpy)₃ with NH₃ (Fig. 8). After the evacuation of Ru(bpy)₃Cl₃/TiO₂, an

Figure 7. Time course of concentration of N₂ and N₂O in the outlet gas over (A) NaNO₂-impregnated N₃-TiO₂ and (B) NaNO₂-impregnated N₃-TiO₂. Loading of NaNO₂ or NaNO₃: 1000 μmol g⁻¹. Loading of N₃-dye: 37.5 μmol g⁻¹. Reaction gas: 1000 ppm NH₃/He. GHSV: 8000 h⁻¹. light source: 300 W Xe lump equipped with a L42 cut-off filter.

Scheme 1. Surface NO₂ species on N₃-TiO₂ catalyst and its reactivity with NH₃ under visible light irradiation.

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visible region, although this should be a significant factor. In the case of DSSCs, carboxylic groups were necessary in terms of the strong adsorption of dyes on the semiconductor surface, and the strong adsorption led to strong photovoltaic properties. In this research, Ru(bpy)$_3$Cl$_2$ dye, which does not possess a carboxylic group, also showed high activity (conversion of NO = 70.5%). A similar result for photo-SCR was obtained in our previous reports using the porphyrin-modified TiO$_2$ photocatalysts with different functional groups.$^{[8]}$ Therefore, carboxylic groups were not important to improve the activity, unlike the DSSCs system. Thus, the life-time of the photo-excited state and the reactivity of the oxidized product of dyes with NH$_3$, which should affect reaction steps 2 and 3 in Scheme 2, would have a significant effect on the photo-SCR activity.

![Scheme 2. Proposed reaction mechanism of photo-SCR under visible-light irradiation over Ru complexes modified TiO$_2$ photocatalyst.](image)

We demonstrated high-performance photocatalysts for NH$_3$-SCR under visible-light irradiation by combining popular dyes with TiO$_2$ photocatalysts. The screening of 15 dyes displayed that N3-dye was most effective for the modification of TiO$_2$. Complete conversion of NO and selectivity to N$_2$ were achieved over N3-TiO$_2$ at a high GHSV of 100000 h$^{-1}$ after 30 min of visible-light irradiation. We proposed a reasonable reaction mechanism of the photo-SCR over dye-modified TiO$_2$ photocatalysts under visible light irradiation by using in situ DRIFT and UV–Vis DR spectroscopies. The reaction proceeds via electron injection from dyes excited by visible-light irradiation into the conduction band of TiO$_2$ (dye-sensitization). The dye oxidation product, generated after the electron injection, oxidatively activates NH$_3$, which then reacts with surface NO$_2^-$ through the Langmuir-Hinshelwood mechanism, to provide selective formation of N$_2$.

**Experimental Section**

**Catalyst preparation.** All dyes were used without further purification, and their structures are shown in Fig. 1. The dyes were impregnated on a TiO$_2$ powder (ST-01, anatase, 273 m$^2$ g$^{-1}$), purchased from Ishihara Sangyo Kaisha, Ltd., using appropriate solvents (see ESI). Sodium nitrite (NaNO$_2$) and sodium nitrate (NaNO$_3$) were impregnated on the N3-dye-modified photocatalyst using water as the solvent (loading of NaNO$_2$ or NaNO$_3$: 1000 μmol g$^{-1}$).

**Photocatalytic reaction.** Photo-SCR was carried out in a conventional fixed-bed flow system at atmospheric pressure, the details of which we have previously reported.$^{[8]}$ In brief, two types of a quartz reactor were used in this research: reactor 1 (12 mm × 10 mm × 1.0 mm, catalyst amount: 110 mg) for a GHSV of 100000 and 250000 h$^{-1}$, and reactor 2 (50 mm × 15 mm × 1.0 mm, catalyst amount: 420 mg) for a GHSV of 8000 h$^{-1}$. The reaction gas (NO 1000 ppm, NH$_3$ 1000 ppm, O$_2$ 2%, He balance) was introduced to the reactors at a flow rate of 100–500 mL min$^{-1}$. A 300 W Xe lamp (PERKIN-ELMER PE300BF) equipped with an L42 cut-off filter was used as a light source (loading of NaNO$_2$ or NaNO$_3$: 1000 μmol g$^{-1}$).

**Characterization.** In situ DRIFT measurements were performed with a JASCO ISDR-600 FTIR spectrometer equipped with a mercury-cadmium-tellurium (MCT) detector cooled by liquid N$_2$ at a resolution of 4 cm$^{-1}$ and with 16 co-added scans. The sample powder (50 mg) was placed in a DR cell, which was fitted with a KBr window at the top. The pretreatment was carried at 353 K under a He gas flow (100 mL min$^{-1}$) for 1 h, and was then cooled to room temperature. Concentrations of gases were the same as in the reaction. The background spectrum was measured after the pretreatment in a He gas flow at room temperature. A 200 W Hg–Xe lamp equipped with a collective lens (San-Ei Electric Co. Ltd., UVF-2045 type C) was used as a light source, and light was irradiated through an L42 cut-off filter. UV–Vis DR spectra were measured using a UV–Vis spectrometer (JASCO V-650) with an integrating sphere. A BaSO$_4$ plate was used as a reference. A sample powder was added to a quartz cell with flat facets and evacuated at 373 K for 1 h before the measurement. CO$_2$ and NH$_3$ gas were added to the cell using a vacuum line.

**Conclusions**

We demonstrated high-performance photocatalysts for NH$_3$-SCR under visible-light irradiation by combining popular dyes with TiO$_2$ photocatalysts. The screening of 15 dyes displayed that N3-dye was most effective for the modification of TiO$_2$. Complete conversion of NO and selectivity to N$_2$ were achieved over N3-TiO$_2$ at a high GHSV of 100000 h$^{-1}$ after 30 min of visible-light irradiation. We proposed a reasonable reaction mechanism of the photo-SCR over dye-modified TiO$_2$ photocatalysts under visible light irradiation by using in situ DRIFT and UV–Vis DR spectroscopies. The reaction proceeds via electron injection from dyes excited by visible-light irradiation into the conduction band of TiO$_2$ (dye-sensitization). The dye oxidation product, generated after the electron injection, oxidatively activates NH$_3$, which then reacts with surface NO$_2^-$ through the Langmuir-Hinshelwood mechanism, to provide selective formation of N$_2$.

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**Keywords:** Photocatalysis • Nitrogen oxides • Dyes • Environmental chemistry • NH$_2$-SCR


Dye-sensitized TiO$_2$ photocatalysts showed high photocatalytic activity for selective catalytic reduction of NO with NH$_3$ (NH$_3$-SCR) under visible-light irradiation. DRIFT and reactions under various conditions revealed that surface NO$_2^-$ species is an intermediate in the reaction and reacts with adsorbed NH$_3$ under visible-light irradiation to selectively form N$_2$.
Supporting Information

1. Preparation of catalyst

The dye-modified TiO$_2$ photocatalysts were prepared by a simple impregnation method using organic solvent as shown Table S1.

**Table S1.** Solvent used for the impregnation

<table>
<thead>
<tr>
<th>Entry</th>
<th>Dye</th>
<th>Solvent used for the impregnation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N3 dye$^{[a]}$</td>
<td>Methanol</td>
</tr>
<tr>
<td>2</td>
<td>Rose bengal</td>
<td>Methanol</td>
</tr>
<tr>
<td>3</td>
<td>Eosin Y</td>
<td>Methanol</td>
</tr>
<tr>
<td>4</td>
<td>Ru(bpy)$_3$Cl$_2$</td>
<td>Methanol</td>
</tr>
<tr>
<td>5</td>
<td>Rhodamine B</td>
<td>Methanol</td>
</tr>
<tr>
<td>6</td>
<td>Coumarin 343</td>
<td>Methanol</td>
</tr>
<tr>
<td>7</td>
<td>TCPP$^{[b]}$</td>
<td>Methanol</td>
</tr>
<tr>
<td>8</td>
<td>Methylene blue</td>
<td>Methanol</td>
</tr>
<tr>
<td>9</td>
<td>Zn phosphacyanine</td>
<td>Trifluoroacetic acid</td>
</tr>
<tr>
<td>10</td>
<td>Congo red</td>
<td>Water</td>
</tr>
<tr>
<td>11</td>
<td>Phthalocyanine</td>
<td>Trifluoroacetic acid</td>
</tr>
<tr>
<td>12</td>
<td>RhCl$_3$</td>
<td>Water</td>
</tr>
<tr>
<td>13</td>
<td>Indigo carmine</td>
<td>Water</td>
</tr>
<tr>
<td>14</td>
<td>Cu phosphacyanine</td>
<td>Trifluoroacetic acid</td>
</tr>
<tr>
<td>15</td>
<td>Carmine</td>
<td>10 mmol L$^{-1}$ NaOH aq.</td>
</tr>
</tbody>
</table>

$^{[a]}$ Ru(4,4’-dicarboxy-2,2’-bipyridine)$_2$(NCS)$_2$

$^{[b]}$ Tetrakis(4-carboxyphenyl)porphyrin
2. Reactivity of oxidation product of N3 dye

As shown in the main text, we tried to prepare the one electron oxidation product of N3-dye using Cl₂ as an oxidant. Figure S1 shows the UV-Vis DR spectra of N3-dye and the photographs of the catalysts. After evacuation, the catalyst color was the dark purple (a), and an absorption band at 515 nm was observed. The band is assigned to a MLCT band of the grand state N3-dye (Ru²⁺). After addition of Cl₂, the catalyst color changed from dark purple into ocher (b), and the absorption peak was shifted to 420 nm. The band at 420 nm is not attributed to the one electron oxidation products (Ru³⁺) of N3-dye because the one electron oxidation product have an adsorption band around 740 nm, which was observed in several transient adsorption experiments.

S. Das and P. V. Kamat [2] investigated the oxidized form of N3-dye by using transient absorption spectroscopy using azide (N3•) radical generated by γ-Radiolysis as an oxidant. Their results provided the spectral evidence for the formation of two different species that follow the oxidation of N3 dye. One oxidized product (species 1, abs. max: 740 nm) was attributed to the one-electron oxidation product of N3-dye, and is undergone further transformations to the other oxidized form (species 2, abs. max: 440 nm) at room temperature. The identification of species 2 was not made in their report. The ocher products (abs. max: 420 nm) observed in our UV-Vis DR experiments can be assigned to the species 2 judging from the position of adsorption maximum.

To examine the reactivity of species 2, NH₃ was introduced to the cell. After addition of NH₃, the catalyst color changed into the initial dark purple as shown in Figure S1(c). This result clearly indicates that species 2 can react with NH₃ and returned to the initial ground state of N3 dye (eq. 3 in the main text). Although the identification is not made, and which oxidation products (species 1 or 2) activate NH₃ in the in situ reaction condition is unclear, the UV-Vis DR spectroscopy revealed that oxidized products (at least, species 2) of N3-dye have a potential to activate NH₃.

Figure S1. UV-Vis DR spectra and photographs of 37.5 μmol g⁻¹ N3-TiO₂ photocatalyst after evacuation (a), after addition of Cl₂ (b), and after addition of NH₃ (c).

3. UV-Vis DR spectra of dye-modified TiO₂ photocatalysts

Figure S2. UV-Vis DR spectra of the dye-modified TiO₂ photocatalysts. Dye loading: 12.5 μmol g⁻¹.