

EES Catalysis

rsc.li/EESCatalysis



ISSN 2753-801X

PAPER

Baodong Wang, Ziran Ma, Yujie Xiong, Yun Wang *et al.*
An anti-poisoning defective catalyst without metal active
sites for NH_3 -SCR via *in situ* stabilization



Cite this: *EES Catal.*, 2023,
1, 134

An anti-poisoning defective catalyst without metal active sites for NH₃-SCR *via in situ* stabilization†

Ge Li,^a Baodong Wang,^{id} *^{ab} Ziran Ma,^{*a} Jing Ma,^a Hongyan Wang,^a Jiali Zhou,^a Shengpan Peng,^{id} ^a Jessica Jain White,^c Yonglong Li,^a Jingyun Chen,^a Zhihua Han,^a Hui Wei,^a Chuang Peng,^{id} ^d Yujie Xiong^{id} *^e and Yun Wang^{id} *^c

NO_x emission can be controlled through selective catalytic reduction (SCR) by ammonia in industry. However, the SCR catalysts are sensitive to contaminants. Searching for anti-poisoning catalysts has become a perpetual quest for large-scale SCR. Here, we report that hydrogenated titanium dioxide particles containing oxygen vacancies undergo *in situ* N-doping during NH₃-SCR reaction. The N-doped hydrogenated TiO_{2-x} exhibits high denitrification activity and selectivity, long-term stability, H₂O and SO₂ tolerance, and high poisoning resistance. The DRIFT spectra combined with density functional theory computations demonstrate that the N-dopant as the catalytic active site can enhance O₂ and NO adsorption, which can be reduced by NH₃ *via* the Eley–Rideal mechanism. This is greatly different from traditional catalysts with metal active sites for NH₃ adsorption. The high anti-poisoning performance can be ascribed to the weak interaction between N and toxic reactants. This discovery creates a new concept that non-metal active sites can replace conventional precious/transition metals to avoid poisoning, while being stabilized by *in situ* doping with reactants.

Received 25th October 2022,
Accepted 16th January 2023

DOI: 10.1039/d2ey00077f

rsc.li/eescatalysis

Broader context

NO_x emission can be controlled through selective catalytic reduction (SCR) by ammonia in industry. However, the SCR catalysts are sensitive to contaminants. Searching for anti-poisoning catalysts has become a perpetual quest for large-scale SCR. We report that hydrogenated titanium dioxide particles containing oxygen vacancies undergo *in situ* N doping during NH₃-SCR reaction. The N-doped hydrogenated TiO_{2-x} exhibits high denitrification activity and selectivity, long-term stability, H₂O and SO₂ tolerance, and high poisoning resistance. The DRIFT spectra combined with density functional theory computations demonstrate that the N-dopant as the catalytic active site can enhance O₂ and NO adsorption, which can be reduced by NH₃ *via* the Eley–Rideal mechanism. This is greatly different from traditional catalysts with metal active sites for NH₃ adsorption. The high anti-poisoning performance can be ascribed to the weak interaction between N and toxic reactants. This discovery creates a new concept that non-metal active sites can replace conventional precious/transition metals. Moreover, the results of this work provide a better understanding of the role of defect engineering for the design of highly poison-resistant, stable catalysts for a wide variety of reactions.

Introduction

Nitrogen oxides (NO_x) are one of the main air pollutants, and the source of acid rain, ozone, photochemical smog, regional ultrafine particle (PM_{2.5}) and haze, which affect human health and sustainable economic development. Selective catalytic reduction (SCR) is the most efficient and mature denitrification technology in stationary and mobile sources. Its success is determined by the development of NH₃-SCR catalysts with high activity, selectivity and long-term stability. The active components are often made of precious/transition metals that account for 50–70% of the total cost of the catalyst. Moreover, in the real denitrification process, alkali/alkaline metals (Na, K, Ca *etc.*), heavy metals (As, Pd, *etc.*), P, SO₂ and water vapor could deactivate the catalysts severely. These poisons can block,

^a National Institute of Clean-and-Low-Carbon Energy, Beijing 102211, China.

E-mail: baodong.wang.d@chnenergy.com.cn, ziran.ma@chnenergy.com.cn

^b NICE Europe Research GmbH, Stockholmer Platz 1, Stuttgart 70173, Germany

^c Centre for Catalysis and Clean Energy, School of Environment and Science,

Gold Coast Campus, Griffith University, Queensland 4222, Australia.

E-mail: yun.wang@griffith.edu.au

^d School of Resource and Environmental Sciences and Hubei International Scientific

and Technological Cooperation Base of Sustainable Resource and Energy,

Wuhan University, Wuhan 430072, China

^e School of Chemistry and Materials Science, University of Science and Technology

of China, Hefei, Anhui 230026, China. E-mail: yjxiong@ustc.edu.cn

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2ey00077f>



directly combine with or react with the active components of the catalysts, leading to limited useable lifespan of the catalysts and high economic cost due to frequent catalyst replacement.^{1–6} To this end, the anti-poisoning performance of denitrification catalysts is not only an important indicator affecting the cost of the catalysts, but also an aspect of the sustainable development of $\text{NH}_3\text{-SCR}$.

Various additives including sacrificial agents or acidic/basic additives have been used to modify the denitrification catalyst support structures. Other approaches have involved controlling the catalyst synthesis to tune the crystalline structure, morphology, distribution of active components and interaction of the metal with the support to improve the anti-poisoning characteristics.^{2–6} However, these methods only reduce poisoning agents without completely eliminating them. Therefore, the development of low-cost, poisoning-resistant denitrification catalysts is an ultimate goal. One promising strategy for the design of anti-poisoning catalysts is through defect engineering.^{7–25} The distortion of the crystal structure can modify the Fermi energy level to promote the electron transitions necessary for the catalytic effect.^{7–9} In addition, the defects can act as the active components for reactant adsorption, facilitate electron interaction and transfer, and reduce intrinsically wide band gaps. More importantly, the precious/transition metals are no longer required to act as active components because the defects can act as the active sites with unsaturated coordination numbers. As such, the poisoning of precious/transition metals would be mitigated, while the expense of the catalysts can be greatly reduced. However, some defects are very unstable, forming a major obstacle for practical applications. For example, the oxygen vacancies can be re-oxidized during prolonged storage in the atmosphere.^{26–29} Therefore, such oxygen vacancy-based catalysts need to be stored in isolation from oxygen, which increases the cost and restricts industrial applications. To address this issue, it is desirable to design poison-resistant defective catalysts with outstanding stability, but this is challenging.

Here, we demonstrated that the defect sites designated for $\text{NH}_3\text{-SCR}$ reaction can be stabilized by their interaction with reactants (NH_3 and NO), overcoming the dilemma between catalyst activity and stability. To eliminate the use of precious/transition metals, oxygen vacancies were created in TiO_2 crystals using a hydrogenation method. The hydrogenated TiO_{2-x} (H-TiO_{2-x}) was used as a catalyst for the $\text{NH}_3\text{-SCR}$, which leads to *in situ* N-doping on the defective H-TiO_{2-x} catalyst (N-H-TiO_{2-x}). Our results reveal that N-H-TiO_{2-x} exhibits superior denitrification activity. More importantly, it has long-term stability because of its tolerance of H_2O and SO_2 and significant poisoning resistance, such as SO_2 , H_2O , P, and alkali metals. The results of this work provide a better understanding of the role of defect engineering for the design of highly poison-resistant, stable catalysts for a wide variety of reactions.

Results and discussion

$\text{NH}_3\text{-SCR}$ performance of the hydrogenated TiO_{2-x} catalyst

Fig. 1 shows the $\text{NH}_3\text{-SCR}$ activity of the H-TiO_{2-x} catalyst compared with those of pristine TiO_2 and commercial VW/Ti



Fig. 1 $\text{NH}_3\text{-SCR}$ denitrification activity of the catalyst. (a) The denitrification performances of pristine TiO_2 , H-TiO_{2-x} and VW/Ti catalysts. (b) Data from 500 h durability trials with the H-TiO_{2-x} catalyst at 350 °C. (c) Tolerance of K_2O and P_2O_5 of the H-TiO_{2-x} catalyst and of commercial VW/Ti catalysts at 350 °C.

catalysts. From Fig. 1a the denitrification efficiency of the pristine TiO_2 was only 7.3–12.8% at 250–400 °C. However, following hydrogenation, the denitrification activity was dramatically increased, to more than 90% at 300–400 °C, representing an increase of approximately 80%, almost reaching the efficiency of the commercial VW/Ti catalyst. The selectivity for N_2 was essentially unchanged after hydrogenation, remaining above 87.5% (Fig. S1, ESI†). The stability and resistance to H_2O , SO_2 , K_2O and P_2O_5 of the H-TiO_{2-x} catalyst were also tested. As shown in Fig. 1b, a 500 h stability test was carried out to investigate the stability of the catalyst at 350 °C. The denitrification efficiency was found to slightly decrease by 4.86%, while the N_2 selectivity dropped by only 3.29% for 200 h with NH_3 , NO and O_2 blowing in. The resistance of the H-TiO_{2-x} catalyst to H_2O and SO_2 at 350 °C is followed, conducted as shown in Fig. 1b, which indicates that the denitrification efficiency dropped sharply (by 31.3%) after 8% H_2O was introduced into the reaction system for 30 h. Water molecules are believed to have covered the oxygen vacancies on the surface of the catalyst or to have competed with NO and/or NH_3 for adsorption on the catalyst surface, resulting in a decrease in denitrification activity. Interestingly, when 800 ppm SO_2 was also introduced into the reaction system, the denitrification activity slowly increased and was maintained at 77–79% for 220 h. These results demonstrate that hydrogenated TiO_{2-x} showed good water and sulfur resistance and suitable long-term stability. The trial using 8% H_2O and 800 ppm SO_2 at 350 °C provided a N_2 selectivity of greater than 98% (Fig. 1b). This performance can possibly be ascribed to the formation of more acidic sites on the surface of the catalyst following the introduction of SO_2 , leading to an increase in the activity and the N_2 selectivity.^{30,31} When the supply of SO_2 was cut off, the NO_x conversion remained relatively constant, while after the H_2O flow was stopped, the NO_x conversion increased sharply and returned to its initial level. These results establish that the effects of water on the catalyst were reversible. To better evaluate the anti-poisoning performance of the hydrogenated TiO_{2-x} catalyst, a conventional SCR catalyst (1V8W/ TiO_2) was prepared for comparison and simulated poisoning experiments were conducted using an impregnation method. Fig. 1c demonstrates that, under the same temperature and reaction conditions, the denitrification activity of the 1V8W/ TiO_2 catalyst was decreased by 7.6% and 22.67% with K and P poisoning, respectively.



Surprisingly, the performances of the hydrogenated TiO_{2-x} catalysts poisoned by K and P were almost unchanged.

Reaction mechanism

The HRTEM and XRD results shown in Fig. S2 and S3 (ESI[†]) demonstrated that the phase composition of the H-TiO_{2-x} was primarily anatase. The Raman, EPR, ^1H NMR and photoluminescence spectra combined with the O_2 -TPD and H_2 -TPD shown in Fig. S4–S9 (ESI[†]) further demonstrate the existence of oxygen vacancies. The *in situ* X-ray photoelectron spectroscopy (XPS; Fig. S10–S12, ESI[†]) results confirm that oxygen vacancies and $\text{Ti}^{3+}/\text{Ti}^{4+}$ were produced on the surface of the H-TiO_{2-x} catalyst. The *in situ* XPS data obtained during the NH_3 -SCR reaction are presented in Fig. 2 and Fig. S13–S15 (ESI[†]). Fig. 2a presents the N 1s spectra of the material. The spectra obtained over the range of 150–400 °C each contain a O–Ti–N peak related to interstitial doping at approximately 399 eV. The transition from a mixture of Ti^{3+} and Ti^{4+} to solely Ti^{4+} after N-doping is shown in Fig. S14 (ESI[†]). Because the electronegativity and radius of the N ions (3.04 and 0.171 nm, respectively) are similar to those of O ions (3.44 and 0.140 nm, respectively), N-doping of the H-TiO_{2-x} crystal lattice is expected. The N-doping into the H-TiO_{2-x} catalyst might have come from NH_3 or NO_x in the reaction gas. Thus, XPS spectra were obtained from the H-TiO_{2-x} after trials in which only NH_3 or $\text{NO} + \text{O}_2$ were present. Fig. S16 (ESI[†]) demonstrates that N-doping of the H-TiO_{2-x} catalyst surface occurred under both conditions. Previous studies have shown that the nitrogen-doping of TiO_2 can proceed under an NH_3 atmosphere at 500 °C as N from NH_3 partially replaces the lattice oxygen of TiO_2 , forming O–Ti–N and oxygen vacancies. The present hydrogenation process generated oxygen vacancies in the TiO_2 in advance, making nitrogen-doping more likely to occur at lower

temperatures (150–400 °C), which is a unique phenomenon in the de NO_x reaction. Based on the NIST database,³² the peaks near 406–407 eV were attributed to N–H bonds in NH_4NO_3 . As shown in Fig. 2b, the N–H peak gradually decreased with increasing temperature, while the O–Ti–N peak gradually increased, suggesting that elevated temperature promotes N-doping. Comparing these data to the results shown in Fig. 1a demonstrates that the degree of N-doping was proportional to the denitrification activity. The results from 200 h stability trials with only NH_3 , NO and O_2 blowing in indicated that *in situ* N-doping improved the stability of the catalyst.

The local atomic structure and cation coordination in the catalyst before and after N-doping were ascertained using XAFS (Fig. 3). The Ti K-edge X-ray absorption near-edge structure (XANES) spectra of hydrogenated TiO_{2-x} and the N-hydrogenated TiO_{2-x} catalyst possessed three typical pre-edge peaks associated with the anatase phase (denoted as A1, A2, and A3 at 4968, 4971, and 4974 eV, respectively), corresponding to quadruple-allowed 1s to 3d transitions.¹⁹ Furthermore, it has recently been suggested that most of the contribution to pre-edge splitting is from the edge and corner sharing of Ti ions in the TiO_6 octahedra with oxygen ions, which lead to non-local, intersite hybrid excitations. Therefore, the variation in pre-edge peak area during sample



Fig. 2 The *in situ* XPS spectra obtained from the H-TiO_{2-x} during the NH_3 -SCR process at 150–400 °C. (a) N1s. (b) Surface N atom concentrations and O–Ti–N concentrations at various temperatures. (c) Percentage content of the active components O, N and Ti ($\text{O}' = \text{O}_\beta + \text{O}_\gamma$).

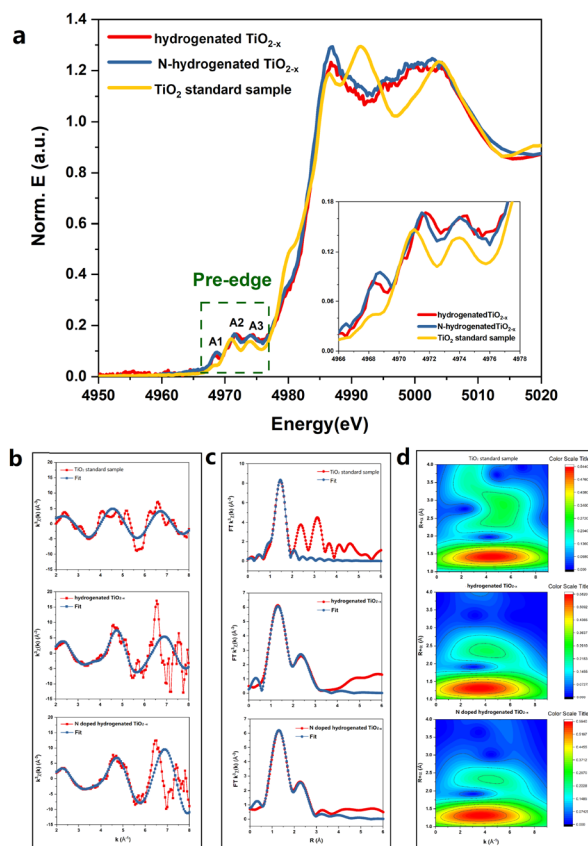


Fig. 3 The XANES spectra of the catalyst samples before and after the SCR reaction. (a) The Ti K-edge, (b) extended region fitting using ARTEMIS in R-space, (c) fitted magnitude of k_3 -weighted Ti K-edge EXAFS spectra, and (d) wavelet transform images obtained for the TiO_2 standard sample (anatase), hydrogenated TiO_{2-x} and N-hydrogenated TiO_{2-x} .



etching can be interpreted as the change in the Ti 3d unoccupied states due to the interaction of Ti 4p, O 2p, and Ti 3d states. The total area of the pre-peaks was associated with the number of unoccupied next-nearest-neighbour Ti 3d states. As clearly shown in Fig. 3, for both hydrogenated TiO_{2-x} and the N-hydrogenated TiO_{2-x} catalyst, the area of the near-side peaks was significantly larger than that of the TiO_2 standard sample (anatase), which was due to oxygen vacancies. For the hydrogenated TiO_{2-x} catalyst and N-hydrogenated TiO_{2-x} catalyst, the A1, A2, and A3 peaks were all observed to shift to a higher energy compared with the TiO_2 standard sample (anatase). This was attributed to the higher oxidation state of the core metal atom (Ti), as induced by oxygen vacancies in the coordination sphere. The intensity of the A2 peak increased with increasing site distortion in the order $\text{TiO}_2 < \text{hydrogenated TiO}_{2-x} \approx \text{N-hydrogenated TiO}_{2-x}$. The introduction of oxygen vacancies made the crystal lattice more disordered. From Fig. 3a, after N-doping, the A2 peak of the catalyst was shifted to a slightly lower energy, supporting that nitrogen filled the oxygen vacancies. Fig. 3b and c show the EXAFS oscillations for the standard, hydrogenated and N-hydrogenated TiO_{2-x} , respectively. Fig. 3d clearly demonstrates that the Ti-O coordination environment was only minimally changed after N-doping, while the Ti-Ti coordination environment changed greatly. These changes confirm the transition from a mixture of Ti^{3+} and Ti^{4+} to solely Ti^{4+} after N-doping.

The distributions of formal valences in the catalyst before and after N-doping were probed using EELS-STEM, while simultaneously acquiring Ti-L, N-K and O-K edge data (Fig. 4). The Ti-L edge provided a fingerprint of the Ti^{4+} and Ti^{3+} states and the O-K edge was sensitive to the presence of oxygen vacancies. In the case of the H- TiO_{2-x} catalyst, the EELS spectra were collected close to (0.9, 1.8, 2.7 and 3.6 nm) and far

from (6.3 nm) the interface and the results are presented in Fig. 4a. These data indicate that the Ti-L2 peak was shifted by 0.6 eV from the crystalline side to the amorphous side, demonstrating the presence of Ti^{3+} in the amorphous layer, at the interface and on the crystalline side close to the interface (within 2.7 nm). In Fig. 4b, the N-K peak appeared at 0.9 nm, showing that the surface nitrogen-doping occurred primarily in the amorphous layer. Furthermore, no Ti-L peak shifts were observed, further demonstrating that Ti^{4+} was the primary state in the N-hydrogenated TiO_{2-x} .

Fig. 5 and Fig. S17 (ESI[†]) provide the *in situ* infrared spectra of H- TiO_{2-x} and pristine TiO_2 . These data indicate that very little NO or O_2 was adsorbed on the pristine TiO_2 (Fig. 5a), while bridged bidentate nitrate (at 1610 cm^{-1}), chelated bidentate nitrate (1578 and 1238 cm^{-1}) and monodentate nitrite (1350 cm^{-1})³⁰ were formed on the hydrogenated TiO_{2-x} . These results are in agreement with the poor denitrification activity of this material. This difference is attributed to the abundant oxygen vacancies present on the H- TiO_{2-x} surface, which are able to oxidize NO to NO_2 and generate a series of nitrates and nitrites. Exposure to NH_3 did not modify the surface of the pristine TiO_2 although the chelated bidentate nitrate on the H- TiO_{2-x} disappeared and no NH_3 adsorption peak was obtained, indicating that gaseous NH_3 reacted with nitrate on the catalyst surface. Following the surface adsorption of NH_3 (Fig. 5b), the pristine TiO_2 generated an NH_3 adsorption peak at the L acid position at 1103 cm^{-1} . The results obtained from NH_3 -temperature programmed desorption (Fig. S18, ESI[†]) and pyridine adsorption infrared spectroscopy (Fig. S19, ESI[†]) show that the pristine TiO_2 was somewhat acidic and was also able to adsorb NH_3 . In contrast, the surface adsorption of NH_3 on the H- TiO_{2-x} generated NH_4^+ at B acid sites (1633 cm^{-1}) together with NH_2 (1322 and 1492 cm^{-1}) and NH_3 at L acid sites (1197 cm^{-1}). Exposure to NO and O_2 had little effect on the surface of the pristine TiO_2 . However, the

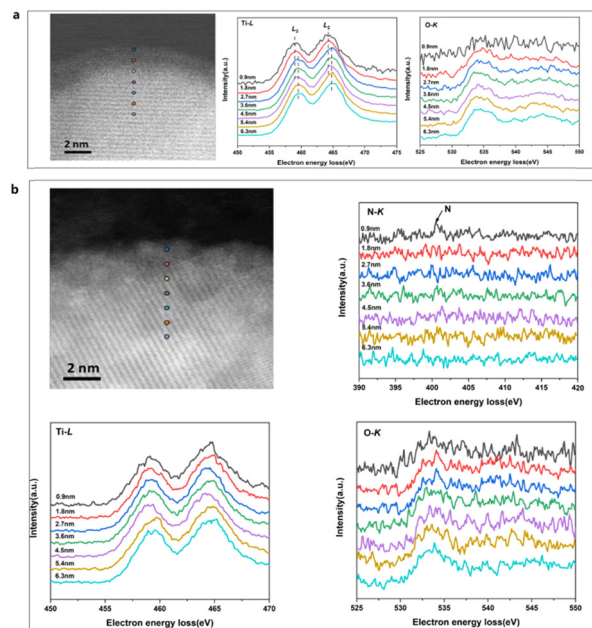


Fig. 4 The EELS-STEM spectra of the catalysts. (a) The H- TiO_{2-x} catalyst and (b) the N-H- TiO_{2-x} catalyst.



Fig. 5 The DRIFT spectra obtained from the hydrogenated TiO_{2-x} and pristine TiO_2 . (a) NO and O_2 followed by NH_3 at $300\text{ }^\circ\text{C}$. (b) NH_3 followed by NO + O_2 at $300\text{ }^\circ\text{C}$. (c) NH_3 + NO + O_2 for 30 min at $300\text{ }^\circ\text{C}$. (d) NH_3 + NO + O_2 with a temperature gradient.

H-TiO_{2-x} formed bridged bidentate nitrate (1606 cm⁻¹), chelated bidentate nitrate (1578 and 1236 cm⁻¹), monodentate nitrite (1517 cm⁻¹) and ammonium nitrate (1346 cm⁻¹). The NH₃ adsorption peaks at L acid and B acid sites also disappeared, indicating that NO_x had reacted with adsorbed NH₃. These results confirmed that the adsorption of NH₃ and gaseous NO_x proceeded according to the Eley-Rideal mechanism.³³⁻³⁵

Fig. 5c shows the *in situ* infrared spectra obtained from the N-H-TiO_{2-x} catalyst at 300 °C following a simultaneous exposure to NO, O₂ and NH₃. When the three gases were introduced for 5 min, peaks related to bridged bidentate nitrate (1655 cm⁻¹), monodentate nitrate (1543 cm⁻¹) and monodentate nitrite (1368, and 1320 cm⁻¹) appeared.³⁶ With prolonged exposure to the three gases simultaneously, the intensity of these peaks changed only minimally, indicating that these compounds were stable on the catalyst surface. No NH₃ adsorption peak was observed, which suggests that NH₃ is the primary participant in the gas phase NH₃-SCR reaction. Fig. 5d provides the steady state *in situ* infrared spectra acquired from the N-H-TiO_{2-x} catalyst surface at different temperatures in conjunction with the simultaneous introduction of NH₃, NO and O₂ during the SCR reaction. At 100 °C, a series of peaks attributed to NO_x species adsorbed on the catalyst surface appeared. The peaks at 1658 and 1540 cm⁻¹ represent bridged and chelated bidentate nitrates, respectively, while those at 1365 and 1326 cm⁻¹ indicate monodentate nitrite. As the temperature was gradually increased, the intensity of the chelated bidentate nitrate peak decreased significantly, due to desorption from the catalyst surface. Again, peaks related to the adsorbed NH₃ were not observed. It is apparent that NH₃ and chelated bidentate nitrate were active on the catalyst surface and participated in the SCR reaction through the Eley-Rideal mechanism. We will carry out kinetic experiments in the subsequent research and quantify the proportion of E-R mechanism according to the kinetic calculation. It is worthy of note that the assignment of the band at 1417 cm⁻¹ still needed further identification. The peaks in some studies³⁷⁻⁴⁰ are close to 1417 cm⁻¹, but their attribution of this peak is various. Moreover, we have not found literature with exactly the same peak as ours. This may be because other studies are all on catalysts with metal active sites and the functional groups on the catalyst surface are different from those of our catalysts without metal active sites. The peak of 1417 cm⁻¹ in the *in situ* infrared spectrum is unique to our catalyst. As such, the ascription of the strong IR absorption peak at 1417 cm⁻¹ could be based on other characterizations and DFT simulation in our subsequent research.

DFT calculations

Density functional theory (DFT) calculations were performed to better understand the role of lattice defects in the catalytic process.³⁷⁻³⁹ The adsorption properties of specific small molecules on the pristine TiO₂ (101), H-TiO_{2-x}, and N-H-TiO_{2-x} surfaces are presented in Fig. 6a-c. The Raman, EPR, ¹H NMR and photoluminescence spectra combined with the O₂-TPD and H₂-TPD shown in Fig. S4-S9 (ESI[†]) demonstrate the existence of oxygen vacancies in H-TiO_{2-x}. As a result, one surface oxygen

vacancy was introduced here to model H-TiO_{2-x}. The oxygen vacancy was highlighted by a blue circle shown in Fig. 6b. The adsorption energies indicate that the pristine TiO₂ has a weak interaction with O₂ and NO. As a comparison, the adsorption of NH₃ on this surface was stronger. The surface Ti⁴⁺ as L acid sites can adsorb a significant quantity of NH₃. On H-TiO_{2-x}, the O₂ and NO can tightly bind with the vacancy. NH₃ can still adsorb on L acid sites with an enhanced interaction strength. The adsorption energies of reactants match the NH₃-TPD and Py-IR spectra shown in Fig. S18 and S19 (ESI[†]). However, the strong adsorption of NO and NH₃ disagrees with DRIFT data with the Eley-Rideal mechanism because NH₃ needs to directly interact with the adsorbed reactants. This indicates that the oxygen vacancy is not the active site during the reactions. Interestingly, the NO and O₂ can tightly adsorb through the interaction with the N-dopant after *in situ* N-doping. This indicates that the surface N-dopant can act as the catalytic active site. In particular, the NO adsorption energy on N via a N-N-O configuration is -2.88 eV (see Fig. 6c), which is 1.04 and 1.80 eV lower than those of O₂ and NH₃. The formation of a N-N bond weakens the N-O bond in NO, as evidenced by the enlarged N-O bond length from 1.17 in NO gas to 1.32 Å after adsorption. More importantly, the NH₃ can dissociatively adsorb on the pre-adsorbed NO to form *OH and *N-NH₂ as shown in Fig. 6d. The dissociative adsorption of NH₃ on the -N-N-O site is because N in NO carries a positive charge and, therefore unoccupied orbitals. On the other hand, the N in NH₃ has lone-pair electrons. As a result, the N in NH₃ can strongly

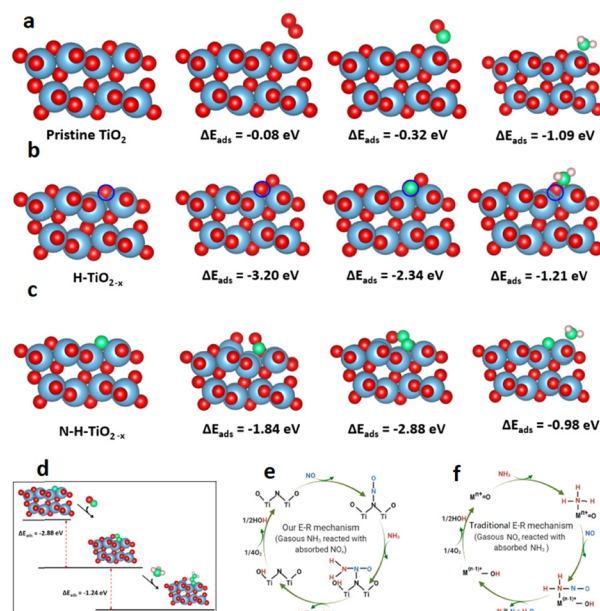


Fig. 6 (a) Adsorption of O₂, NO and NH₃ on pristine TiO₂ (101), (b) adsorption of O₂, NO and NH₃ on H-TiO_{2-x}, (c) adsorption of O₂, NO and NH₃ on N-H-TiO_{2-x}, (d) reaction coordinates of NH₃-SCR via the Eley-Rideal mechanism, (e) SCR reaction routes at the N active sites in the N-H-TiO_{2-x} catalyst, and (f) SCR reaction routes at the metal active sites in the traditional catalysts. Legend: red = O; blue = Ti; pink = H; and green = N; blue circle = oxygen vacancy.



bind with N in adsorbed NO through dative covalent bonding. At the same time, the NH_3 was dissociated after the adsorption because of the strong O–H bonding between the negatively charged O in NO and positively charged H in NH_3 . The adsorption energy is -1.24 eV, which is 26.5% lower than that of the direct adsorption of NH_3 on the Ti^{4+} L acid site. Moreover, there is no steric effect in the interaction between NH_3 and NO. Consequently, the Eley–Rideal mechanism derived from the DRIFT spectra is supported by the DFT results. The novel SCR reaction route through the adsorption of NO on the N active sites in the N-H-TiO_{2-x} catalyst is illustrated in Fig. 6e, which is compared with the mechanism through the adsorption of NH_3 on metal active sites in the traditional catalysts shown in Fig. 6f.

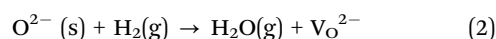
The DFT computations combined with *in situ* DRIFTS experiments were also used to explain the resistance of the N-H-TiO_{2-x} catalyst to H_2O , SO_2 and K poisoning. Fig. 7a shows that the water can adsorb at the bridge site between surface Ti^{4+} and N atoms on N-H-TiO_{2-x} *via* hydrogen bonding. As a result, the N active sites can be blocked by adsorbed H_2O . This explains why the activity drops after the exposure of water, as shown in Fig. 1b. However, as the interaction strength of -0.87 eV is moderate *via* hydrogen bonding, the impact of H_2O adsorption on the electronic properties of N-H-TiO_{2-x} is limited. As such, the selectivity only changes slightly. After the further exposure of SO_2 , the adsorbed water can interact with SO_2 and O_2 to form H_2SO_4 .^{40,41} The formation and desorption of H_2SO_4 is an exothermal process with the reaction energy of -1.32 eV. This indicates that the adsorbed water can be removed after the exposure of SO_2 and O_2 , which can reactivate N active sites for denitrification, as shown in Fig. 1b, so that the activity of the N-H-TiO_{2-x} catalysts recovers after the exposure of SO_2 to the catalyst with pre-adsorbed water. The DFT calculations also reveal that K atoms prefer not to adsorb on the oxygen vacancy, even when the K atom was initially placed at the vacancy site. The most stable configuration is shown in

Fig. 7b. This is reasonable because the system becomes more stable when the K atom is bonded with more surface oxygen atoms. This means that the vacancy for the formation of active sites *via in situ* N-doping will not be poisoned by K. More interestingly, the NO adsorption can be strengthened when K is next to the N active site since K can extract O from NO, which leads to the formation of N_2 at the active site. This result explains why the denitrification efficiency increases slightly after K poisoning, as shown in Fig. 1c. When the metal acts as the active site in traditional NH_3 -SCR catalysts, *e.g.*, VW/Ti, the metal as L acid sites can accommodate the lone pair electrons of O and S in toxic substances, which is the origin of the poisoning of these catalysts. Our results, therefore, demonstrate the unique anti-poisoning advantage of the non-metal active site for NH_3 -SCR.

Experimental

Synthesis of hydrogenated TiO_{2-x} catalysts

Commercial titanium dioxide (Denox Advanced Material Co., Ltd in China, TiO_2 97%, BET 323.36 $\text{m}^2 \text{g}^{-1}$, rutile and anatase) powder was placed into a fixed bed reactor. Hydrogenated TiO_{2-x} catalysts with Ti^{3+} were prepared by a hydrogen thermal reduction treatment method by heating commercial titanium dioxide powders in 99.99% H_2 at 450 °C (heating rate 5 °C min^{-1}) under ambient pressure for 12 h. The H_2 flow velocity (100 mL min^{-1}) was controlled using a gas flow controller during hydrogen reduction treatment until cooling to room temperature. The hydrogenated TiO_{2-x} powder is placed in a vacuum dryer to prevent the oxygen in the air from further oxidizing the catalyst. Hydrogenated TiO_{2-x} powder was obtained as shown in eqn (1) and (2).



where V_{O}^{2-} represents the oxygen vacancy.

A typical impregnation method was applied to prepare the alkali and P-poisoned catalysts. According to the literature, the mass ratios of K and P are 0.6 and 1 wt%, respectively. Therefore, 1 g of catalyst, 50 mL of deionized water, and a corresponding amount of KCl or/and $\text{NH}_4\text{H}_2\text{PO}_4$ were stirred together, dried, and calcined at 550 °C for 4 h in N_2 . For comparison, commercial 1%V8%W/Ti catalyst poisoning was also prepared according to the above method. The poisoned samples were denoted as K-hydrogenated TiO_{2-x}, P-hydrogenated TiO_{2-x}, K-VW/Ti and P-VW/Ti.

Characterization of the materials

X-Ray diffraction (XRD) was performed using a D8 ADVANCE diffractometer (Bruker, Germany), using Cu K α radiation and a step size of 0.02°. Data were collected from 5° to 90° at a scanning rate of 3° min^{-1} .

High-resolution transmission electron microscopy (HRTEM) was performed using a JEOL JEM ARM200F instrument (Japan).



Fig. 7 (a) Reaction coordinates of adsorption of water followed by SO_2 on N-H-TiO_{2-x}, and (b) adsorption of K on H-TiO_{2-x} and N-H-TiO_{2-x} and NO adsorption on K-N-H-TiO_{2-x}. Legend: red = O; blue = Ti; pink = H; green = N; yellow = S; purple = K; and blue circle = oxygen vacancy.



The electron paramagnetic resonance (EPR) spectra of the samples were acquired using a Bruker A320 instrument. The samples (0.12 g) were loaded into quartz tubes. EPR experiments of titanium dioxide powders and hydrogenated TiO_{2-x} samples were conducted under normal temperature and pressure conditions. The reactor was placed in a heating furnace and heated to 500 °C at a heating rate of 10 °C min⁻¹ and pretreated with 2% O₂ for 1 h. After pretreatment, the gas supply was stopped and the reactor was sealed and cooled. Upon reaching room temperature, the EPR test was repeated. The magnetic field was swept from 1500 to 5000 G.

The Raman spectra were obtained using a LabRam HR-800 spectrometer (Horiba Jobin Yvon, France) with laser excitation at 532 nm.

X-Ray photoelectron spectroscopy (XPS) was performed using an ESCALAB 250xi instrument (Thermo Scientific, UK) using monochromatic Al K α radiation (1486.6 eV) at 25 W. The samples were outgassed overnight at room temperature in an ultrahigh-vacuum chamber ($<5 \times 10^{-7}$ Pa). All binding energies were referenced to the C 1s peak at 284.6 eV. Experimental errors were within ± 0.1 eV.

Solid-state NMR experiments were conducted on a Bruker Avance III HD/89 mm spectrometer with a 4 mm triple-resonance magic angle spinning probe.

O₂-temperature-programmed desorption (TPD) experiments were performed to determine the adsorption/desorption characteristics of each species over the catalyst. Each catalyst (200 mg) was loaded into the reactor, pretreated with N₂ (50 mL min⁻¹) at 100 °C for 30 min, and then cooled to room temperature in the same stream. The pretreated sample was then exposed to O₂ (3%) at a flow rate of 70 mL min⁻¹ for 30 min. Physisorbed O₂ was removed by flushing the catalyst with He at a flow rate of 30 mL min⁻¹ for 30 min at 120 °C prior to TPD. The samples were subjected to TPD in He (30 mL min⁻¹) from 100 to 600 °C at a heating rate of 10 °C min⁻¹.

H₂-temperature-programmed reduction (TPR) experiments were performed with an AutoChem II 2920 instrument (USA). The catalyst (0.3 g) was pretreated with Ar flow (50 mL min⁻¹) for 30 min at 500 °C to remove water and other impurities. As the samples cooled, the Ar flow was replaced with a reductive mixture of 10.0% H₂ in Ar and the reactor temperature was increased to 800 °C at a heating rate of 10 °C min⁻¹.

NH₃-TPD experiments were performed using an automatic physical and chemical adsorption instrument (AutoChem II 2920, Micromeritics). Before NH₃ adsorption at 373 K, the samples were heated at 773 K under He flow. The amount of NH₃ desorbed between 373 and 873 K at a heating rate of 10 K min⁻¹ was determined using an on-line gas chromatograph equipped with a thermal conductivity detector.

The diffuse reflectance infrared Fourier transform (DRIFT) spectra were recorded using an IR Prestige-21 instrument (Shimadzu) at a resolution of 4 cm⁻¹ and averaged over 500 scans. These experiments were performed by heating precalcined powder samples *in situ* from room temperature to 673 K at a heating rate of 5 K min⁻¹ under a pure N₂ flow (40 mL min⁻¹). The samples were kept at 673 K for 3 h and then

cooled to 323 K. Pyridine vapor (20 μL) was then introduced under a N₂ flow. The IR spectra were recorded at various stages of pyridine desorption, which was maintained by evacuation at progressively higher temperatures (323–473 K). A resolution of 4 cm⁻¹ was achieved after averaging 500 scans for all the IR spectra recorded.

The *in situ* X-ray photoelectron spectroscopy (*in situ* XPS) measurements were conducted on a near ambient pressure (up to 2.5 kPa) X-ray photoelectron spectroscopy system (SPECS) equipped with a monochromatized Al K α source ($h\nu = 1486.6$ eV), gas atmosphere XPS analysis chamber (up to 2.5 kPa, 1000 K), electron analyzer (Phoibos 150), three-differential pumping stage that separates the analysis chamber from the electron energy analyzer, and sample preparation chamber (up to 3.0 MPa and 873 K). The X-ray source was set at an acceleration voltage of 15 kV and an irradiation power of 80 W. A preparation chamber was used for catalyst activation. Afterwards, the chamber was evacuated, and the sample was directly transferred into the analysis chamber under vacuum to avoid exposure to air. Firstly, the temperature was raised to 150 °C and then NO (1% NO, N₂, and 2 L h⁻¹) and O₂ (99.99%, 2 L h⁻¹) were blown in simultaneously. NH₃ (1% NH₃, N₂, and 2 L h⁻¹) is then introduced one hour later. After the catalyst adsorption equilibrium, the Ti spectra (including the valence band spectra), O spectra and N spectra of the catalyst at 150 °C, 200 °C, 250 °C, 300 °C, 350 °C and 400 °C were collected, respectively.

The distribution of Brønsted (B) and Lewis (L) acids on the synthesized catalyst was characterized using the pyridine infrared adsorption (Py-IR) method (IRPrestige-21, Shimadzu, Japan). Catalyst powder (20–30 mg) was weighed onto a sheet with a diameter of 13 mm, which was then fixed in an infrared cell. The temperature was increased to 500 °C for 60 min, then decreased to 350, 200, 100, and 30 °C, holding at each temperature for 5 min to measure the background value. Pyridine was adsorbed at 30 °C for 1 h, then purged for 30 min, and the adsorption spectrum was obtained. The temperature was then increased to 100, 200, and 350 °C, holding at each temperature for 5 min to measure the desorption spectra. The infrared spectra of the catalyst were recorded in the region of 1700–1400 cm⁻¹.

Photoluminescence spectroscopy (PL) was used to investigate oxygen vacancies on the catalyst surface (LabRam HR-800, Horiba Jobin Yvon, France). The light-induced spectral curve was measured at room temperature, and He–Cd was used as the laser source ($\lambda = 325$ nm).

Thermogravimetric analysis, conducted on an STA 449 F3/QMS 403C instrument (Netzsch, Germany), was used to assess catalyst loss.

The catalyst electronic structure was determined using electron energy loss spectroscopy (EELS). The energy resolution of EELS with a monochromator was 0.15 eV measured at the full width at half-maximum of the zero-loss peak under vacuum, with the highest energy dispersion of 0.025 eV per channel. To obtain surface structures through direct observation of the atomic arrangement, an aberration-corrected dedicated FEI Titan Themis 60–300 instrument was used, achieving



atomic resolution (70 pm) in the high-angle annular dark-field imaging (HAADF) mode.

The X-ray absorption fine structure (XAFS) Ti K-edge spectra were collected at the BL07A1 beamline of the National Synchrotron Radiation Research Center (NSRRC). Data were collected in fluorescence mode using a Lytle detector, while the corresponding reference samples were collected in transmission mode. Samples were ground and uniformly coated on a special adhesive tape. The as-obtained XAFS data were processed in Athena (version 0.9.26) for background, pre-edge line, and post-edge line calibrations. Fourier transform fitting was then conducted in Artemis (version 0.9.26). The k_3 weighting, k range of 1–6 Å^{−1}, and R range of 1–4 Å were used for the fitting. The four parameters, namely, coordination number, bond length, Debye–Waller factor, and E_0 shift (CN, R , σ^2 , and ΔE_0), were fitted without any being fixed, constrained, or correlated. For wavelet transform analysis, $\chi(k)$ exported from Athena was imported into the Hama Fortran code. The parameters were as follows: R range, 1–4 Å; k range, 0–6 Å^{−1}; and k weight, 2; the Morlet function with $\kappa = 10$ and $\sigma = 1$ was used as the mother wavelet to provide the overall distribution.

NH₃-SCR activity measurements

The SCR reaction was evaluated in a fixed-bed reactor. The samples (0.3 g) were placed in reaction tubes, which were then placed in simulated flue gas for 2 h. The gas mixture contained NO (300 ppm), NH₃ (300 ppm), and O₂ (3%), with N₂ as the balancing gas. The gas hourly space velocity was ~30 000 h^{−1}. The catalytic activity was determined by analyzing the inlet and outlet gases using a flue gas analyzer (MultiGas 6030, MKS) at temperatures between 100 and 400 °C. At each temperature (100, 150, 200, 250, 300, 350, and 400 °C), the catalyst activity was determined after a reaction time of 1 h. The NO_x conversion and N₂ selectivity were calculated as follows:

$$\text{NO}_x \text{ conversion} = \frac{[\text{NO}_x]_{\text{in}} - [\text{NO}_x]_{\text{out}}}{[\text{NO}_x]_{\text{in}}} \times 100\% \quad (3)$$

$$\text{N}_2 \text{ selectivity} = \left(1 - \frac{2[\text{N}_2\text{O}]_{\text{out}}}{[\text{NO}_x]_{\text{in}} + [\text{NH}_3]_{\text{in}} - [\text{NO}_x]_{\text{out}} - [\text{NH}_3]_{\text{out}}} \right) \times 100\% \quad (4)$$

where NO_x is the sum of the NO and NO₂ concentrations, $[\text{NO}_x]_{\text{out}}$ is the outlet concentration of NO_x, $[\text{NO}_x]_{\text{in}}$ is the inlet concentration of NO_x, $[\text{NH}_3]_{\text{out}}$ is the outlet concentration of NH₃, $[\text{NH}_3]_{\text{in}}$ is the inlet concentration of NH₃, and $[\text{N}_2\text{O}]_{\text{out}}$ is the outlet concentration of N₂O.

For H₂O and combined SO₂ + H₂O resistance experiments, the SCR reaction was allowed to stabilize for 200 h at 350 °C with only 300 ppm NO + 3% O₂ + 300 ppm NH₃ blew in, generating steady-state conditions prior to introducing 8% H₂O for 40 h and a 500 ppm SO₂ + 8% H₂O combination for 340 h at 350 °C into the flue gas, respectively. Finally, SO₂ and H₂O were successively cut off.

DFT calculations

The Vienna *ab initio* package (VASP) was used to perform all density functional theory (DFT) calculations within the generalized gradient approximation (GGA) using the PBE formulation. The spin-polarization was considered in all computations. The projected augmented wave (PAW) potentials were selected to describe the ionic cores and account for valence electrons using a plane wave basis set with a kinetic energy cutoff of 500 eV. Partial occupancies of the Kohn–Sham orbitals were allowed using the Gaussian smearing method and a width of 0.05 eV. The electronic energy was considered self-consistent when the energy change was smaller than 10^{−5} eV. A geometry optimization was considered convergent when the force change was smaller than 0.01 eV Å^{−1}. On-site corrections (DFT+*U*) were applied to the 3d electrons of Ti atoms ($U_{\text{eff}} = 4.5$ eV) using the approach of Dudarev *et al.*

The equilibrium lattice constants of the anatase TiO₂ unit cell were optimized to $a = b = 3.858$ Å, $c = 9.652$ Å using a 10 × 10 × 4 Monkhorst-Pack k -point grid for Brillouin zone sampling. These constants were then used to construct a TiO₂(101) surface model with $p(1 \times 3)$ periodicity in the x and y directions and two stoichiometric layers in the z direction with a vacuum depth of 15 Å to separate the surface slab from its periodic duplicates. This TiO₂(101) surface model contained 24 Ti and 48 O atoms. The TiO₂(101) surface with one oxygen vacancy was used to represent the hydrogenated TiO₂ (H-TiO_{2−x}). The N-doped hydrogenated TiO₂ (N-H-TiO_{2−x}) was simulated by using one N atom to replace the surface O atoms in TiO₂(101). During structural optimization, a (2 × 2 × 1) k -point grid in the Brillouin zone was used for k -point sampling and the bottom stoichiometric layer was fixed, while the remaining atoms were allowed to fully relax.

The adsorption energy (E_{ads}) of adsorbate A was defined as follows:

$$\Delta E_{\text{ads}} = E_{A/\text{surf}} - E_{\text{surf}} - E_{A(\text{g})} \quad (5)$$

where $E_{A/\text{surf}}$, E_{surf} , and $E_{A(\text{g})}$ are the energies of adsorbate A adsorbed on the surface, the surface, and isolated molecule A . The isolated molecule was in a cubic periodic box with a side length of 20 Å, which was investigated by using a 1 × 1 × 1 Monkhorst-Pack k -point grid for Brillouin zone sampling.

Conclusions

This work shows that N-H-TiO_{2−x} constructed in conjunction with lattice defect engineering exhibited good NH₃-SCR performance. The denitrification efficiency of N-H-TiO_{2−x} was greater than 90% at 300–400 °C. More importantly, this catalyst exhibited long-term stability, resistance to H₂O and SO₂ and good poisoning tolerance. The results of this study confirmed that the *in situ* N-doping on oxygen vacancies in hydrogenated TiO_{2−x} is the key step. The DFT calculations combined with the DRIFT spectra data demonstrate that the N-dopant acts as the catalytic active site for the NH₃-SCR denitrification process *via* the Eley–Rideal mechanism. The introduction of nonmetal



active sites greatly reduces the impact of toxic substances. This is because precious/transition metals are no longer required to act as active components. As such, the poisoning of precious/transition metals would be mitigated, while the expense of the catalysts can be greatly reduced. We anticipate that this research will assist in the future design of anti-poisoning catalysts with non-metal active sites through lattice defect engineering, which can be used in wide industrial catalysis applications.

Author contributions

G. L. carried out all the relevant experiments, data analysis and wrote the first draft of the manuscript. B. D. W. led the research program and supervised this project. Y. J. X. provided suggestions for the project development. B. D. W., Y. W., Y. J. X. and C. P. advised and revised the manuscript. J. J. W. and Y. W. performed all the DFT calculations and analyzed the catalytic mechanisms. Y. L. L. and J. Y. C. did the *in situ* XPS experiments of hydrogenation of TiO_{2-x} . Z. H. H. did the EELS-STEM measurements. H. W. did some catalyst characterization measurements. H. Y. W. drew some figures. S. P. P., Z. R. M., J. M. and J. L. Z. did some NH_3 -SCR measurements.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We gratefully acknowledge W. F. Tu for the assistance during the *in situ* XPS experiments and data analysis. The *in situ* XPS experiments were performed at the School of Chemical Engineering and Energy, Zhengzhou University, China. This work was supported by the National Key Research and Development Program of China (grant no. 2019YFC1907500) and by the National Energy Group Project (grant no. ST930021011C and no. ST930022006C). This research was undertaken on the supercomputers in the National Computational Infrastructure (NCI) in Canberra, Australia, which is supported by the Australian Commonwealth Government and the Pawsey Supercomputing Centre in Perth with funding from the Australian Government and the Government of Western Australia.

Notes and references

- 1 Catalyst Deactivation, in *Advances in Chemistry*, ed. J. B. Butt, American Chemical Society, Washington, DC, 1972, vol. 109, pp. 259–518.
- 2 Y. Peng, J. H. Li, W. Z. Si, J. M. Luo, Y. Wang, J. Fu, X. Li, J. Crittenden and J. M. Hao, *Appl. Catal., B*, 2015, **168–169**, 195–202.
- 3 Z. W. Huang, H. Li, J. Y. Gao, X. Gu, L. Zheng, P. P. Hu, Y. Xin, J. X. Chen, Y. X. Chen, Z. L. Zhang, J. M. Chen and X. F. Tang, *Environ. Sci. Technol.*, 2015, **49**, 14460–14465.
- 4 F. Tang, B. Xu, H. Shi, J. Qiu and Y. Fan, *Appl. Catal., B*, 2010, **94**, 71–76.
- 5 J. X. Liu, H. F. Cheng, H. L. Zheng, L. Zhang, B. Liu, W. Y. Song, J. Liu, W. S. Zhu, H. M. Li and Z. Zhao, *ACS Catal.*, 2021, **11**(24), 14727–14739.
- 6 Z. Chen, C. Bian, Y. B. Guo, L. Pang and T. Li, *ACS Catal.*, 2021, **11**(21), 12963–12976.
- 7 C. Xie, D. F. Yan, H. Li, S. Q. Du, W. Chen, Y. Y. Wang, Y. Q. Zou, R. Chen and S. Y. Wang, *ACS Catal.*, 2020, **10**, 11082–11098.
- 8 C. M. Yang, Y. X. Lu, L. Zhang, Z. J. Kong, T. Y. Yang, L. Tao, Y. Q. Zou and S. Y. Wang, *Small Struct.*, 2021, **2100058**, 1–25.
- 9 Y. Q. Zhang, L. Tao, C. Xie, D. D. Wang, Y. Q. Zou, R. Chen, Y. Y. Wang, C. K. Jia and S. Y. Wang, *Adv. Mater.*, 2020, **1905923**, 1–22.
- 10 X. B. Chen, L. Liu, P. Y. Yu and S. S. Mao, *Science*, 2011, **331**, 746–750.
- 11 Y. Liu, L. H. Tian, X. Y. Tan, X. Li and X. B. Chen, *Sci. Bull.*, 2017, **62**, 431–441.
- 12 V. A. Glezakou and R. Rousseau, *Nat. Mater.*, 2018, **17**, 856–857.
- 13 S. G. Ullattil, S. B. Narendranath, S. C. Pillai and P. Periyat, *Chem. Eng. J.*, 2018, **343**, 708–736.
- 14 T. S. Rajaraman, S. P. Parikh and V. G. Gandhi, *Chem. Eng. J.*, 2020, **389**, 123918.
- 15 H. Y. Hu, Y. Lin and Y. H. Hu, *Phys. Lett. A*, 2019, **383**, 2978–2982.
- 16 S. X. Liu, S. Yuan, Q. Zhang, B. Xu, C. Wang, Z. Ming and O. Teruhisa, *J. Catal.*, 2018, **366**, 282–288.
- 17 C. Y. Han, S. L. Zhang, L. N. Guo, Y. Q. Zeng, X. H. Li, Z. C. Shi, Y. Zhang, B. Q. Zhang and Q. Zhong, *Chem. Eng. Res. Des.*, 2018, **136**, 219–229.
- 18 Y. Q. Zeng, Y. N. Wang, S. L. Zhang and Q. Zhong, *Phys. Chem. Chem. Phys.*, 2018, **20**, 22744–22752.
- 19 H. Q. Tan, Z. Zhao, M. Niu, C. Y. Mao, D. P. Cao, D. J. Cheng, P. Y. Feng and Z. C. Sun, *Nanoscale*, 2014, **6**, 10216–10223.
- 20 Y. Lu, W. J. Yin, K. L. Peng, K. Wang, Q. Hu, A. Selloni, F. R. Chen, L. M. Liu and M. L. Sui, *Nat. Commun.*, 2018, **9**, 2752.
- 21 K. Lan, R. C. Wang, Q. L. Wei, Y. X. Wang, A. Hong, P. Y. Feng and D. Y. Zhao, *Angew. Chem., Int. Ed.*, 2020, **59**, 17676–17683.
- 22 T. Q. Lin, C. Y. Yang, Z. Wang, H. Yin, X. J. Lü, F. Q. Huang, J. H. Lin, X. M. Xie and M. H. Jiang, *Energ. Environ. Sci.*, 2014, **7**, 967.
- 23 P. Pichat, *Catal. Today*, 2020, **340**, 26–33.
- 24 L. Pan, M. H. Ai, C. Y. Huang, L. Yin, X. Liu, R. R. Zhang, S. B. Wang, Z. Jiang, X. W. Zhang, J. J. Zou and W. B. Mi, *Nat. Commun.*, 2020, **11**, 418.
- 25 F. Li, W. H. Huang and X. Q. Gong, *Chin. Chem. Lett.*, 2018, **29**, 765–768.
- 26 A. Naldoni, M. Allieta, S. Santangelo, M. Marelli, F. Fabbri, S. Cappelli, C. L. Bianchi, R. Psaro and V. D. Santo, *J. Am. Chem. Soc.*, 2012, **134**, 7600–7603.



- 27 M. I. Nandasiri, V. Shutthanandan, S. Manandhar, A. M. Schwarz, L. Oxenford, J. V. Kennedy, S. Thevuthasan and M. A. Henderson, *J. Phys. Chem. Lett.*, 2015, **6**, 4627–4632.
- 28 R. Schaub, E. Wahlström, A. Rønnau, E. Lægsgaard, I. Stensgaard and F. Besenbacher, *Science*, 2003, **299**, 377–379.
- 29 D. N. Pei, L. Gong, A. Y. Zhang, X. Zhang, J. J. Chen, Y. Mu and H. Q. Yu, *Nat. Commun.*, 2015, **6**, 8696.
- 30 D. Pietrogiaconi, D. Sannino, A. Magliano, P. Ciambelli, S. Tuti and V. Indovina, *Appl. Catal., B*, 2002, **36**, 217–230.
- 31 L. Ma, J. Li, R. Ke and L. Fu, *J. Phys. Chem. C*, 2011, **115**, 7603–7612.
- 32 U.S. Department of Commerce. The National Institute of Standards and Technology (NIST) X-ray Photoelectron Spectroscopy (XPS) Database Main Search Menu (2003); <https://www.nist.gov/>.
- 33 N. Y. Topsoe, *Science*, 1994, **265**, 1217–1219.
- 34 N. Y. Topsoe, J. A. Dumesic and H. Topsoe, *J. Catal.*, 1995, **151**, 241–252.
- 35 G. Z. He, Z. H. Lian, Y. B. Yu, Y. Yang, K. Liu, X. Y. Shi, Z. D. Yan, W. P. Shan and H. He, *Sci. Adv.*, 2018, **4**, eaau4637.
- 36 S. J. Yang, Y. F. Guo, H. Z. Chang, L. Ma, Y. Peng, Z. Qu, N. Q. Yan, C. Z. Wang and J. H. Li, *Appl. Catal., B*, 2013, **136–137**, 19–28.
- 37 G. Kresse and J. Furthmüller, *Comput. Mater. Sci.*, 1996, **6**, 15–50.
- 38 G. Kresse and J. Furthmüller, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, **54**, 11169–11186.
- 39 J. P. Perdew, K. Burke and M. Ernzerhof, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- 40 R. T. Wilburn and T. L. Wright, *PowerPlant Chem.*, 2004, **6**, 295–314.
- 41 J. M. Burke and K. L. Johnson, *Environmental Protection Agency*, Washington, DC, United States, 1982.

