

# LITERATURE STUDY OF THE EFFECT ON DOPING COMPONENT ON THE CE-TI OXIDE CATALYST FOR FLUE GAS DENITRATION WITH NH<sub>3</sub>-SCR

Rias Becik Sinawang<sup>1,2</sup> and Cucuk Evi Lusiani<sup>1</sup>

<sup>1</sup>Department of Chemical Engineering, Politeknik Negeri Malang, Soekarno-Hatta Street No. 9, Malang 65141, Indonesia

<sup>2</sup>College of Chemical and Biological Engineering, Shandong University of Science and Technology, 579 Qianwangang Road, Qingdao, China  
riasebecik@gmail.com ; [lusiani1891@polinema.ac.id]

## ABSTRACT

The Ce-Ti oxide catalyst is viewed as an innovation for the reduction of nitrogen oxide (NO<sub>x</sub>) and owns outstanding activity in ammonia-selective catalytic reduction (NH<sub>3</sub>-SCR) that became the most used denitration reaction in industry. In the flue gas, there will be many substances that inhibit the catalytic activity. Therefore, adding some components to the Ce-Ti oxide catalyst can be a solution. The aim of this literature study is to analyze the effect of doping components (Fe, Zr, Cu, K) on Ce-Ti oxide catalyst in the NH<sub>3</sub>-SCR reaction. Several theories and data methods were collected by comparing data based on catalytic activity and characterization of the catalysts. The activity of the catalyst was obtained by calculating the NO<sub>x</sub> conversion. The characterization of the catalysts was detected by BET, H<sub>2</sub>-TPR, NH<sub>3</sub>-TPD, and XPS. The analysis based on the literature study exhibited a catalyst with the best activities, structures, and properties required to successfully reduce NO<sub>x</sub>. The results indicate that the effect on doping components of Fe, Zr, and Cu can enhance the characteristics and protect the reduction ability, whilst the doping of K decreases surface acidity and reducibility on Ce-Ti oxide catalyst.

**Keywords:** *catalytic activity, characterization, denitration, flue gas, NH<sub>3</sub>-SCR*

## 1. INTRODUCTION

The flue gas coming from the combustion process contains many components that can damage the environment, so a strategy is expected to reduce these poisonous gases. Currently, several studies discuss reducing nitrogen oxide gas. Two major contaminants that are produced from fossil fuel combustion, which are sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>). In any case, discharges of NO<sub>x</sub> have proceeded to rise, and today NO<sub>x</sub> pollution is a major issue in industrialized countries [1].

Nitrogen oxides contribute a lot to corrosive downpours, photochemical exhaust clouds, and the consumption of tropospheric ozone [1]. These problems have immediate and round impacts on human well-being and the ecological environment [2]. Ammonia-selective catalytic reduction (NH<sub>3</sub>-SCR) as a solution to reduce nitrogen oxide with a catalyst that works effectively. Numerous catalysts have been performed in that process but still have some limitations. V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub>/TiO<sub>2</sub> catalyst was the most widely used industrial catalyst [3]. However, vanadium-based catalysts have many disadvantages, such as poor activity at

low temperature, low  $N_2$  selectivity at high temperatures, biotoxicity of  $V_2O_5$ , low resistance to alkaline and alkaline earth metals from ash [4]. Therefore, it is especially important to develop new environmentally-friendly catalysts with high activity and selectivity for  $NO_x$  removal. The  $CeO_2$ - $TiO_2$  catalyst has gained wide attention for its excellent properties. A study on characterization of  $CeO_2$ - $TiO_2$  catalysts by the single step sol-gel method from Gao et al. (2010) showed that the catalyst achieves excellent  $NH_3$ -SCR performance due to the high concentration of amorphous or highly dispersed nano-crystalline ceria and a high concentration of amorphous Ce on the surface played a fundamental part in  $NO_x$  reduction [5].

It is widely reported that the destruction of reducing property and surface acidity are two important points in deactivating the catalysts of  $NH_3$ -SCR. Du et al. (2012) found that the alkali metal atoms ( $K^+$ ,  $Na^+$ ,  $Ca^+$ ) could interact with the oxygen atoms of  $CeO_2$  and  $TiO_2$  to reduce the reducibility and surface acidity of  $CeTiO_x$  catalyst, respectively [6]. Another research from Liu et al. (2013) discovered that CuO-doped  $CeTiO_x$  catalyst could improve the denitration activity at low temperature, and they ascribed this prompting effect to double redox cycles [7].

Furthermore, adding active additives to improve the reducibility and surface acidity has caught extensive attention for its high efficiency and flexibility [8]. The addition of  $Fe^{3+}$  can efficiently improve the  $NH_3$ -SCR activity of Ce-Ti catalyst, which originated from the synergetic effect of Fe and Ce to form reactive intermediates [9]. Moreover,  $ZrO_2$  is widely used as an additive or co-catalyst for  $NH_3$ -SCR for its redox ability, acidity, and excellent dispersing effect by inhibiting particle aggregation. Doping of  $Zr^{4+}$  has been proved to efficiently improve the SCR performance and thermal stability of the Ce-based catalyst [10].

According to many substances in the flue gas that inhibit the activity of the catalyst, doping components to the catalyst could be the way to help the catalyst perform optimally. Therefore, the aim of this literature study is to analyze the effect of doping components on Ce-Ti oxide catalyst for flue gas denitration with  $NH_3$ -SCR. The evaluation of catalytic activity was performed under  $NH_3$ -SCR reaction by calculating the  $NO_x$  conversion. The textural features, reductive behaviors, surface acidity, and properties of the catalysts were characterized by BET,  $H_2$ -TPR,  $NH_3$ -TPD, and XPS.

## 2. METHODOLOGY

This article is a literature study that is carried out by collecting several theories and data methods. The data are sourced from pre-existing research. The form of this research is qualitative by collecting data on catalytic activity and catalyst characterization, then the analysis comparisons are made and lead to conclusions. These data were concluded to analyze the effect of the doping component on the Ce-Ti oxide catalyst in  $NH_3$ -SCR reaction. The data obtained are presented in the form of graphs, and tables are discussed in the next sub-chapter.

### 2.1. The Procedure of Journal Search

The journal search procedure includes determining the keywords searched for in journal databases such as Science direct, Google scholar, MDPI, and ACS Journal with the same research topic. The selection research results are based on the same variables and

analysis test. The journal search is related to the effect of the doping component on the Ce-Ti oxide catalyst for flue gas denitration with  $\text{NH}_3$ -SCR. The selection of journals has been prioritized internationally in the last ten years. The data from the journal will be compiled and written as a conclusion.

## 2.2. The Technique of Data Collection

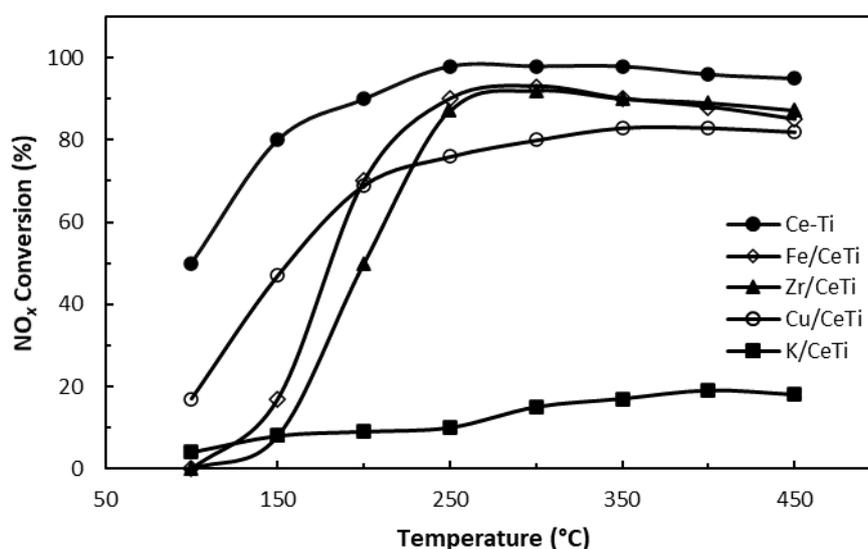
Data collection is done by comparing data from one journal to the other. Data collection is based on variables:

- The catalytic activity on Ce-Ti catalyst with doping components in  $\text{NH}_3$ -SCR
- The characterization of the Ce-Ti catalyst with doping components in  $\text{NH}_3$ -SCR

## 3. RESULTS AND DISCUSSION

### 3.1. Catalytic Evaluation on $\text{NH}_3$ -SCR Activity

Catalytic performances of the samples for  $\text{NH}_3$ -SCR of  $\text{NO}_x$  are shown in Figure 1.  $\text{NO}_x$  conversion describes percentages of the amount of  $\text{NO}_x$  that reacted in the reactant. The higher the conversion means the least amount of  $\text{NO}_x$  [6]. The  $\text{NO}_x$  conversion of the Ce-Ti catalyst was formed with a mole ratio of 0.5, and it shows the best  $\text{NH}_3$ -SCR performance [11]. Furthermore, it reaches a maximum  $\text{NO}_x$  conversion of about 100% within 250 – 350°C. However, the catalytic performance of Ce-Ti catalyst at low-temperature (below 300°C) is still not ideal [12].



**Figure 1.**  $\text{NH}_3$ -SCR catalytic activity of the samples within temperature to the value of  $\text{NO}_x$  conversion [11]–[13]

The Fe/CeTi and Zr/CeTi, both basically retain excellent catalytic activity in the test range. The  $\text{NO}_x$  conversion of Fe/CeTi and Zr/CeTi is also reduced to some extent [13]. Cu modification can effectively improve the low-temperature activity of Ce-Ti catalysts [12]. It is noteworthy that Cu/CeTi shows better catalytic performance than K/CeTi catalyst over the entire temperature range of the test. The above results show that Cu/CeTi catalysts have good stability in long-term tests. Meanwhile, the catalytic activity of K/CeTi is too low to even reach 20% over the entire test temperature interval, and the result

indicates that the potassium resistance of the Ce-Ti catalyst to the NH<sub>3</sub>-SCR reaction is very poor [6]. The major by-product of NH<sub>3</sub>-SCR is N<sub>2</sub>O. However, the N<sub>2</sub>O cannot be detected in these samples. It means that NO<sub>x</sub> is directly converted to N<sub>2</sub> through those catalysts without the production of N<sub>2</sub>O [14].

### 3.2. Characterization (Textural Features, Reductive Behaviors, and Surface Acidity and Properties) of the Catalysts in NH<sub>3</sub>-SCR

The textural features of the samples are exhibited in Table 1. The specific surface area, pore diameter, and pore volume of the catalysts were calculated by the BET (Brunauer-Emmett-Teller) method that calculates based on the adsorption layer thickness [14].

**Table 1.** The textural data of the catalyst samples using the BET method

Sample	Surface area (m <sup>2</sup> ·g <sup>-1</sup> )	Pore volume (cm <sup>3</sup> ·g <sup>-1</sup> )	Pore diameter (nm)
Ce-Ti [11]	141	0.14	4.04
Fe/CeTi [13]	200	0.36	7.2
Zr/CeTi [13]	193	0.37	7.7
Cu/CeTi [12]	70	0.23	13.4
K/CeTi [12]	67	0.25	14.5

As shown in Table 1, catalysts with larger specific surface areas and larger pore volumes provide more active sites for adsorption of reactants and intermediates, as well as improving the spread of reactant and product molecules, and further enhancing the activity of catalysts [15]. It is also showing the values with the smallest pore diameter of the Ce-Ti catalyst. The introduction of small amounts of cerium species inhibited the formation of nanoparticles, but the further introduction of cerium increased the pore diameter due to the formation of secondary particle piled pore due to the agglomeration of nanoparticle building blocks [11].

On the other hand, Fe/CeTi retains maximum specific surface area, further promoting Fe dispersion and grain growth. Doping of Fe, Zr, and Cu can partially inhibit crystallization and further increase the specific surface area compared to K/CeTi [13]. The surface of the doped K catalyst is smaller than the others, indicating that K species are predominantly present on the pore structure and the surface of the catalyst, which can have a certain adverse effect on catalytic activity. However, the BET specific surface area and total pore volume of the catalyst decrease after Cu modification, but the average pore diameter increases. This can cause some of the loaded Cu particles to cover the surface and block it in the pores of the catalyst [12].

The reductive behaviors of the catalyst are generally accepted to be important for NH<sub>3</sub>-SCR, which can be tested with H<sub>2</sub>-temperature programmed reduction (H<sub>2</sub>-TPR), and the results are summarized in Table 2.

**Table 2.** The reductive behaviors of the catalysts tested using H<sub>2</sub>-TPR

Sample	Peak temperature (°C)		H <sub>2</sub> consumption (μmol·g <sup>-1</sup> )		
	T <sub>1</sub>	T <sub>2</sub>	S <sub>1</sub>	S <sub>2</sub>	S <sub>1</sub> + S <sub>2</sub>
Ce-Ti [12]	463	598	107	7	114
Fe/CeTi [13]	401	551	143	25	168
Zr/CeTi [13]	519	617	97	24	121
Cu/CeTi [12]	186	234	88	103	191
K/CeTi [12]	539	630	73	10	83

Table 2 present of Ce-Ti catalyst has the broad temperature peaks that are shown near 463, and 598°C belong to the reduction of Ce-O-Ti structure due to surface and bulk. The reduction of peak temperature of the Ce-Ti catalyst is much lower than those of pure TiO<sub>2</sub> and CeO<sub>2</sub> due to the interaction between Ce and Ti caused by the incorporation of Ce<sup>4+</sup> into the lattice of TiO<sub>2</sub> [16].

In contrast to the Ce-Ti catalyst, the K/CeTi has a reduction peak that moves towards high temperature orientation, and the H<sub>2</sub> consumption of the K/CeTi reaches 83 μmol·g<sup>-1</sup> lower than the 114 μmol·g<sup>-1</sup> of Ce-Ti. This indicates that K-doping adversely affects the reducing properties of the catalyst [12]. The strong bond between K and Ce weakens the Ce-Ti catalyst [17]. Otherwise, the H<sub>2</sub> consumption of Fe/CeTi, Zr/CeTi, and Cu/CeTi have higher values. It means that doping of Fe, Zr, and Cu plays an important role in improving the reducing ability [13]. Moreover, the H<sub>2</sub> consumption of Cu/CeTi has the highest value means that the Ce-Ti component in this catalyst is hard to be fully reduced [12].

An important role in NH<sub>3</sub>-SCR reaction is the amount and strength of surface acid over Ce-Ti based catalysts [18]. Therefore, the catalysts are investigated by NH<sub>3</sub>-temperature programmed desorption (NH<sub>3</sub>-TPD) that is conducted in Table 3.

Three kinds of desorption peaks are marked as I, II, and III, which are attributed to weak acid sites (including physical adsorption of NH<sub>3</sub>), medium-strong acid sites, and strong acid sites, respectively [19]. These three kinds of acid sites are all present on the Ce-Ti catalyst. The desorption peak III is missing in the K/CeTi and Cu/CeTi catalysts and leaves only two desorption peaks.

From the amounts in Table 3, it can be shown that the total acid content of the K/CeTi catalyst is 849 a.u. which is lower than Ce-Ti catalyst with 3026 a.u. The results show that K seriously damages the surface acidity of the Ce-Ti catalyst. The total amount of acid in the Cu/CeTi catalyst is 2016 a.u. that can be seen it is clearly not as high as K/CeTi. The result of this Cu can further protect the surface acidity of the Ce-O-Ti component in the Cu/CeTi catalyst [12].

It is worth noting that the total acid content of the Fe/CeTi has the highest acid content among all samples. This suggests that Fe<sup>3+</sup> doping can effectively increase the surface acidity of Ce-Ti, but is strongly influenced by other inhibitors. The Zr/CeTi has the

strongest acidic center ( $S_{III}$ ), and  $Zr^{4+}$  doping can effectively reduce the adverse effects on surface acidity [12].

Identify the surface properties (surface constituents and element oxidation states) of those catalyst samples can be characterized by x-ray photoelectron spectroscopy (XPS) that is shown in Table 4. XPS was used to test the atomic conversion of the active site and the atomic properties of the tested catalyst. Each binding energy (B.E.) was calibrated using C 1s (B.E. = 284.8 eV) as a standard [11]. It is known that the surface composition and oxidation state of the catalyst is very important for the  $NH_3$ -SCR reaction and can have a significant effect on the adsorption and activation of reactant molecules [20].

**Table 3.** The amount of surface acidity on the catalysts tested using  $NH_3$ -TPD

Sample	Acid amount (a.u.)			Total acid amount (a.u.)
	$S_I$	$S_{II}$	$S_{III}$	$S_I + S_{II} + S_{III}$
Ce-Ti [12]	968	1937	121	3026
Fe/CeTi [13]	1289	2749	324	4362
Zr/CeTi [13]	1158	2287	415	3860
Cu/CeTi [12]	927	1089	-	2016
K/CeTi [12]	365	484	-	849

**Table 4.** Surface atomic concentration and ratio of the catalysts by XPS

Sample	Atomic concentration (%)							Atomic ratio (%)			
	Ce	Ti	O	Fe	Zr	Cu	K	Ce/Ti	Fe/Ti	Zr/Ti	Cu/Ti
Ce-Ti [12]	0.65	28.06	72.05	-	-	-	-	3.52	-	-	-
Fe/CeTi [13]	0.77	24.88	69.86	4.49	-	-	-	3.09	18.05	-	-
Zr/CeTi [13]	0.44	25.25	71.38	-	2.93	-	-	1.74	-	11.60	-
Cu/CeTi [12]	0.63	25.26	72.16	-	-	1.95	-	2.92	-	-	9.64
K/CeTi [12]	0.87	24.33	70.21	-	-	-	4.59	3.34	-	-	-

In Table 4, we can see that the Cu/CeTi content is the lowest at 9.64%. While the result of atomic ratio on K-doping is not detected, it probably has some negative effect on the electron interaction between Ce and Ti species [12]. The surface Ce/Ti atomic ratio of the Ce-Ti catalyst decreases after adding the component. This may be due to the added component covering the surface of Ce species, thus reducing the active Ce-O-Ti species

further reduces the SCR activity of Ce-Ti. The atomic ratio of Ce/Ti becomes the lowest compared to Zr/Ti, and it can be pointed out that Zr<sup>4+</sup> doping can effectively suppress Ce species on the surface [13].

The Ce<sup>3+</sup> ratios could be ranked as follows: Ce-Ti (3.52) > K/CeTi (3.34) > Fe/CeTi (3.09) > Cu/CeTi (2.92) > Zr/CeTi (1.74). The highest Ce<sup>3+</sup> ratio of 3.52 was observed for Ce-Ti. An excellent SCR activity was achieved at higher Ce<sup>3+</sup> ratios [11]. The presence of more Ce<sup>3+</sup> species was beneficial in creating more oxygen vacancies, promoting the redox conversion between Ce<sup>3+</sup> and Ce<sup>4+</sup> [21]. Moreover, the enrichment of Ce<sup>3+</sup> species could result in more charge imbalance and unsaturated chemical bonds, which increase the number of oxygen species adsorbed and further improve the performance of NH<sub>3</sub>-SCR [22].

#### 4. CONCLUSION

The excellent catalytic activity has been shown by the Ce-Ti catalyst over a broad operating temperature window. Furthermore, the doping components of Fe, Zr, and Cu performed in good catalytic activity. The textural features, reductive behaviors, surface acidity, and properties have slightly different results. But, overall can efficiently protect the reduction ability of the catalyst. On the other hand, K/CeTi has poor catalytic activity, and doping K to the Ce-Ti oxide catalyst causes decreasing of surface acidity and reducibility. Since the doping component could improve the activity and characteristics of the Ce-Ti oxide catalyst, the reaction will have significant enhancements and perform more effectively.

It should be noted that, despite significant progress, there are still challenges in the use of doping components on the Ce-Ti oxide catalyst in NH<sub>3</sub>-SCR. The improvement of this study is very helpful for the future. Future research should concentrate on the significant advancements in the improvement of the doping component and the other factors that influence the catalyst, such as the preparation method, the gas hourly space velocity, and the mole ratio.

#### REFERENCES

- [1] F. Liu, Y. Yu, and H. He, "Environmentally-benign catalysts for the selective catalytic reduction of NO<sub>x</sub> from diesel engines: structure-activity relationship and reaction mechanism aspects," *Chem. Commun.*, vol. 50, no. 62, pp. 8445–8463, 2014, doi: 10.1039/C4CC01098A.
- [2] X. Wang *et al.*, "Understanding the deposition and reaction mechanism of ammonium bisulfate on a vanadia SCR catalyst: A combined DFT and experimental study," *Appl. Catal. B Environ.*, vol. 260, p. 118168, 2020, doi: <https://doi.org/10.1016/j.apcatb.2019.118168>.
- [3] X. Xie, J. Lu, E. Hums, Q. Huang, and Z. Lu, "Study on the deactivation of V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub>/TiO<sub>2</sub> selective catalytic reduction catalysts through transient kinetics," *Energy and Fuels*, vol. 29, no. 6, pp. 3890–3896, 2015, doi: 10.1021/acs.energyfuels.5b01034.
- [4] Y. Shen and S. Zhu, "Deactivation mechanism of potassium additives on Ti<sub>0.8</sub>Zr<sub>0.2</sub>Ce<sub>0.2</sub>O<sub>2.4</sub> for NH<sub>3</sub>-SCR of NO<sub>x</sub>" *Catal. Sci. Technol.*, vol. 2, no. 9, pp. 1806–1810, 2012, doi: 10.1039/C2CY20238G.
- [5] X. Gao, Y. Jiang, Y. Fu, Y. Zhong, Z. Luo, and K. Cen, "Preparation and characterization of CeO<sub>2</sub>/TiO<sub>2</sub> catalysts for selective catalytic reduction of NO with NH<sub>3</sub>," vol. 11, pp.

- 465–469, 2010, doi: 10.1016/j.catcom.2009.11.024.
- [6] X. Du, X. Gao, R. Qu, P. Ji, Z. Luo, and K. fa Cen, “The Influence of Alkali Metals on the Ce-Ti Mixed Oxide Catalyst for the Selective Catalytic Reduction of NO<sub>x</sub>,” *ChemCatChem*, vol. 4, no. 12, pp. 2075–2081, 2012, doi: 10.1002/cctc.201200316.
- [7] Z. Liu *et al.*, “A superior catalyst with dual redox cycles for the selective reduction of NO<sub>x</sub> by ammonia,” *Chem. Commun.*, vol. 49, no. 70, pp. 7726–7728, 2013, doi: 10.1039/C3CC43041C.
- [8] Y. Peng *et al.*, “Alkali Metal Poisoning of a CeO<sub>2</sub>-WO<sub>3</sub> Catalyst Used in the Selective Catalytic Reduction of NO<sub>x</sub> with NH<sub>3</sub>: an Experimental and Theoretical Study,” *Environ. Sci. Technol.*, vol. 46, no. 5, pp. 2864–2869, Mar. 2012, doi: 10.1021/es203619w.
- [9] Z. Liu, Y. Liu, B. Chen, T. Zhu, and L. Ma, “Novel Fe-Ce-Ti catalyst with remarkable performance for the selective catalytic reduction of NO<sub>x</sub> by NH<sub>3</sub>,” *Catal. Sci. Technol.*, vol. 6, no. 17, pp. 6688–6696, 2016, doi: 10.1039/C5CY02278A.
- [10] A. Shi, X. Wang, T. Yu, and M. Shen, “The effect of zirconia additive on the activity and structure stability of V<sub>2</sub>O<sub>5</sub>/WO<sub>3</sub>-TiO<sub>2</sub> ammonia SCR catalysts,” *Appl. Catal. B Environ.*, vol. 106, no. 3, pp. 359–369, 2011, doi: <https://doi.org/10.1016/j.apcatb.2011.05.040>.
- [11] Z. Fei *et al.*, “Precisely fabricating Ce-O-Ti structure to enhance performance of Ce-Ti based catalysts for selective catalytic reduction of NO with NH<sub>3</sub>,” *Chem. Eng. J.*, vol. 353, no. July, pp. 930–939, 2018, doi: 10.1016/j.cej.2018.07.198.
- [12] K. Kang *et al.*, “Enhancing the K resistance of CeTiO<sub>x</sub> catalyst in NH<sub>3</sub>-SCR reaction by CuO modification,” *J. Hazard. Mater.*, vol. 402, no. May 2020, p. 123551, 2021, doi: 10.1016/j.jhazmat.2020.123551.
- [13] K. Kang *et al.*, “Insights into the co-doping effect of Fe<sup>3+</sup> and Zr<sup>4+</sup> on the anti-K performance of CeTiO<sub>x</sub> catalyst for NH<sub>3</sub>-SCR reaction,” *J. Hazard. Mater.*, vol. 416, no. January, p. 125821, 2021, doi: 10.1016/j.jhazmat.2021.125821.
- [14] D. W. Kwon and S. C. Hong, “Promotional effect of tungsten-doped CeO<sub>2</sub>/TiO<sub>2</sub> for selective catalytic reduction of NO<sub>x</sub> with ammonia,” *Appl. Surf. Sci.*, vol. 356, pp. 181–190, 2015, doi: 10.1016/j.apsusc.2015.08.073.
- [15] L. Chen, X. Yao, J. Cao, F. Yang, C. Tang, and L. Dong, “Effect of Ti<sup>4+</sup> and Sn<sup>4+</sup> co-incorporation on the catalytic performance of CeO<sub>2</sub>-MnO<sub>x</sub> catalyst for low temperature NH<sub>3</sub>-SCR,” *Appl. Surf. Sci.*, vol. 476, pp. 283–292, 2019, doi: <https://doi.org/10.1016/j.apsusc.2019.01.095>.
- [16] X. Yao *et al.*, “Investigation of the structure, acidity, and catalytic performance of CuO/Ti<sub>0.95</sub>Ce<sub>0.05</sub>O<sub>2</sub> catalyst for the selective catalytic reduction of NO by NH<sub>3</sub> at low temperature,” *Appl. Catal. B Environ.*, vol. 150–151, pp. 315–329, 2014, doi: <https://doi.org/10.1016/j.apcatb.2013.12.007>.
- [17] Y. Peng, K. Li, and J. Li, “Identification of the active sites on CeO<sub>2</sub>-WO<sub>3</sub> catalysts for SCR of NO<sub>x</sub> with NH<sub>3</sub>: An in situ IR and Raman spectroscopy study,” *Appl. Catal. B Environ.*, vol. 140–141, pp. 483–492, 2013, doi: <https://doi.org/10.1016/j.apcatb.2013.04.043>.
- [18] S. Deng, K. Zhuang, B. Xu, Y. Ding, L. Yu, and Y. Fan, “Promotional effect of iron oxide on the catalytic properties of Fe-MnO<sub>x</sub>/TiO<sub>2</sub> (anatase) catalysts for the SCR reaction at low temperatures,” *Catal. Sci. Technol.*, vol. 6, no. 6, pp. 1772–1778, 2016, doi: 10.1039/C5CY01217A.
- [19] Z. Liu, Y. Yang, J. Mi, X. Tan, and Y. Song, “Synthesis of copper-containing ordered mesoporous carbons for selective hydrogenation of cinnamaldehyde,” *Catal. Commun.*, vol. 21, pp. 58–62, 2012, doi: <https://doi.org/10.1016/j.catcom.2012.01.024>.

- [20] Y. Jiang *et al.*, "Effect of Ca Doping on the Selective Catalytic Reduction of NO with NH<sub>3</sub> Over Ce-Ti Oxide Catalyst," *Catal. Letters*, vol. 148, no. 9, pp. 2911–2917, 2018, doi: 10.1007/s10562-018-2494-1.
- [21] X. Chen *et al.*, "CeO<sub>2</sub> nanodots embedded in a porous silica matrix as an active yet durable catalyst for HCl oxidation," *Catal. Sci. Technol.*, vol. 6, no. 13, pp. 5116–5123, 2016, doi: 10.1039/C5CY02300A.
- [22] H. Li, C.-Y. Wu, Y. Li, and J. Zhang, "Superior activity of MnO<sub>x</sub>-CeO<sub>2</sub>/TiO<sub>2</sub> catalyst for catalytic oxidation of elemental mercury at low flue gas temperatures," *Appl. Catal. B Environ.*, vol. 111–112, pp. 381–388, 2012, doi: <https://doi.org/10.1016/j.apcatb.2011.10.021>.