Lewis acidic strength controlled highly selective synthesis of oxime *via* liquid-phase ammoximation over titanosilicates†

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The Lewis acidity of titanosilicates determines the selectivity of the oxime in ammoximation. Higher Lewis acidic strength of Ti active sites could promote free H_2O_2 to participate in the highly efficient formation of NH_2OH by lowering the reaction activation energy for the formation of Ti–OOH species, and thus fundamentally suppress the side reactions of deep oxidation.

Finding a selective catalyst for the synthesis of a desired product is very often the beginning step of catalysis in industry.[1] The successful manufacture of cyclohexanone oxime *via* liquid-phase ammoximation over TS-1(MFI) is considered a new milestone in the field of zeolite catalysis.[2] However, applying this green chemical process to the production of high-value fine oximes (*e.g.* methyl ethyl ketone oxime, acetone oxime and acetaldehyde oxime) is hampered due to the relatively lower selectivity for the target product.[3] The typical side reaction in ammoximation can be concluded to be the deep oxidation of reactant or oxime, which depends greatly on the behavior of free H_2O_2 oxidation.[3,4] It is well accepted that the ammoximation reaction proceeds *via* NH_2OH intermediates (S2 ESI†),[5] and it was proven that a higher concentration of NH_3 favors NH_2OH formation so that can inhibit side reaction of oxidation.[4] Hence, promoting the highly efficient formation of NH_2OH, and thus suppress free H_2O_2-induced oxidation reactions would contribute to the high selectivity of oxime.

It has been confirmed that the active site of titanosilicates is tetracoordinated framework Ti[IV],[6] and many publications have supported that the catalytic nature of titanosilicates is attributed to Lewis acidic sites related to these framework Ti species.[7] Thus, it is reasonable to employ Lewis acidity of Ti active sites to represent the catalytic activity of titanosilicates. In ammoximation, the ammonia oxidation by free H_2O_2 over

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titanosilicates can be divided into two parts:[8] first, the activation of H_2O_2 on framework tetrahedral Ti^{4+} to form the oxygen donating-intermediates of Ti–OOH species, which depends on the catalytic activity of titanosilicates, has been proven to be the most crucial step in titanosilicate-catalyzed oxidation reactions;[6b,9] then, the surrounding NH_3 can capture the active oxygen in Ti–OOH species to give NH_2OH intermediates (S3 ESI†). Thus, in order to fundamentally promote the highly efficient formation of NH_2OH, it is important to accelerate the activation of free H_2O_2 *via* lowering the reaction energy barrier of Ti–OOH species. Furthermore, it also well known that reaction activation energy is strongly reduced with the increase of acid strength in hydrocarbon conversion over zeolites.[10] Reasonably, titanosilicate catalyst equipped with stronger Lewis acidity of Ti active sites is inclined to remarkably reduce the reaction activation energy of Ti–OOH species, thereby activating free H_2O_2 to produce NH_2OH more efficiently and further cutting off the side reaction of oxidation. Therefore, we infer that the Lewis acidity of titanosilicates determines oxime selectivity in ammoximation by controlling reaction path of free H_2O_2 to NH_2OH intermediates.

In this communication, to demonstrate that the Lewis acidic strength of Ti active sites is the decisive factor in the highly selective synthesis of oxime, a series of ammoximation reactions of linear ketones and acetaldehyde over representative titanosilicates with varied strength of Lewis acidity (TS-1 < Ti-MWW < F-Ti-MWW) (S4 ESI†) has been carried out. As anticipated, a titanosilicate catalyst with stronger Lewis acidity gives better selectivity to oxime.

Table 1 shows the results of ammoximation of linear ketones (acetone and MEK) over Ti-MWW and TS-1. To focus on the issue of product selectivity, the ketone conversion was maintained at over 99% by optimizing the reaction conditions, such as supplying a sufficient catalyst concentration (15 g mol^{-1}) and loading the free H_2O_2 drop-wise in case of further oxidation decomposition of NH_2OH intermediates (S2 ESI†).[5a,11] Ti-MWW was proven to be a selective catalyst for linear ketone ammoximation, and the selectivity of DMKO and MEKO both were

Table 1 A comparison of products selectivity in different ammoximation processes[a]

No.	Catalyst	DMK[b] (mol%)			MEK[c] (mol%)		
		Conv.	Sel.	Sel.[d]	Conv.	Sel.	Sel.[e]
1	Ti-MWW	99.6	99.8	0.2	99.7	99.7	0.3
2	TS-1	99.3	94.9	5.1	99.7	95.9	4.1

[a] Reaction conditions: catalyst 0.15 g; ketone 10 mmol, H_2O_2 12 mmol; NH_3, 21 mmol; temp. 335 K for Ti-MWW (Si/Ti = 42) and 345 K for TS-1 (Si/Ti = 38); time 2 h. [b] DMK for dimethyl ketone or acetone. [c] MEK for methyl ethyl ketone. [d] The selectivity of 2-nitropropane. [e] The selectivity of 2-nitrobutane.

higher than 99.5% (Table 1, no. 1). When it comes to TS-1, the oxime selectivity was reduced to a certain extent because of the existence of 2-nitropropane and 2-nitrobutane that originated from the consecutive oxidation of oxime (Table 1, no. 2).[3a] Although Song *et al.* attributed the decline in linear oxime selectivity to diffusion constraints induced by TS-1 catalyst,[3a] our further study demonstrates that the diffusion constraints of catalyst merely intensify the side reaction of deep oxidation instead of deciding the oxime selectivity (S5 ESI†). Thus, combined with the ammoximation of linear ketones of different carbon chains (S6 ESI†), the oxime selectivity differences existing between Ti-MWW and TS-1 conform quite well to our assumption; namely, Ti-MWW possessing higher Lewis acidic strength displays superior oxime selectivity compared to that of TS-1 with relatively weaker Lewis acidity.

In order to further clarify that the effect of Lewis acidity of titanosilicates on the improvement of oxime selectivity is derived from promotion of the formation of NH_2OH intermediates, we have correlated the Lewis acidic strength of Ti-MWW and TS-1 with their corresponding abilities to produce NH_2OH. Fig. 1b compares the yield of NH_2OH obtained by Ti-MWW and TS-1 with different Ti contents according to the relevant results of cyclohexanone ammoximation. Ti-MWW kept a much better yield of NH_2OH than TS-1 under the same Ti content, and the maximum yield gained by Ti-MWW was close to 95%, which is
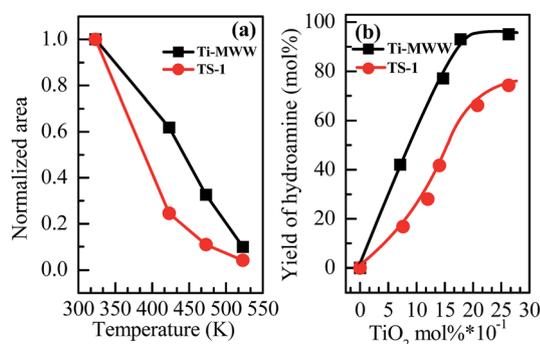
nearly 25% higher than that of TS-1. Thus, the catalytic abilities of forming NH_2OH between Ti-MWW and TS-1 are consistent with their order of Lewis acidic strength (Fig. 1a) and also agree with the change in oxime selectivity (Table 1). These positive correlations fully verify our inference that titanosilicates with higher Lewis acidic strength are beneficial for the acceleration of the reaction path of NH_2OH. Therefore, the above results support well our opinion that the Lewis acidity of titanosilicates decides the highly selective synthesis of oxime *via* affecting the highly efficient formation of NH_2OH intermediates.

In order to better demonstrate the decisive relations between the Lewis acidity and oxime selectivity, a series of linear ketone ammoximation reactions over mixed catalysts of TS-1/Ti-MWW was further conducted. The results showed that TS-1 possesses weaker Lewis acidity than Ti-MWW (Fig. 1a), and thus, it is feasible to prepare a catalyst sample with adjustable Lewis acidic strength by mixing these two types of titanosilicates in different proportions. Reasonably, upon increasing the weight proportion of Ti-MWW, the Lewis acidic strength of the mixed catalysts is enhanced simultaneously. If oxime selectivity is decided by the Lewis acidity of titanosilicates, then the selectivity would be changed along with the acid strength. Fig. 2 reports the results of DMK and MEK ammoximation over the TS-1/Ti-MWW mixed catalysts. As expected, the oxime selectivity was improved gradually with the increase in the Ti-MWW proportion. This gradual change in selectivity also excludes the possibility that the positive effect on oxime selectivity enhancement is merely caused by the introduced Ti-MWW. No further variation in oxime selectivity was noted when the Ti-MWW proportion was higher than 30%, which means this specific composition of mixed catalysts has enough Lewis acidic strength to prepare oxime with high selectivity. These findings show that the Lewis acidic strength of titanosilicate catalyst is able to regulate the oxime selectivity in ammoximation. Correspondingly, 2-nitroalkane selectivity also decreased with an increase in the proportion of Ti-MWW, and the by-product was nearly eliminated when adopting the mixed sample consisting of 30% Ti-MWW and 70% TS-1 as the catalyst. This implies that the deep oxidation of oxime, even in the presence of diffusion
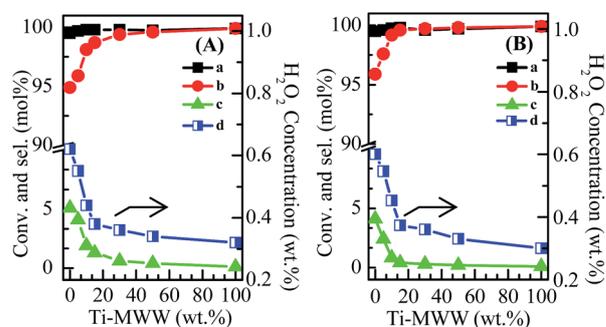

Fig. 1 Correlation between the formation of NH_2OH (b) and the Lewis acidic strength of titanosilicates (a). Reaction conditions: catalyst, 0.05 g; cyclohexanone, 20 mmol; H_2O_2, 10 mmol; NH_3, 10 mmol, others see Table 1.

Fig. 2 The ammoximation of DMK (A) and MEK (B) over the TS-1/Ti-MWW mixed catalysts. (a) Ketone conv., (b) oxime sel., (c) 2-nitroalkane sel., (d) H_2O_2 residual concentration. Reaction conditions: catalyst, 0.45 g; ketone, 30 mmol; H_2O_2, 36 mmol; NH_3, 63 mmol; sol., 10 g, temp., 341 K; time, 2 h.

constraints caused by TS-1, can be mostly suppressed by strengthening the Lewis acidity of the catalyst. Furthermore, the variation of residual free H_2O_2 also supports that titanosilicates with stronger Lewis acidity prefer to activate more free H_2O_2 molecules to form NH_2OH. Thus, it is well confirmed that the Lewis acidity of titanosilicates is the decisive factor in the synthesis of oxime with high selectivity.

In comparison to linear ketones, acetaldehyde (AA) is chemically more active, so that the selectivity issue in the AA ammoximation becomes more complicated.[3b,12] On the one hand, it was shown that AA would be further oxidized to acetic acid by Ti–OOH species,[3a] although this may be unlikely in an actual ammoximation due to the existence of excess NH_3. On the other hand, it has been proven that certain amount of acetic acid and acetamide can be generated from homogenous deep oxidation of AA or oxime with free H_2O_2 under alkaline conditions (S7 ESI†), which also closely relies on the free H_2O_2 oxidation actions. Consequently, in order to achieve an excellent selectivity of acetaldehyde oxime (AAO), a selective titanosilicate with much stronger Lewis acidity is required based on our present opinion. Table 2 compares the results of linear ketone and AA ammoximation over titanosilicates with different Lewis acidic strength. TS-1 exhibited much poorer selectivity for AAO than linear oximes (Table 2, no. 1–3), which indicates a higher chemical activity of AA. Then, AAO selectivity was significantly increased to 98.6% when adopting Ti-MWW as the catalyst because of the notable enhancement in Lewis acidity. Nevertheless, the AAO selectivity still failed to reach the parallel level of linear oximes obtained under the same reaction conditions (Table, no. 1). These consequences fully sustain our speculation that with regard to the chemically more active AA, achieving high oxime selectivity becomes much harder than linear ketones by choosing titanosilicates with considerable strength of Lewis acidity. Hence, a titanosilicate catalyst with more superior Lewis acidity than Ti-MWW is needed for the AA ammoximation.

Recently, the Lewis acidic strength of Ti active sites in F-Ti-MWW has been proven to be further enhanced compared to Ti-MWW due to the strong electron-withdrawing effect of incorporated fluorine species.[13] Therefore, F-Ti-MWW was applied to the AA ammoximation to further verify our inference about Lewis acidity controlling the oxime selectivity. Expectantly, Table 2 (no. 5) shows that the AAO selectivity was further increased up to 99.6% and it was equal to the linear oxime selectivity achieved with Ti-MWW (Table 1, no. 1). Hence, the titanosilicates investigated for AA ammoximation displayed the following order of oxime selectivity: F-Ti-MWW > 99.5% > Ti-MWW > 90% > TS-1, which also entirely conforms to their relevant Lewis acidic strength. This indicates that to highly selectively obtain chemically more active oxime, stronger Lewis acidity of titanosilicates is needed. Moreover, by comparing the by-product selectivity between acetic acid and acetamide, we find that acetic acid selectivity is lower than that of acetamide. This proves that Ti–OOH species would not promote the deep oxidation of AA in the presence of excess NH_3, and the side reactions are still mainly ascribed to those deep oxidations induced by free H_2O_2. These phenomena further indicate that the fundamental role of Lewis acidity in oxime selectivity is controlling the oxidation behavior of free H_2O_2. This role was also supported by the apparent activation energy of Ti–OOH active species formed using TS-1 (32.29 kJ mol^{-1}), Ti-MWW (24.72 kJ mol^{-1}), and F-Ti-MWW (10.02 kJ mol^{-1}) (S8 ESI†), which demonstrates that the increase in Lewis acidic strength can remarkably lower the activation barrier of free H_2O_2 and thus promote participation of free H_2O_2 molecules in the formation of NH_2OH intermediates.

In summary, the Lewis acidic strength of Ti active sites is confirmed to be responsible for the high selectivity of oxime based on the catalytic nature of titanosilicates and the ammoximation mechanism. A stronger Lewis acid promotes the formation of NH_2OH, while weaker acid strength is less able to suppress the free H_2O_2-induced side reactions. Therefore, regulating the Lewis acidity of titanosilicates could become a crucial guideline for designing or modifying catalysts for highly selective synthesis of oximes or even other oxygenated fine chemicals.

Acknowledgements

Table 2 A comparison of acetaldehyde and ketone ammoximation over titanosilicates with different Lewis acidic strength[a]

No.	Reactant	Catalyst	Conv. (mol%)	Sel.(mol%)		
				Oxime	By-product	
					I[c]	II[d]
1[b]	MEK	TS-1(38)	99.7	95.9		4.1
2[b]	DMK	TS-1(38)	99.3	94.9		5.1
3	AA	TS-1(38)	99.1	86.6	5.0	8.4
4	AA	Ti-MWW(42)	99.3	98.5	0.5	1.0
5	AA	F-Ti-MWW(29)	99.3	99.6	0	0.4

[a] Reaction conditions: see Table 1. [b] The main by-product was 2-nitroalkane. [c] By-product I was acetic acid. [d] By-product II was acetamide.

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