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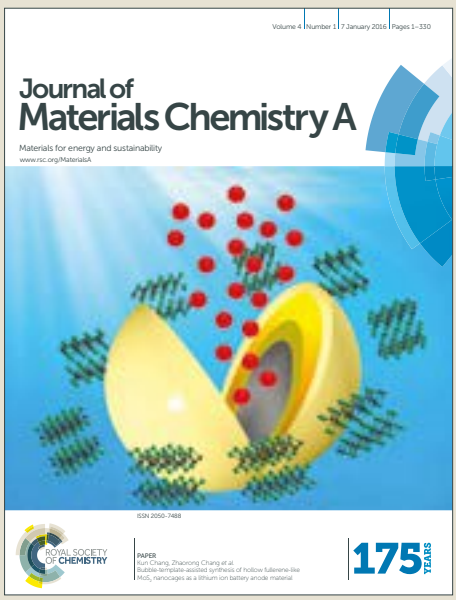

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Journal of Materials Chemistry A
View Article Online
DOI: 10.1039/C8TA01242C

Three-step cascade over one single catalyst: synthesis of 5-(ethoxymethyl)furfural from glucose over hierarchical lamellar multi-functional zeolite catalyst

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DOI: 10.1039/C8TA01242C

Abstract: The synthesis of hierarchical lamellar zeolites with controlled meso-/microporous morphology and acidity is an expanding area of research interest for a wide range of applications. Here, we report a one-step synthesis of hierarchical meso-/microporous lamellar MFI-Sn/Al zeolite (*i.e.*, containing both Lewis acidic Sn- and Al-sites and Brønsted acidic Al–O(H)–Si site and its catalytic application for conversion of glucose into 5-(ethoxymethyl)furfural (EMF). Particularly, the MFI-Sn/Al zeolite was prepared under the assistance of a diquaternary ammonium ($[C_{22}H_{45}\text{-}N^{+}(CH_3)_2\text{-}C_6H_{12}\text{-}N^{+}(CH_3)_2\text{-}C_6H_{13}]Br^{2-}$, $C_{22\text{-}6\text{-}6}$) template in a composition of $100SiO_2/5C_{22\text{-}6\text{-}6}/18.5Na_2O/xAl_2O_3/ySnO_2/2957H_2O$ (x=0.5, 1, and 2, y=1 and 2, respectively). The MFI-Sn/Al zeolites innovatively feature dual meso-/microporosity and dual Lewis and Brønsted acidity, which enabled three-step reaction cascade for EMF synthesis from glucose in the ethanol solvent. The reaction proceeded via the isomerization of glucose to fructose over Lewis acidic Sn-sites and dehydration of fructose to 5-hydroxymethylfurfural (HMF) and then etherification of HMF and ethanol to EMF over the Brønsted acidic Al–O(H)–Si sites. The co-existence of multiple acidities in one single zeolite catalyst enabled one-pot cascade reactions for carbohydrate upgrading. The dual meso-/microporosity in the MFI-Sn/Al zeolites facilitated mass transport in processing of bulky biomass molecules. The balance of both types of acidity and meso-/microporosity realized EMF yield as high as 44% from the glucose reactant.

Keywords: 5-Ethoxymethylfurfural; Glucose; Biomass; Zeolites; Meso-/microporosity; Hierarchical structure.

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Introduction

Over the past century, the world society has been heavily relied on fossil resources, such as coal, gas, and oil, to produce human beings' daily needed fuels and chemicals.[1-3] The carbon dioxide produced from usage of these non-renewable fossil resources has been significantly changing the climate on earth,[2] and the heavy reliance on these fossil resources makes them more expensive and less abundant. As a widely available and sustainable carbon source, biomass has the potential to replace the non-renewable fossil resources for the production of fuels and chemicals.[4] Lignocellulosic biomass, consisting of 60~80% carbohydrate component,[5] is the most promising renewable carbon source for production of both fuels and platform chemicals. Many strategies have been explored for the conversion of carbohydrates in lignocellulosic biomass into chemicals and fuels.[6-8] The use of an appropriate catalyst plays a crucial role in achieving high conversion and high selectivity to the end fuel and/or chemical alternative products in a green and economic process.[9,10]

5-(Ethoxymethyl)furfural (EMF), a liquid with boiling point of 508 K and an energy density of 30.3 MJ L^{-1}, close to that of diesel (33.6 MJ L^{-1}), gasoline (31.1 MJ L^{-1}) and ethanol (23.5 MJ L^{-1}), is an attractive and potential end biofuel alternative product.[11-13] The synthesis of EMF from biomass feedstock has been practiced via a single step etherification of 5-hydroxymethylfurfural (HMF),[14] two-step cascade of dehydration-etherification of fructose,[15] three-step cascade of decomposition-dehydration-etherification of disaccharide (e.g., sucrose)[16] or oligosaccharide (e.g., inulin)[17], and three-step cascade of isomerization-dehydration-etherification of monosaccharide such as glucose[12] in ethanol solvent. The single-step synthesis of EMF from HMF can occur over a variety of acidic catalysts[5] with > 90% yield. The high cost

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and non-stability of HMF, however, restrict its wide application in EMF production. The two-step and three-step cascade reactions of fructose-based feedstocks on acidic catalysts overcome the shortcomings in EMF synthesis via the single-step approach, but these saccharides are less abundant in nature. In contrast, glucose or glucose-based oligosaccharide and polysaccharide is the most abundant carbohydrate in lignocellulosic biomass.

The synthesis of EMF from glucose feedstock is desired, but requires multiple types of catalysts for different steps in the reaction cascade. For example, a combination of Sn-BEA and Amberlyst-15 catalysts has been used for glucose conversion to EMF[12], in which the former catalyst acts as Lewis acid for isomerization of glucose to fructose and the latter one catalyzes the dehydration and etherification of fructose to EMF. In this three-step reaction cascade, transport of reaction intermediates from one catalyst to the other in the reactor is needed, which might impede the efficiency in EMF production from the process point of view. The usage of multiple catalysts also complicates the catalyst preparation and/or separation steps if the catalyst recycling is needed. Multifunctional catalyst, *i.e.*, a single catalyst comprised of structurally and/or compositionally different active components within nanoscale distance, can enable multiple reaction steps successively and efficiently in the catalysis cascade. The precise position of active centers in the multifunctional catalysts, like the enzymatic catalyst systems in nature,[18-20] can also facilitate cooperative catalysis. The synthesis of EMF from glucose or glucose-based abundant carbohydrates is desired to take place over such a multifunctional catalyst, but such a catalyst system has been rarely reported.

In the present study, we report a hierarchical lamellar multifunctional MFI-Sn/Al zeolite catalyst that contains dual meso-/microporosity and dual Lewis and Brønsted acidity for glucose conversion into the EMF product. The MFI-Sn/Al catalyst was prepared via a single-step

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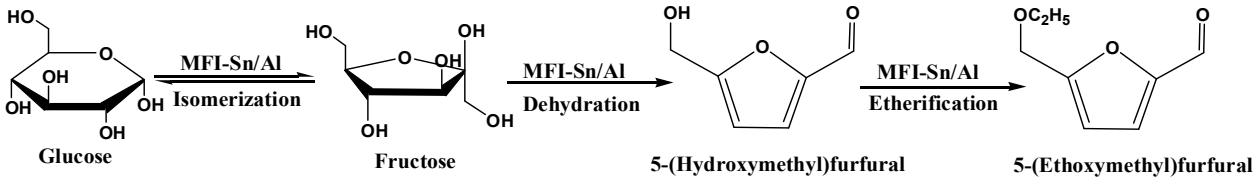
hydrothermal crystallization method under the assistance of a diquaternary ammonium template ($[C_{22}H_{45}\text{-}N^{+}(CH_3)_2\text{-}C_6H_{12}\text{-}N^{+}(CH_3)_2\text{-}C_6H_{13}]Br^{2-}$, $C_{22\text{-}6\text{-}6}$) in a composition of $100SiO_2/5C_{22\text{-}6\text{-}6}/18.5Na_2O/xAl_2O_3/ySnO_2/2957H_2O$ (x=0.5, 1, and 2, y=1 and 2, respectively). The co-existence of Sn and Al elements in the MFI-Sn/Al zeolite endows both Lewis acidic Sn- and Al-sites and Brønsted acidic Al–O(H)–Si sites for the three-step reaction cascade of isomerization-dehydration-etherification in the EMF production (Scheme 1). Tetravalent Sn site has showed good performance for catalyzing the isomerization of a series of pentose and hexose sugars with activities comparable to biological processes[19,20] by a mechanism similar to enzymatic catalysts.[18] Therefore, the Sn-sites in the MFI-Sn/Al catalyst were used to catalyze the isomerization step in the reaction cascade. The Brønsted acidic Al–O(H)–Si sites catalyze the subsequent dehydration of fructose to HMF and etherification of HMF to EMF product. The presence of hierarchical meso- and microporosity in the MFI-Sn/Al catalyst allows for facile transport of bulky molecules, and thereby further improving the catalyst performance in this reaction cascade. A high EMF yield (44%) has been achieved from glucose conversion over the multifunctional MFI-Sn/Al catalyst.



Scheme 1 Schematic illustration of EMF synthesis from glucose via a three-step reaction cascade over single MFI-Sn/Al zeolite catalyst.

Experimental

Materials

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Aluminum isopropoxide ($Al[OCH(CH_3)_2]_3$, 99.99+% purity), tetraethyl orthosilicate (TEOS, 98%), tetrapropylammonium hydroxide (TPAOH, 40 wt%), D (+)-glucose (98%), D-fructose (98%), sucrose (98%) and inulin (98%) were purchased from Alfa Aesar. Tin chloride pentahydrate ($SnCl_4 \cdot 5H_2O$, 98%), sodium hydroxide (NaOH, ≥ 97.0%), and ammonium nitrate (NH_4NO_3, ≥99.0%) were supplied by Sigma-Aldrich. Deionized (DI) water was used throughout the experiment. Diquaternary ammonium template ($[C_{22}H_{45}\text{-}N^+(CH_3)_2\text{-}C_6H_{12}\text{-}N^+(CH_3)_2\text{-}C_6H_{13}]Br_2$, ($C_{22\text{-}6\text{-}6}$)) was synthesized following the method reported by Choi et al[21] and the detailed synthesis procedure has been described in our previous work.[22,23]

Catalyst preparation

The MFI-Sn/Al zeolite catalysts were synthesized in a one-step hydrothermal crystallization process using the following recipe: $100SiO_2/5C_{22\text{-}6\text{-}6}/18.5Na_2O/xAl_2O_3/ySnO_2/2957H_2O$, where x=0.5, 1, and 2, y=1 and 2, respectively. Typically, the synthesis started by dissolving 0.41 g NaOH in 11.50 g DI water, followed by addition of desired amount of $SnCl_4 \cdot 5H_2O$ and $Al[OCH(CH_3)_2]_3$, separately. After a clear solution was formed, 5.78 g TEOS was added and the resultant mixture was stirred vigorously at room temperature for 8 h. A $C_{22\text{-}6\text{-}6}$ solution was prepared by dissolving 0.95 g $C_{22\text{-}6\text{-}6}$ in 2.83 g of DI water at 333 K and then added into above mixture. The resultant zeolite synthesis gel was continuously stirred at room temperature for 2 h. Finally, the synthesis gel was transferred into a Teflon vessel in a stainless steel autoclave. The autoclave was tumbled vertically at 30 rpm and 423 K in an oven for 14 days. After the hydrothermal synthesis, the zeolite products were collected by centrifugation at 6000 rpm for 15 min and then washed by dispersing in DI water. The water washing and centrifugation steps were repeated 6 times. A vacuum oven was utilized to dry the wet zeolite product at room temperature overnight. Finally, the zeolite samples were calcined in a flowing air (1.67 mL s^{-1}, ultrapure air,

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Airgas) at 873 K for 6 h. The obtained samples were named as MFI-Sn/Al (Si/Sn molar ratio, Si/Al molar ratio). According to the synthesis recipe, the following samples, MFI-Sn/Al (100/100), MFI-Sn/Al (100/50), MFI-Sn/Al (100/25), MFI-Sn/Al (50/50), MFI-Sn/Al (∞/100), have been prepared, respectively.

For comparison purpose, the conventional microporous MFI zeolite containing both Sn and Al (designated as C-MFI-Sn/Al (100/100)) was prepared according to the work of Mal et al.,[24] and the synthesis procedure was as follows. Firstly, 0.26 g of $SnCl_4{\cdot}5H_2O$ and 0.15 g of $Al[OCH(CH_3)_2]_3$ were dissolved with 19.00 g of DI water in a polyethylene bottle. Then, 15.61 g TEOS was added and the resultant mixture was stirred magnetically for 30 min. 16.50 g TPAOH solution was then added and the mixture was continuously stirred for 1 h. The molar ratio of the C-MFI-Sn/Al (100/100) synthesis gel was $100SiO_2/SnO_2/0.5Al_2O_3/44TPAOH/3430H_2O$. Finally, the mixture was transferred into a Teflon-lined autoclave and kept at 433 K for 2 days under static condition. After the synthesis, the sample was collected by centrifugation, washed by DI water and calcined using the procedures described for preparation of MFI-Sn/Al zeolites above.

Prior to catalysis tests, all the zeolite samples were ion-exchanged three times using 1.0 M aqueous NH_4NO_3 solution (weight ratio of zeolite to NH_4NO_3 solution = 1:10) for 3 hours at 353 K. The sample was collected by centrifugation, washed with DI water, and dried at 353 K for 12 h. All zeolite samples in their NH_4^+-form were treated in air (1.67 mL s^{-1}, ultrapure air, Airgas) by increasing the temperature from ambient to 823 K at 0.167 K s^{-1} rate and holding them at this temperature for 4 h.

Catalyst characterization

The scanning electron microscopy (SEM) images taken from a Hitachi Su-70 electron microscope were used to detect the morphologies of the synthesized zeolite samples. The powder

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X-ray diffraction (XRD) patterns were recorded using a Bruker D8 Advance Lynx Powder Diffractometer (LynxEye PSD detector, sealed tube, Cu Kα radiation with Ni β-filter) in the 2 θ ranging from 1.2° to 40°. The N_2 adsorption-desorption isotherms were measured at 77 K with an Autosorb-iQ analyzer (Quantachrome Instruments) to characterize the textual properties of the zeolite samples. Prior to the measurement, all the zeolite samples were evacuated overnight at 623 K and 1mm Hg pressure. The solid state magic angle spinning NMR (MAS NMR) spectra were recorded at a field of 7 T (Bruker DSX 300) for ^{29}Si and ^{27}Al. ^{29}Si MAS NMR spectra were recorded at 59.64 MHz using 4 mm rotors at a spinning speed of 10 kHz, a dwell time of 20 μs, a π/2 pulse of 5.0 μs, and a recycle delay of 60 s. The spectra were referenced with respect to 3-(trimethylsilyl)-1-propanesulfonic acid salt. ^{27}Al MAS NMR spectra were recorded at 78.22 MHz using 4 mm rotors at 10 kHz spinning speed, a dwell time of 1.0 μs, a selective π/10 pulse of 0.6 μs, and a recycle delay of 4 s. An aqueous solution of aluminum nitrate (0.1 M) was used as the reference. The ultraviolet-visible diffuse reflectance spectroscopy (UV-Vis-DRS) was performed using a Perkin-Elmer Lambda 650S model to understand the structure of the Sn-sites in zeolite samples. The integrating sphere is 60 mm and is made by LabSphere. The coating in the LabSphere 60 mm integrating attachment is Spectrolong. Typical scan rate was 1 nm/second and the scan range was from 200 nm to 800 nm. All the spectra were recorded in ambient condition.

Composition and acidity measurement

The Si, Al, and Sn contents of zeolite samples were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES, iCAP 6500 dual view). The concentration of active Brønsted acid sites in each zeolite sample was determined via the reactive gas chromatography (RGC) method using isopropylamine ($CH_3CH(NH_2)CH_3$) as the probe molecule. The selective

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decomposition of isopropylamine adsorbate on Brønsted acid site ($CH_3CH(NH_2)CH_3\cdots AlO(H)Si$) in zeolites via Hoffmann elimination forms propylene and ammonia, $CH_3CH(NH_2)CH_3$ + AlO(H)Si → $CH_3CH(NH_2)CH_3\cdots AlO(H)Si$ → $CH_2{=}CHCH_3$ + NH_3 + AlO(H)Si.[25,26] The quantification of propylene by a GC instrument determined the number of AlO(H)Si sties in each zeolite sample. The experimental setup and reaction conditions for chemical titration of Brønsted acid site were the same as those reported by Abdelrahman, et al.[26]

The types of acid sites were identified by the recorded Fourier transform infrared (FTIR) spectra on a Nicolet iS-50R spectrometer with an associated Harrick Scientific Praying Mantis optical accessory and high temperature reaction chamber (HVC-DRP-5). In a typical run, the DRIFTS sample cell was filled with a zeolite sample that was pre-treated at 823 K for 6 h under following helium (He, 0.083 mL s^{-1}) in a furnace. The zeolite sample was then activated at 823 K under the He flow (0.083 mL s^{-1}) for 1 h in the DRIFTS cell. After cooling the sample to 393 K, a spectrum was recorded against the background spectrum of KBr powder measured under the same conditions. Afterwards, adsorption of pyridine was performed by flowing a mixed pyridine and He gas stream through the catalyst. Following adsorption, the sample was heated to 523 K under a flowing He to desorb the physisorbed pyridine, cooled to the temperature of 393 K, and then FTIR spectra were recorded in the range of 4000−600 cm^{-1} with 128 scans at an effective resolution of 2 cm^{-1}. The as-recorded FTIR spectra of adsorbed pyridine were used to determine the type and concentration of Brønsted and Lewis acid sites in the catalyst. Alternatively, the activated zeolite sample in the DRIFT cell was cooled to 303 K and then exposed to a mixed trideuteroacetonitrile (CD3CN) and argon (Ar) gas stream using a bubbler with Ar as the carrier gas. After the excess CD3CN was flushed out from the zeolite sample using a flowing Ar gas

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(0.083 mL s^{-1}), the spectra were collected at 2 cm^{-1} resolution. The recorded FTIR spectra of CD3CN were used to analyze the Sn-site in each zeolite sample.

The acidity of the zeolite was further evaluated by ammonia temperature programmed desorption (NH_3-TPD) using an Autosorb-iQ instrument (Quantachrome, ASIQM000-4) equipped with a thermal conductivity detector (TCD). In the NH_3-TPD measurement, the zeolite sample (0.10 g) was loaded into a quartz cell and heated to 873 K at a rate of 0.05 K s^{-1} under He (0.67 mL s^{-1}) and maintained at this temperature for 1 h. After cooling to 423 K under the He stream, the sample was exposed to NH_3 stream (0.5 mL s^{-1}, ultrapure, Airgas) for 0.5 h, and then back to the helium flow (0.5 mL s^{-1}) for 2 h to remove NH_3 residue in the system. Lastly, the catalyst sample was ramped to 823 K at a ramp rate of 0.167 K s^{-1}, and the NH_3 desorption profile was recorded.

Catalytic reaction for EMF synthesis from carbohydrates

In a typical catalytic reaction, a 20 mL thick-walled glass reactor sealed with crimp tops (PTFE/silicone septum) was charged with glucose (0.090 g), zeolite catalyst (0.074 g), and ethanol (3 mL), respectively. The glass reactor was then heated to a desired temperature and the magnetic stirring was controlled at 600 rpm in all the catalysis experiment. After a certain reaction time, the reactor was quenched in an ice bath and the reaction mixture was sampled for composition analysis. A high performance liquid chromatography (HPLC, Agilent 1100) equipped with an Aminex HPX-87H column connected to an auto-sampler and a refractive index detector was used to calibrate and separate the reactant and products. During the measurement, the column was kept at 413 K with 0.005 M sulfuric acid at a flow rate of 0.5 mL min^{-1} as the mobile phase. For comparison purpose, the same reaction and composition analysis conditions were applied to the fructose, sucrose, and inulin reactant in ethanol solvent, respectively. The

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effect of types of reactants on the EMF production over MFI-Sn/Al zeolite catalysts was thus examined.

Results and Discussion

Morphology and textural properties of MFI-Sn/Al zeolite catalysts

Fig. 1 shows XRD patterns of the synthesized hierarchical lamellar MFI-Sn/Al zeolite catalysts. For comparison purpose, the XRD patterns of lamellar MFI that only contains Al sites (MFI-Sn/Al (∞/100)) and conventional microporous MFI that comprises of both Sn and Al sites (C-MFI-Sn/Al (100/100)) are included. As indicated in Fig. 1, all the MFI-Sn/Al zeolite samples exhibit similar diffraction patterns, resembling the characteristics of crystalline MFI zeolite.[21,27,28] This result confirms the successful synthesis of hierarchical lamellar MFI in the presence of both Sn and Al species in the synthesis gels. The absence of small-angle diffraction peaks in Fig. 1 suggests that long-range ordering of the layered zeolitic structure does not exist in the hierarchical lamellar MFI-Sn/Al zeolites. A comparison for the peak intensity between the MFI-Sn/Al samples and C-MFI-Sn/Al (100/100) shows that the diffraction peak intensities of the former samples are all relatively lower than the latter one. This is mainly caused by the small framework thickness along the *b*-axis direction in the hierarchical lamellar MFI-Sn/Al zeolites compared to that in the three dimensional microporous C-MFI-Sn/Al (100/100) zeolite.[20]

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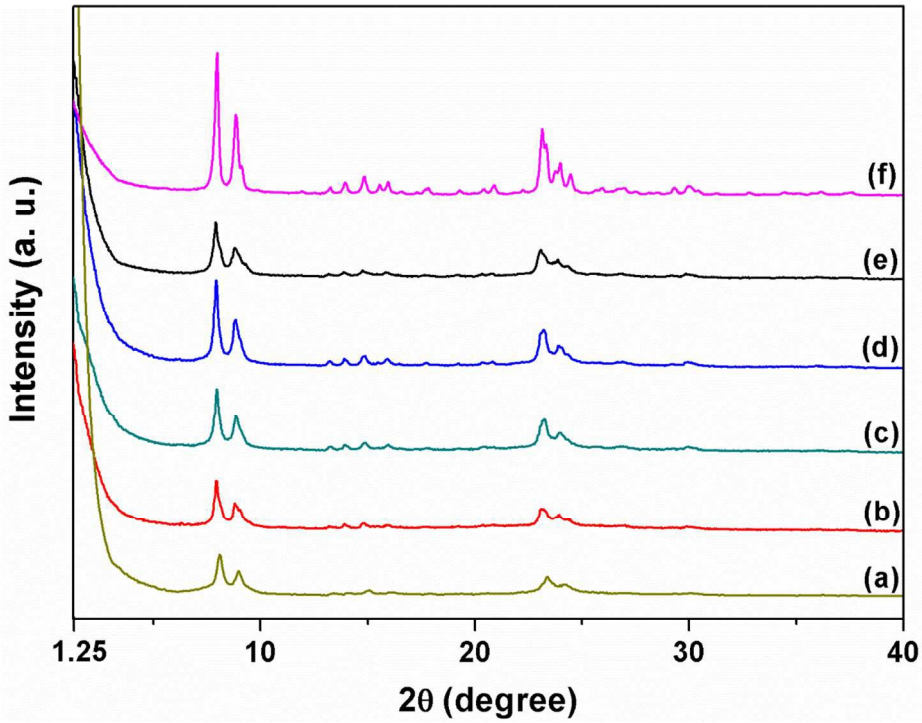

Fig. 1 XRD patterns of (a) MFI-Sn/Al (∞/100), (b) MFI-Sn/Al (50/50), (c) MFI-Sn/Al (100/25), (d) MFI-Sn/Al (100/50), (e) MFI-Sn/Al (100/100) and (f) C-MFI-Sn/Al (100/100), respectively.

The morphologies of the hierarchical lamellar MFI-Sn/Al zeolites together with C-MFI-Sn/Al (100/100) and MFI-Sn/Al (∞/100) samples are shown by the SEM images in Fig. 2 and Fig. S1 in the supplementary information. All the MFI-Sn/Al zeolites (Figs. 2(a)-(e)) are comprised of interweaved platelet-like structure that formed flower-like aggregates with irregular sizes (Fig. S1), while the C-MFI-Sn/Al (100/100) sample is composed of uniform but irregular shaped particles, whose sizes are in the range of 150 – 200 nm (Fig. 2(f)). A closer examination on the MFI-Sn/Al zeolite samples shows that the width and thickness of the platelet-like structure decreases with increasing Al content in the synthesis recipe (Figs. 2a-b-c). Moreover, the platelet-like structures change from curved to straight ones with increasing Al content. Similarly, the increase in Sn content in the synthesis recipe decreases the thickness of the zeolite platelet-like structure in the MFI-Sn/Al samples (refer to Figs. 2b-d). The effect of Si/Al and

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Si/Sn ratios in the synthesis recipe on the morphology of derived MFI-Sn/Al zeolites is the same as that observed by Machoke et al[29] on synthesis of multilamellar MFI under static condition. The introduction of aluminum and/or tin into the lamellar zeolite synthesis recipe leads to defects in zeolite nanosheet structures, which consequently affect the growth of nanosheets along the a-c plane. Therefore, more randomly oriented and smaller sized zeolite nanosheets are formed in the crystallization process, which results in the thinner and straighter zeolite plates from the synthetic gels containing higher aluminum and/or tin contents.

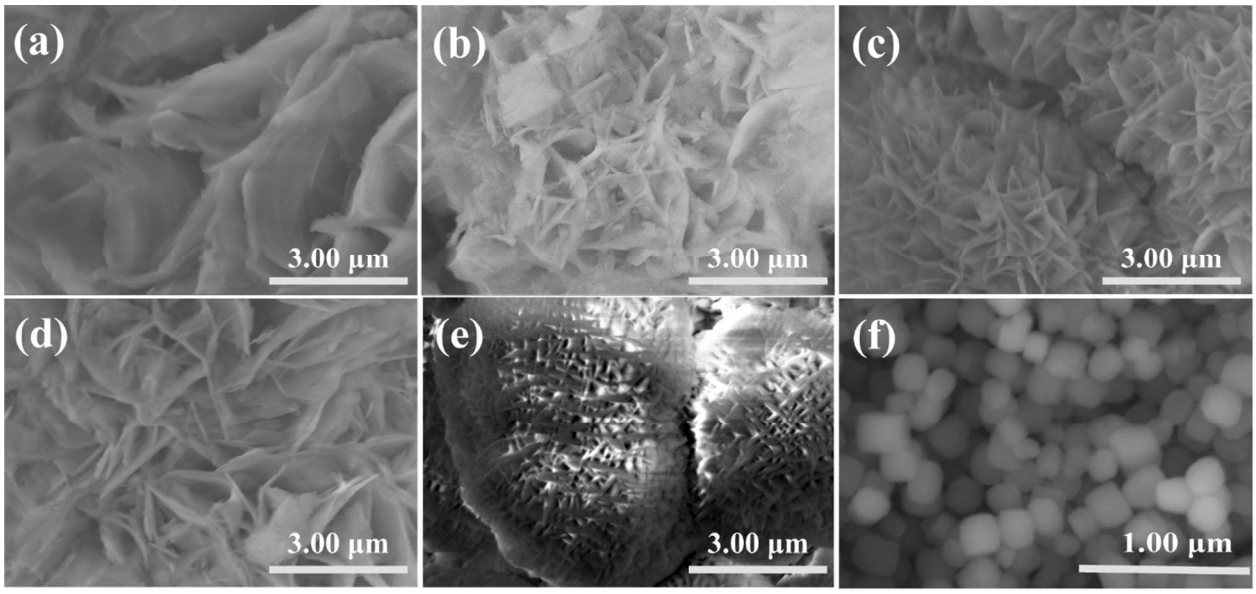

Fig. 2 SEM images of (a) MFI-Sn/Al (100/100), (b) MFI-Sn/Al (100/50), (c) MFI-Sn/Al (100/25), (d) MFI-Sn/Al (50/50), (e) MFI-Sn/Al (∞/100) and (f) C-MFI-Sn/Al (100/100), respectively.

N_2 adsorption-desorption isotherms were used to study the textural properties of the MFI-Sn/Al zeolite samples. The textural parameters of each sample are included in Table S1 of the supplementary information. Fig. 3A illustrates that all the synthesized hierarchical lamellar MFI-Sn/Al zeolites exhibit type-IV isotherms with hysteresis loops corresponding to capillary condensation in mesopores.[21,30] Particularly, at low relative pressures ($P/P_0 < 0.45$), the

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isotherms of these zeolites are similar and comparable to that of C-MFI-Sn/Al (100/100) zeolite. This suggests all the synthesized MFI-Sn/Al samples have similar micropore structures. At high relative pressures ($P/P_0 > 0.45$), the isotherms of the MFI-Sn/Al samples show hysteresis loops, different from that of C-MFI-Sn/Al (100/100). For all the MFI-Sn/Al samples, the hysteresis loops in their isotherms are relatively narrow and flat, which indicates these materials have disordered mesopores and broad pore size distributions.[31,32] Fig. 3B shows the nonlocal density functional theory (NLDFT) pore size distributions of all MFI-Sn/Al samples. As suggested from the shape of hysteresis loops in their isotherms, the MFI-Sn/Al (100/100), MFI-Sn/Al (50/50), MFI-Sn/Al (100/50), and MFI-Sn/Al (100/25) zeolites have broad mesopore size distributions. In contrast, the C-MFI-Sn/Al (100/100) zeolite does not have significant mesoporosity.

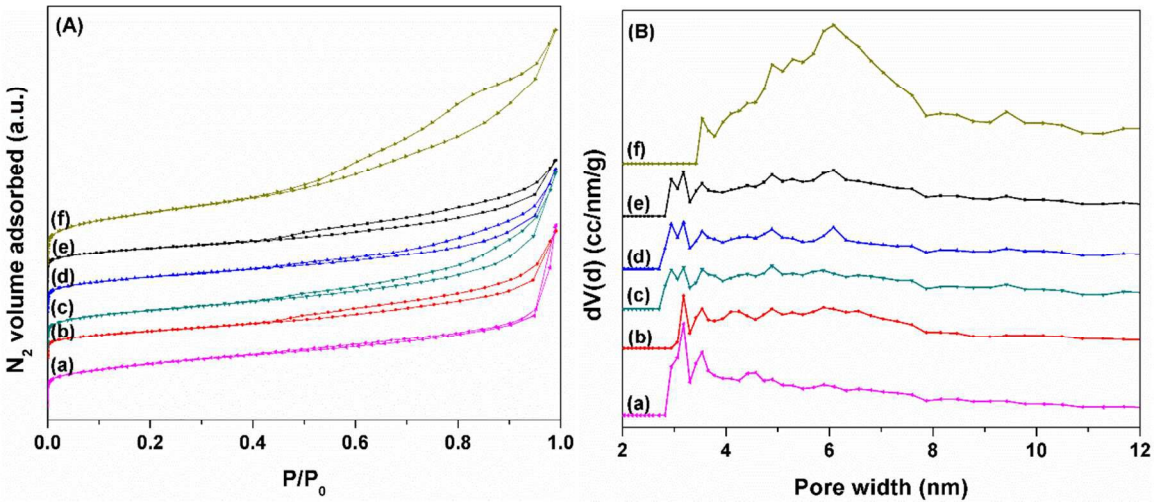

Fig. 3 N_2 isotherms (A) and the corresponding NLDFT pore size distributions (B) as determined from adsorption branch of (a) C-MFI-Sn/Al (100/100), (b) MFI-Sn/Al (50/50), (c) MFI-Sn/Al (100/25), (d) MFI-Sn/Al (100/50), (e) MFI-Sn/Al (100/100) and (f) MFI-Sn/Al (∞/100), respectively.

Solid state NMR was employed to investigate the local bonding environment of Si and Al species in the MFI-Sn/Al zeolite catalysts. Figs. 4A and 4B show the ^{29}Si single pulse (SP) and

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^{27}Al NMR spectra of the MFI-Sn/Al (100/100), MFI-Sn/Al (50/50), MFI-Sn/Al (100/50), and MFI-Sn/Al (100/25) zeolites, respectively. In Fig. 4A, one well-resolved peak at -113 ppm and one shoulder peak at -103 ppm can be observed. These two peaks correspond to the crystallographically nonequivalent Q^4 tetrahedral sites (Q^n stands for $X_{4-n}Si[OSi]_n$)[33-36] and Q^3 sites that arise from the silanol groups on the zeolite surface,[23,37] respectively. The similarity of ^{29}Si SP NMR spectra of MFI-Sn/Al zeolites suggests similar local bonding environments exist in these samples. In Fig. 4B, the two peaks (at 55 ppm and 0 ppm) in the ^{27}Al MAS NMR spectra were observed. The peak at 55 ppm is due to the tetrahedrally coordinated framework aluminum (Al_F), whereas the peak around 0 ppm is due to an octahedral coordination typical of extra-framework Al (Al_{EF}).[38-40] The percentages of the Al_{EF} sites in MFI-Sn/Al (50/50), MFI-Sn/Al (100/25), MFI-Sn/Al (100/50), and MFI-Sn/Al (100/100) samples were calculated from the intensities of the peak around 0 ppm over the peak around 55 ppm, which are 3.6%, 8.1%, 4.4% and 2.0%, respectively. Obviously, the higher Al content in the synthesis led to higher proportions of Al_{EF} in MFI-Sn/Al zeolites. When the concentration of Al was the same, the one with higher Sn content in the synthesis recipe resulted in a higher proportion of Al_{EF} in the as-obtained MFI-Sn/Al samples.

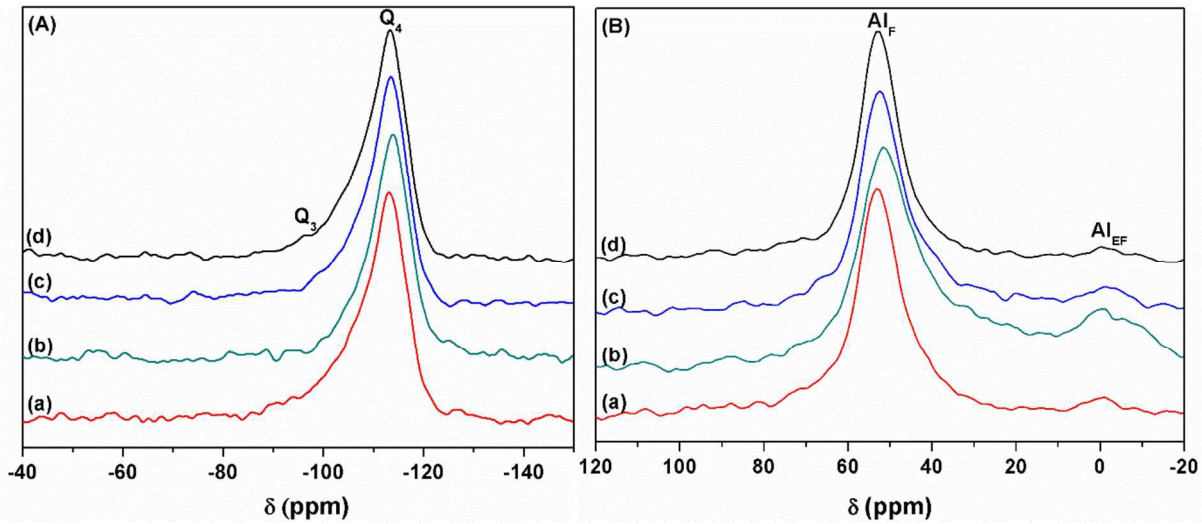

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Fig. 4 Solid-state ^{29}Si MAS NMR (A) and ^{27}Al MAS NMR (B) spectra of hierarchical lamellar MFI-Sn/Al zeolite samples: (a) MFI-Sn/Al (50/50), (b) MFI-Sn/Al (100/25), (c) MFI-Sn/Al (100/50), and (d) MFI-Sn/Al (100/100), respectively.

Composition and acidity of MFI-Sn/Al zeolite catalysts

The tin (Sn) and aluminum (Al) contents of the MFI-Sn/Al zeolite samples were analyzed by ICP-AES technique, represented by Si/Sn and Si/Al ratios, as shown in Table S2 of the supplementary information. The Sn and Al concentrations of the synthesized MFI-Sn/Al samples are generally higher than those determined from the synthesis recipe. Table 1 lists the concentrations of Al and Sn sites determined by elemental analysis and the concentration of Brønsted acid sites measured by RGC method. The concentration of Al sites is higher than Brønsted acid sites, suggesting that there is a considerable amount of non-framework Al in the synthesized MFI-Sn/Al zeolite samples. If we assume all the Al species that could not be detected by the RGC method as Lewis acid site ($L_{(Al)}$), the ratio of the Brønsted to Lewis (Al) acid site can be calculated, as shown by entry 6 in Table 1. The overall Brønsted to Lewis acid site ratio (entry 7 in Table 1) in each zeolite sample can also evaluated by division of Brønsted acid sites with the sum of Lewis (Al) acid and Sn sites. Apparently, the increase in Al or Sn content in the hydrothermal synthesis increased more Lewis acid sites compared to Brønsted acid sites in the MFI-Sn/Al samples.

Table 1 Concentration of Sn, Al and acid sites in MFI-Sn/Al zeolite catalysts.

Zeolite	Sn [a] (mmol/g)	Al [a] (mmol/g)	Brønsted acid site [b] (mmol/g)	Lewis (Al) acid site ($L_{(Al)}$) [c], (mmol/g)	Brønsted/Lewis (Al) acid site ratio [d] ($I_B/I_{L(Al)}$)	Brønsted/Lewis (Al + Sn) acid site ratio [e] ($I_B/I_{L\,(Al+Sn)}$)	Brønsted/Lewis acid site ratio [f] (I_B/I_L)
MFI-Sn/Al (100/100)	0.219	0.245	0.141	0.104	1.351	0.436	0.989
MFI-Sn/Al (100/50)	0.317	0.505	0.239	0.266	0.895	0.410	0.893
MFI-Sn/Al (100/25)	0.299	0.794	0.274	0.520	0.528	0.334	0.744

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MFI-Sn/Al (50/50)	0.523	0.438	0.121	0.317	0.379	0.144	0.464
MFI-Sn/Al (∞/100)	0	0.228	0.159	0.069	-	-	-

[a] Calculated from elemental analysis (ICP-AES); [b] Determined from RGC by selective decomposition of isopropyl amine on Brønsted acid sites; [c] Determined from deduction of concentration of Brønsted acid sites determined by RGC from Al concentration measured by elemental analysis; [d] Calculated by ratio of data in column 4 relative to that in column 5; [e] Calculated by ratio of data in column 4 relative to the sum of data in columns 2 and 5; [f] Evaluated by FITR spectra of adsorbed pyridine. I_B/I_L is the ratio of peak intently of 1545 cm^{-1} relative to that of 1450 cm^{-1}.

To understand the types of acidity, the FTIR spectra of the OH-stretching mode (ν(OH)) and adsorbed pyridine in the MFI-Sn/Al samples were recorded, as presented in Fig. 5(A) and (B), respectively. In Fig. 5(A), there are four peaks centered around 3739 cm^{-1}, 3676 cm^{-1}, 3605 cm^{-1}, and 3501 cm^{-1}, in sequence, which are associated with terminal silanol (Si-OH) groups, Lewis acidic or non-acidic extraframework Al-OH, Bronsted acid sites (Si-O(H)-Al), and hydrogen-bonded internal silanol (Si-OH) groups.[41-45] In the absence of Al in MFI-Sn/Al (100/∞) zeolite, the peak of Si-O(H)-Al does not exist, in contrast to the 3605 cm^{-1} peak in all other MFI-Sn/Al samples. The same trend is observed in Al-OH sites in all these samples. The increase in Al (sample (b)-(d) or Sn (sample (a) and (c)) content increased the Al-OH and (Si-O(H)-Al) sites, as indicated by increasing intensity of 3676 cm^{-1}, 3605 cm^{-1} peaks. The control sample, commercial MFI, and the conventional microporous MFI-Sn/Al (100/∞) both contain a big peak at 3500cm^{-1}, indicating the presence of internal Si-OH groups in these samples. The hierarchical MFI-Sn/Al, apparently, have quite low amount of such internal groups. Fig. 5(B) presents the FTIR spectra of adsorbed pyridine on zeolites, which hints the relative quantity of Brønsted to Lewis acid sites in the MFI-Sn/Al samples.[46] MFI-Sn/Al (50/50), MFI-Sn/Al (100/25), MFI-Sn/Al (100/50) and MFI-Sn/Al (100/100) all showed characteristic peaks for Brøsnted (1545 cm^{-1}) and Lewis (1450 cm^{-1}) acid sites. MFI-Sn/Al (100/∞) only showed the peak of Lewis acid sites due to the absence of Al in the structure. The difficulty in determining accurate molar extinction coefficients of

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solid acid materials in DRIFT mode restricts our capability of calculating the accurate number of Brøsnted and Lewis acid sites in each sample.[47,48] The intensities of the signals in Fig. 5(B), due to both types of acid sites, are proportional to their concentrations. Therefore, we conducted semi-quantitative analyses of the ratio of Brønsted to Lewis acid sites in MFI-Sn/Al zeolites by calculating the intensity ratio of Brønsted relative to the Lewis (I_B/I_L) acid sites in these samples. As listed in Table 1, the I_B/I_L decreases with increasing Al content from samples (b)-(d). The increase in Sn content from samples (a) and (c) enhanced the Lewis acidity. These results are consistent with the type of acidity determination by the combination of elemental analysis and RGC measurement in Table 1.

FTIR spectroscopy of adsorbed deuterated acetonitrile can be used for characterization of the framework and extra-framework Lewis acid Sn sites in Sn-Beta[49,50] or Sn-MFI[51] zeolites. We also used this technique to understand the structure of Sn sites existing in the synthesized MFI-Sn/Al zeolites. As shown in Fig. 5(C), three peaks at 2266, 2273 and 2316 cm^{-1} are observed, which are assigned to the C-N stretching vibration of the adsorbed deuterated acetonitrile[49]. The band at 2266 and 2273 cm^{-1} corresponds to the deuterated acetonitrile physisorbed and adsorbed on silanol groups. The band at 2316 cm^{-1} can be assigned to the stronger deuterated acetonitrile adsorption on Lewis acid sites[49]. According to the previous report[50], the features near 2316 cm^{-1} are clearly associated with framework Sn sites, which confirmed the presence of framework Sn in the zeolite structures. Furthermore, the structure of Sn sites was evaluated by the UV-vis-DRS spectra, as shown in Fig. 5(D). The absorbance around 210 nm was observed for all the MFI-Sn/Al samples, showing the presence of isolated, tetrahedral Sn^{4+} species within the zeolite framework. The increase in Sn content in the synthesis increased the Sn^{4+} sites in the resultant MFI-Sn/Al zeolites, as indicated by the sample (a) and (c) in Fig. 5(D). The increase in Al

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content in zeolite synthesis affected the incorporation of Sn sites into the framework, as reflected by the increase in 210 nm peak intensity from sample (b), (c) and (d). Apparently, no Sn oxide is observed in all MFI-Sn/Al zeolite samples, as indicated by the absence of characteristic peak of SnO_2 sample.

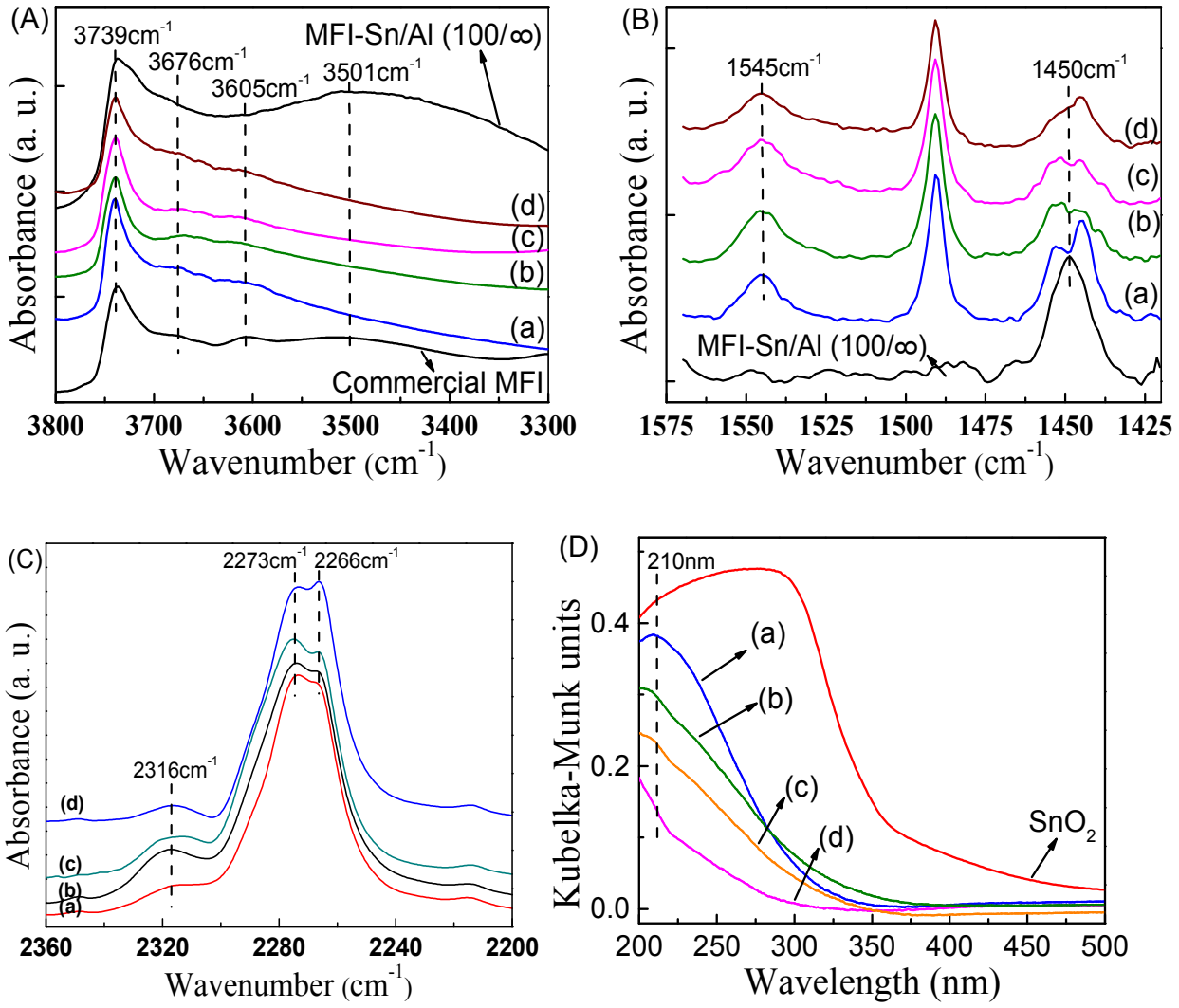

Fig. 5 (A) DRIFTS spectra of MFI-Sn/Al zeolites; FTIR spectra of pyridine (B) and deuterated acetonitrile (C) adsorbed on the MFI-Sn/Al zeolites; and (D) DR-UV-vis spectra of MFI-Sn/Al samples, respectably. (Denotation in each figure: (a) MFI-Sn/Al (50/50), (b) MFI-Sn/Al (100/25), (c) MFI-Sn/Al (100/50) and (d) MFI-Sn/Al (100/100). MFI-Sn/Al (100/∞) stands for

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conventional microporous MFI comprised of only Sn sites. The commercial MFI with Si/Al ratio of 40 (Supplier No. 45882-36) in Fig. 5(A) and SnO_2 (Supplier No. 44606-18) in Fig. 5(D) were purchased from Alfa Aesar.)

The acidity of the MFI-Sn/Al zeolite catalysts were further characterized by the NH_3-TPD measurement, and the results are shown in Fig. 6. Two desorption peaks located in the temperature range of 400-550 K (low temperature desorption peak) and 550-750 K (high temperature desorption peak), respectively, are observed in all the tested zeolite samples. It has been generally reported that the low temperature peak is associated with the physical and Lewis acid site adsorption of NH_3, while the high temperature desorption peak is assigned to the adsorption of NH_3 on the Brøsnted acid sites in the catalysts[52-54], although caution must be paid since desorption of NH_3 from non-acidic sites in catalysts scan take place over a wide temperature range.[55,56] Additionally, the intensity is correlated to the quantity of acid sites in the zeolite catalysts.[57] Fig. 6 shows that the low and high temperature desorption peaks are increased with increasing Al sites from MFI-Sn/Al (100/∞), MFI-Sn/Al (100/100), MFI-Sn/Al (100/50) to MFI-Sn/Al (100/25) materials. The increase in Sn sites mainly increases the low temperature peak, as the zeolite samples transit from MFI-Sn/Al (∞/100) to MFI-Sn/Al (100/100) and MFI-Sn/Al (50/50) to MFI-Sn/Al (100/50). The results suggest that Al in the MFI-Sn/Al zeolites led to both Lewis and Brønsted acidity, while Sn-site predominately contributes to the Lewis acidity.

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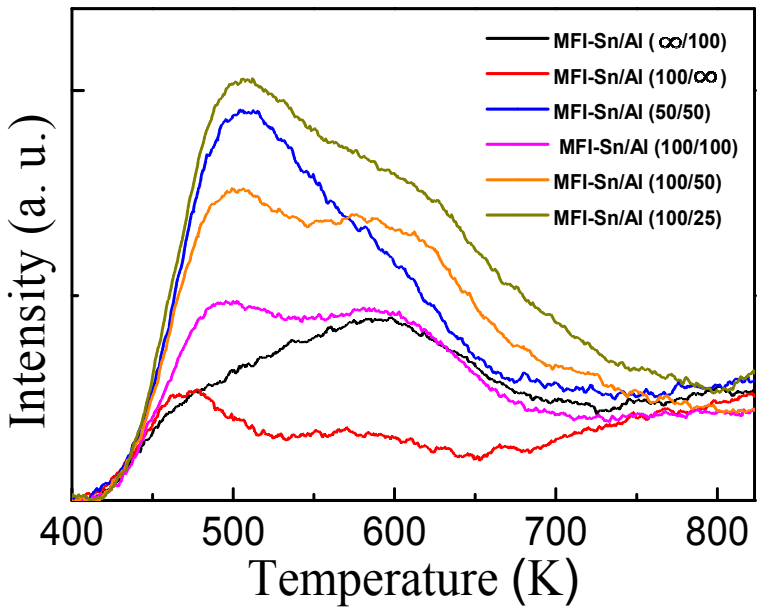

Fig. 6 NH_3-TPD profiles of MFI-Sn/Al zeolites with different Si/Al and Si/Sn ratios. (MFI-Sn/Al (∞/100) and MFI-Sn/Al (100/∞) stand for the conventional microporous MFI zeolites containing only Al and Sn sites, respectively.)

Reaction cascade for EMF synthesis from carbohydrates over MFI-Sn/Al zeolite catalysts

As shown in Scheme 1, the EMF synthesis from glucose carbohydrate occurs via a three-step reaction cascade, in which the first step is isomerization of glucose into fructose and the next two steps are dehydration of fructose to HMF and etherification of HMF to EMF final product. The first step reaction can be catalyzed by the Lewis acidic Sn sites and the last two steps can take place over the Brønsted acidic Al–O(H)–Si sites in the MFI-Sn/Al zeolite catalysts. The acidity characterizations in Section 3.2 indicate the co-existence of both Sn and Al sites, *i.e.*, both Lewis and Brønsted acid sites, in the MFI-Sn/Al zeolites. We expect that they are efficient catalysts for this three-step reaction cascade. Moreover, the morphological and textural property characterizations in Section 3.1 indicates the presence of mesoporosity in the synthesized MFI-Sn/Al zeolites, which could be beneficial for the reaction cascade compared to the conventional

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microporous zeolite analogue. We, therefore, studied the performance of the MFI-Sn/Al zeolite catalysts in EMF synthesis from carbohydrate reactants. The effects of catalyst structure, reaction temperature, catalyst acidity and carbohydrate reactant type on EMF synthesis were examined in sequence via a series of catalytic reactions. The reaction conditions used for EMF synthesis from glucose reactant over MFI-Sn/Al (100/100) catalyst at 413 K were used as the base case for comparison. Individual experimental variables were changed, and the effects of changing these variables were investigated by comparing the catalysis data to that obtained with the standard conditions, as discussed below.

EMF synthesis from glucose over MFI-Sn/Al (100/100), C-MFI-Sn/Al (100/100) and MFI-Sn/Al (∞/100) catalysts

The synthesis of EMF from glucose was firstly tested over the MFI-Sn/Al (100/100), C-MFI-Sn/Al (100/100), and MFI-Sn/Al (∞/100) zeolite catalysts. Figs. 7a-c show the glucose conversion and product yields versus the reaction time over each catalyst. It should be noted that the products are mainly comprised of fructose, HMF and EMF in the glucose-to-EMF conversion, and thus only these major products were analyzed in the present study. Fig. 7d shows the EMF yield at the reaction time of 9 h over each tested catalyst. As demonstrated in Figs. 7a-c, the glucose conversion was higher in MFI-Sn/Al (100/100) than C-MFI-Sn/Al (100/100), so did the EMF yield (Fig. 7d). A closer examination on the kinetic data (e.g., reaction time: < 5 h) in Figs. 7a and b shows that the EMF formation took place at a much faster rate in MFI-Sn/Al (100/100) than C-MFI-Sn/Al (100/100) catalyst. These results indicate that mesoporosity in the hierarchical lamellar MFI zeolite plays an important role in enhancing this three-step reaction cascade. As reported previously, the Stokes diameter of glucose is 0.73 nm,[58] larger than the micropore sizes of MFI zeolite. As a result, the reaction mainly takes place on the external surface of

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conventional C-MFI-Sn/Al (100/100) zeolite. The presence of mesopores in MFI-Sn/Al (100/100) apparently promotes the access of reactant to acid sites in interior of MFI-Sn/Al (100/100) zeolite. The mesopores also enhance the transport of reactant onto or product (or reaction intermediate) away from the active sites in the catalyst in these three steps in the reaction cascade. The sole presence of Al sites in the hierarchical lamellar MFI zeolite (MFI-Sn/Al (∞/100)) also enabled glucose conversion, but the conversion was lower than MFI-Sn/Al (100/100) and produced nearly zero EMF production (Figs.7c and d). Both glucose conversion and EMF yield suggest the efficiency of Lewis Sn sites in catalysts for glucose isomerization, as well as the dehydration and etherification steps in the three-step reaction cascade. Additionally, the comparison between the performances of MFI-Sn/Al (100/100) and MFI-Sn/Al (∞/100) also suggests the efficiency of the cooperative catalysis offered from both types of acid sites in this three-step reaction cascade.

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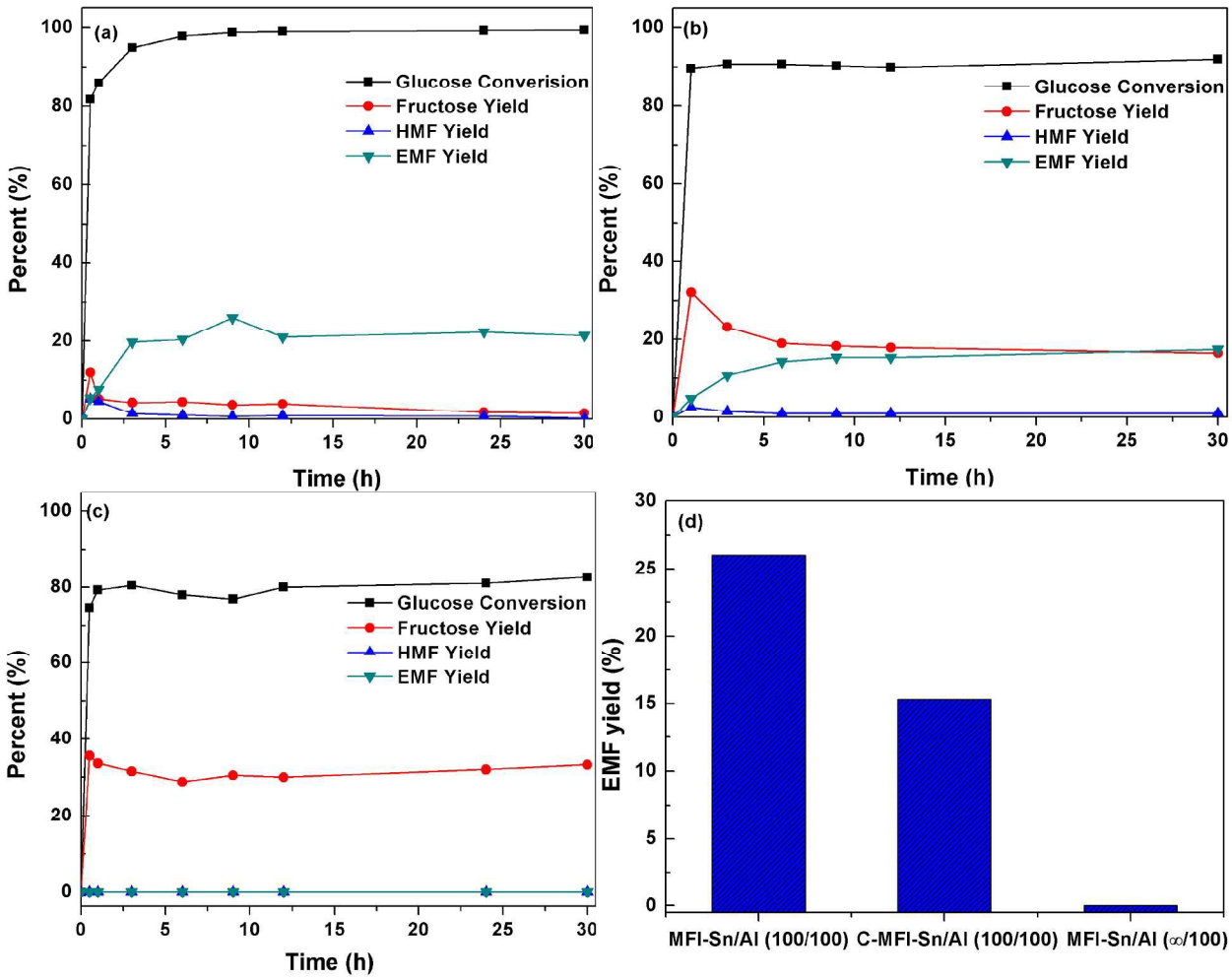

Fig. 7 Catalytic conversion of glucose to EMF over (a) MFI-Sn/Al (100/100), (b) C-MFI-Sn/Al (100/100) and (c) MFI-Sn/Al (∞/100), respectively, versus reaction time. (d) shows the EMF yield at reaction time of 9 h across these three zeolite catalysts. (reaction condition: glucose: 0.090 g; zeolite: 0.074 g; temperature: 413 K; ethanol: 3 mL).

Effect of reaction temperature on EMF synthesis from glucose over MFI-Sn/Al (100/100) catalyst

The effect of reaction temperature on glucose conversion to EMF over the MFI-Sn/Al zeolite catalysts was examined by employing the MFI-Sn/Al (100/100) catalyst at the reaction temperature of 398 K, 406 K, and 413 K, respectively. Fig. 8 shows the glucose conversion and

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product yields as a function of the reaction time (Figs. 8a-c) together with the EMF yield at the reaction time of 9 h (Fig. 8d) at these three reaction temperatures. By increasing the reaction temperature from 398 K to 413 K, the rate of glucose conversion increased, so did the fructose conversion and EMF production (refer to reaction time of 0-5 h in Figs. 8a-c). The changes of HMF yields follow the same trend of fructose. This indicates the successive three-step reaction nature in glucose-to-EMF reaction cascade, besides the endothermic nature of these three reaction steps. The maximum EMF yields in the course of this reaction are slightly increased with an increase in the reaction temperature. As shown in Fig. 8d, the EMF yield was increased from 23.2% to 24.5% to 26.0% when the reaction temperature was increased from 398 K to 406 K and then to 413 K. These results indicate that higher temperature increases the conversion of glucose reactant and the successive step of dehydration of fructose in the three-step reaction cascade.

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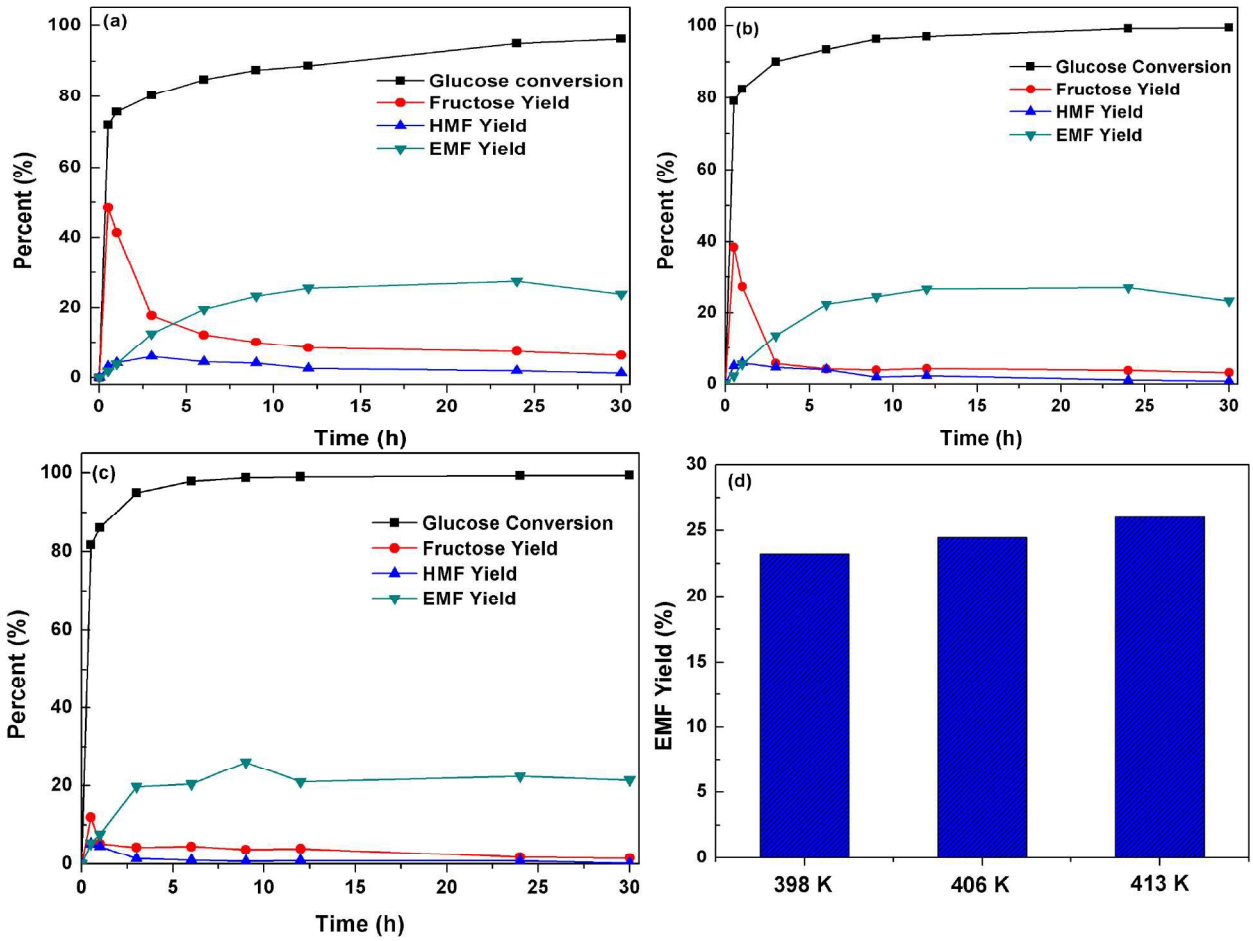

Fig. 8 Effect of reaction temperature ((a) 398 K, (b) 406 K, and (c) 413 K, respectively) on catalytic conversion of glucose to EMF over MFI-Sn/Al (100/100). (d) shows the maximum EMF yield at the reaction process at these three temperatures. (reaction condition: glucose: 0.090 g; zeolite: 0.074 g; ethanol: 3 mL).

Effect of zeolite acidity on EMF synthesis from glucose over MFI-Sn/Al catalysts

The influences of Sn and Al contents (*i.e.*, acidity, represented by Si/Sn and Si/Al ratios) in MFI-Sn/Al zeolite catalysts on their catalytic performances in the glucose-to-EMF reaction was studied at 413 K. Fig. 9 shows the product yields from the reaction over MFI-Sn/Al (100/100), MFI-Sn/Al (100/50), MFI-Sn/Al (100/25), and MFI-Sn/Al (50/50) catalysts, respectively. As indicated in this figure, all the MFI-Sn/Al zeolites enabled EMF, HMF and fructose production.

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The yields of these three products follow the order of EMF > fructose > HMF in each catalyst, suggesting the etherification of HMF to EMF happened much faster than dehydration of fructose in this reaction cascade. Fig. 9 also shows that the HMF and EMF yields from this reaction cascade increases in the order of MFI-Sn/Al (100/100) < MFI-Sn/Al (100/50) < MFI-Sn/Al (100/25) << MFI-Sn/Al (50/50). The fructose yield also follows the same order as that of EMF and HMF over the MFI-Sn/Al (100/100), MFI-Sn/Al (100/50) and MFI-Sn/Al (100/25) catalysts that have similar number of Sn sites but different Al sites. The increase in Al content increases Brønsted acidity of the MFI-Sn/Al catalysts, which benefits etherification of HMF to EMF reaction step. Additionally, this acidity enhances dehydration of fructose to HMF and isomerization of glucose to fructose reaction steps. It should be noted that the glucose conversion happened at a slower rate with increasing Al content in MFI-Sn/Al catalysts (refer to Figs. S2a-b-c in Section S2 of the Supplementary Information). The controversy between the glucose conversion and fructose/HMF/EMF formation with increasing Al content in the MFI-Sn/Al catalysts suggests that the increased Brønsted acidity affected the performance of Lewis acidity from Sn sites, *i.e.*, promoted fructose formation from glucose isomerization and suppressed glucose conversion to side products and thus glucose conversion rate, which overall might be the consequences of cooperative catalysis between both types of acidity in a single catalyst for this three-step reaction cascade.

The comparison for glucose conversion and product yields between MFI-Sn/Al (100/50) and MFI-Sn/Al (50/50) catalysts in Fig. 9 and Fig. S2 (Section S1 in supplementary information) shows the effect of Sn sites (i.e., Lewis acidity) on the performance of the hierarchical lamellar MFI-Sn/Al catalysts. The increase in Sn sites promoted the glucose conversion as well as HMF and EMF formation, while the fructose yield was reduced. It is suggested that Sn sites in zeolite

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function as Lewis acidity that is beneficial for isomerization of glucose to fructose product,[59] and thus the higher glucose conversion and fructose formation are expected with increasing Sn sites while keeping Al site concentration in the MFI-Sn/Al catalysts. The discrepancy for observed lower fructose formation (or yield) and higher glucose conversion as well as higher HMF and EMF formation in this three-step reaction cascade hints that the cooperative catalysis between the Brønsted acidic Al–O(H)–Si sites and Lewis acidic Sn sites might exist for this observed catalytic results. The nearly complete conversion of glucose over each catalyst (Section S2 of the Supplementary Information) suggests that Sn sites in each MFI-Sn/Al catalyst are efficient for isomerization of glucose reactant in this reaction cascade. Overall, the increase in Sn or Al content in the catalyst facilitates the particular reaction step in the reaction cascade, which consequently influences the whole reaction network and exhibits different catalytic performances. A good balance between the two types of acid sites can be optimized to realize cooperative catalysis for further optimizing the EMF yield in glucose conversion in the reaction cascade. As shown in Fig. 9, the MFI-Sn/Al (50/50) zeolite showed best performance, with as high as ~44% EMF yield, among these four MFI-Sn/Al catalyst formulations.

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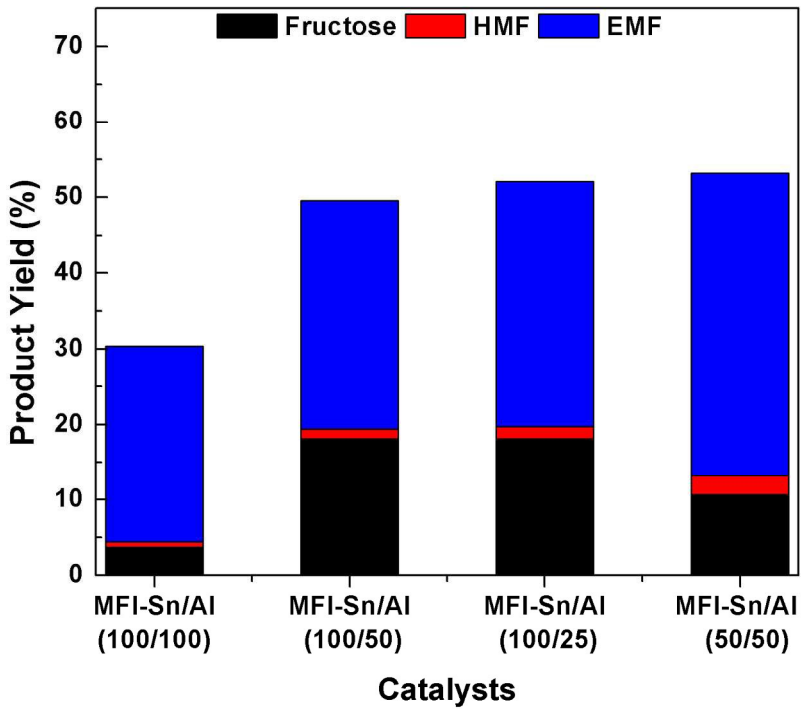

Fig. 9 Effect of Al and Sn contents in hierarchical lamellar MFI-Si/Al zeolites on conversion of glucose to EMF at 413 K. (reaction condition: glucose: 0.090 g; zeolite: 0.074 g; time: 9 h; ethanol: 3 mL).

Effect of carbohydrate type on EMF synthesis over MFI-Sn/Al (100/100) catalyst

Glucose is one type of monosaccharides and simple carbohydrates in lignocellulosic biomass, which has been shown the feasibility of conversion into EMF over the MFI-Sn/Al zeolite catalysts. In reality, the natural biomass produces various types of saccharides, including other monosaccharides, disaccharides and polysaccharides. To investigate the applicability of the hierarchical lamellar MFI-Sn/Al in enabling reaction cascades for conversion of other types of biomass feedstock into more valuable EMF product, we purposely studied the performance of the MFI-Sn/Al (100/100) catalyst in EMF synthesis from fructose monosaccharide, sucrose disaccharide and inulin polysaccharides (a polymer of ~24 fructose and 1 glucose units), respectively. The effect of temperature on conversion of these carbohydrate feedstocks for EMF

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production was also studied. For comparison purpose, the EMF yields from glucose conversion at different temperatures were included in this section.

Fig. 10 shows product yield from conversion of different carbohydrates over the MFI-Sn/Al (100/100) catalyst at the temperature of 398 K, 406 K, and 413 K, respectively. As shown in Fig. 10a, the EMF yield at 398 K increases with the reactant changes from glucose, sucrose, inulin, to fructose in sequence. This trend is consistent with the fructose composition of the glucose, sucrose, inulin and fructose carbohydrates. It is known that glucose is a simple monosaccharide; Sucrose is a disaccharide that is composed of 1 glucose and 1 fructose units; Inulin is a polysaccharide that is comprised of 1 glucose and ~24 fructose units; and Fructose is a simple monosaccharide. The formation of EMF from fructose only needs to go through a two-step (dehydration of fructose to HMF and etherification of HMF to EMF) reaction cascade, which eases the reaction network. The increase in fructose units in these four reactants incrementally shifts the reaction cascade from three steps to two steps, and thus leads to higher EMF yield. It should be noted that reaction intermediates were all observed in these reaction cascades over the MFI-Sn/Al (100/100) catalyst, although EMF is the major product. For example, when sucrose was used as the reactant, the glucose, fructose and HMF reaction intermediates in minor quantities were all observed. This indicates the occurrence of the reaction cascade effectively enabled by the dual Lewis and Brønsted acidic catalyst. The nearly complete conversion of each carbohydrate reactant and fast reactant conversion rates (see Figs. S3-S5 in section S3 of the Supplementary Information) indicates that mass transport limitation is negligible due to the dual meso-/microporosity in the hierarchical lamellar MFI-Sn/Al (100/100) catalyst.

Figs. 10b and c show the product yields from carbohydrate conversion over the MFI-Sn/Al (100/100) catalyst at 406 K and 413 K, respectively. First of all, EMF is still the major product

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although the total detectable product yields are decreased at different degrees with respect to different reactant with increasing reaction temperature. Specifically, the EMF yield from glucose reactant slightly increases with the reaction temperature, as discussed above. The EMF yield keeps almost constant from the sucrose reactant, while it decreases significantly with the increasing temperature from the fructose and inulin carbohydrate reactants. The changes in EMF yield from different reactants over the MFI-Sn/Al catalyst reveal that higher temperature benefits isomerization of glucose than dehydration of fructose and etherification of HMF to EMF product. The decrease in the EMF yield from fructose and inulin may be caused by the increased side reactions along with the reaction cascade with increasing reaction temperature.

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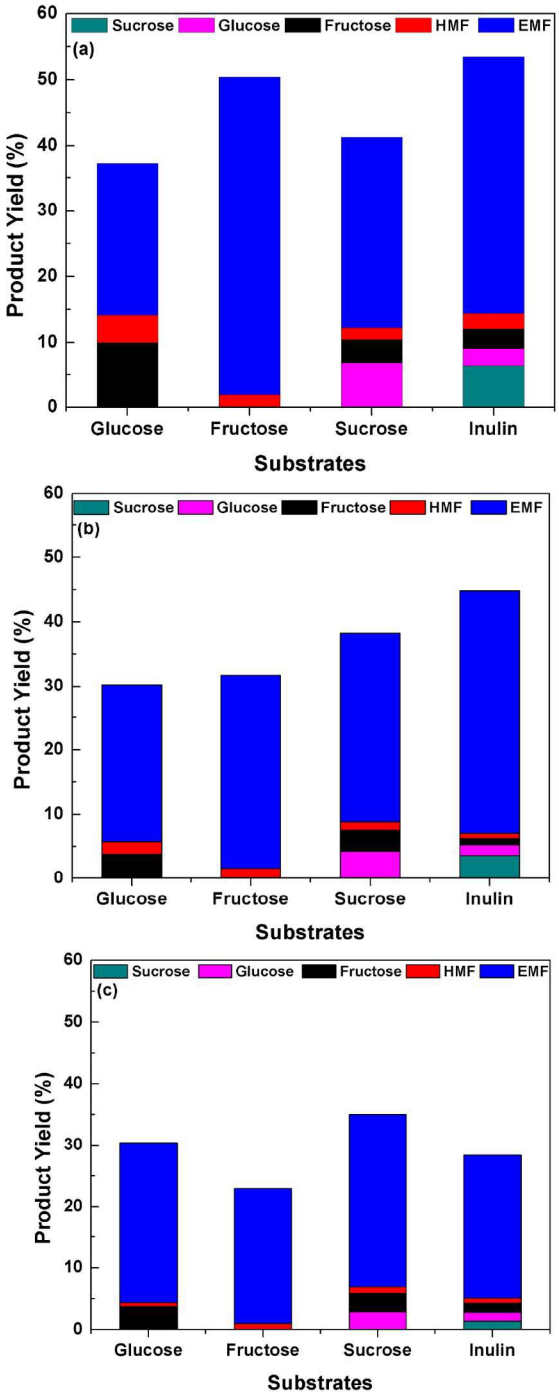

Fig. 10 Effect of carbohydrate reactants on synthesis of EMF over MFI-Sn/Al (100/100) at temperature of (a) 398 K, (b) 406 K, and (c) 413 K, respectively. (reaction condition: carbohydrate reactant: 0.090 g; zeolite: 0.074 g; time: 9 h; ethanol: 3 mL)

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Conclusions

The hierarchical lamellar MFI-Sn/Al zeolites that comprise of dual meso-/microporosity and dual Lewis acidic Sn and Brønsted acidic Al–O(H)–Si sites in single zeolite particles have been successfully prepared. The one-step crystallization of MFI zeolites in the presence of both Sn and Al precursors under the assistance of the diquaternary ammonium template has been simply employed to create this multifunctional MFI-Sn/Al zeolite. The morphology and textural property measurements confirm the presence of mesoporosities in these zeolite catalysts. The acidity characterizations show the existence of dual types of acidity and variations of these acidities with the Si/Al and Si/Sn ratios in the zeolite synthesis recipe. As a consequence of the dual porosity and acidity features, the MFI-Sn/Al zeolites were studied as catalysts for conversion of glucose into EMF product in ethanol solvent. The reaction proceeded via the isomerization of glucose to fructose over Lewis acidic Sn-sites and dehydration of fructose to HMF and then etherification of HMF and ethanol to EMF over the Brønsted acidic Al–O(H)–Si sites. The dual meso-/microporosity in the MFI-Sn/Al zeolites facilitated mass transport in processing of bulky molecules involved in this reaction cascade. The balance between two types of acidities possibly facilitated the cooperative catalysis, which led to as high as 44% from the glucose reactant. The co-existence of multiple acidities and porosities in one single zeolite catalyst enabled one-pot cascade reactions for carbohydrate upgrading, which is potentially applicable for processing of other complex reaction network for efficient production of end chemicals/fuels from renewable biomass resources.

Acknowledgements

The authors gratefully acknowledge the support from the National Science Foundation (NSF-CBET 1642405, 1705284 and 1351384). This work is supported in part by the U. S. Army

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Research Laboratory (contract/grant number: W911NF-16-2-0036) and the U. S. Army Research Office (contract/grant number: W911NF-17-1-0363). The authors also acknowledge the support of the Maryland NanoCenter and its NispLab. The NispLab is supported in part by the NSF as a MRSEC Shared Experimental Facility. Y. Bai acknowledges China National Science Foundation (No. 31470605) for financial support for her study at University of Maryland.

Supplementary information available: Morphology and textural properties of MFI-Sn/Al zeolites; the glucose conversion and product yields versus reaction time over the MFI-Sn/Al zeolite with variable Si/Sn and Si/Al ratios; and the EMF synthesis versus reaction time from different carbohydrate reactants at different reaction temperatures over the MFI-Sn/Al (100/100) zeolite catalyst.

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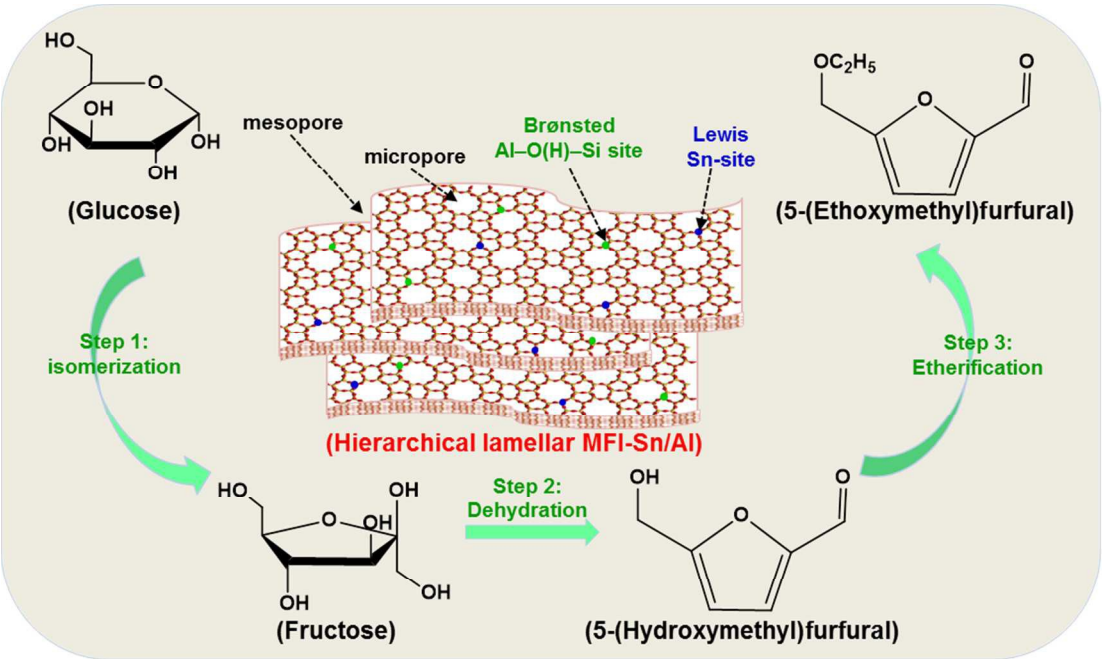

Glucose conversion over hierarchical lamellar MFI-Sn/Al: accommodating three-step reaction cascade over one single catalyst for high yield production of 5-(ethoxymethyl)furfural.