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The catalytic hydrogenation of carbon dioxide into methanol is one of the key strategies for the utilization of captured CO_2 . For this reason, the development of stable catalysts such as ZnZrO_x has attracted considerable interest. In this paper, ZnZrO_x has been produced by a hydrothermal method. Altering the synthesis pH significantly impacts both the structural and catalytic properties of the material. Different reaction selectivity was correlated with the presence of different phases and variations in Zn distribution.

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Hydrothermal synthesis of ZnZrO_x catalysts for CO₂ hydrogenation to methanol: the effect of pH on structure and activity†

Issaraporn Rakngam,^{†a} Gustavo A. S. Alves,^{†bc} Nattawut Osakoo,^d Jatuporn Wittayakun,^a Thomas Konegger,^e and Karin Föttinger^{*bc}

With the growing necessity of achieving carbon neutrality in the industrial sector, the catalytic hydrogenation of carbon dioxide into methanol has been widely considered one of the key strategies for the utilization of captured CO₂. For this reason, the development of alternative catalysts such as ZnZrO_x has attracted considerable interest, given its superior stability and versatility in comparison to the conventional Cu-based materials. In this work, ZnZrO_x has been produced by a hydrothermal synthesis method at varied synthesis pH between 7 and 10 and a positive association between pH and catalytic CO₂ conversion is observed. At 2.0 MPa and 250 °C, ZnZrO_x produced at pH 10 shows a methanol selectivity of 95% at a CO₂ conversion of 3.4%. According to characterization, basic pH conditions enable the formation of abundant t-ZrO₂ and the subsequent incorporation of Zn²⁺ into this phase, although the content of surface Zn does not increase between pH 8 and 10. Nevertheless, synthesis pH values can be correlated with surface oxygen content and CO₂ adsorption capacity, which could be important contributors to the higher catalytic activity observed as a result of higher synthesis pH values. However, upon synthesis at pH 10, an inferior selectivity to methanol is observed above 250 °C, as a possible result of the excessive formation of ZnO. Interestingly, this secondary phase can be prevented and the selectivity can be slightly improved by utilizing NH₄OH instead of NaOH in the hydrothermal method.

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Sustainability spotlight

One of the key building blocks in the chemical industry, methanol, has been primarily obtained from fossil feedstocks over the last decades. With the growing necessity of developing sustainable alternatives, the production of renewable methanol from CO₂ has been recently proposed as a strategy to utilize carbon derived from biomass or industrial emissions from hard-to-abate sectors. In this context, the development of more stable and versatile catalysts may facilitate the implementation of CO₂ hydrogenation to methanol on a large scale. This research work addresses the following Sustainable Development Goals: Industry, Innovation and Infrastructure (SDG 9), Sustainable Consumption and Production (SDG 12) and Climate Action (SDG 13).

Introduction

The relentless increase in atmospheric carbon dioxide (CO₂) levels and the urgent need to mitigate climate change have been

motivating intensive research into sustainable solutions for CO₂ utilization,¹ often involving its hydrogenation into carbon monoxide,² alcohols³ and olefins.⁴ Among these strategies, the conversion of CO₂ to methanol has been considered a promising route for the utilization of CO₂ emissions due to the versatility and energy density of methanol as a liquid fuel and chemical feedstock. Typically, the industrial synthesis of methanol from CO-rich syngas at high pressure employs the Cu/ZnO/Al₂O₃ catalyst, which can also be applied for the direct hydrogenation of CO₂.⁵ Nevertheless, one of the drawbacks of such copper-based materials is the deactivation due to the limited stability of the catalyst under exposure to moisture and sulfur-containing gases, which may pose a considerable obstacle to the continuous long-term operation of the methanol synthesis from industrial CO₂ feedstocks.^{6,7} For this reason, the development of more stable and robust catalysts could benefit

^aSchool of Chemistry, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand

^bInstitute of Materials Chemistry, TU Wien, Getreidemarkt 9, 1060, Vienna, Austria. E-mail: karin.foettinger@tuwien.ac.at

^cChair of Physical Chemistry, Montanuniversität Leoben, Franz-Josef-Straße 18, 8700 Leoben, Austria

^dInstitute of Research and Development, Suranaree University of Technology, Thailand

^eInstitute of Chemical Technologies and Analytics, TU Wien, Getreidemarkt 9, 1060, Vienna, Austria

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* These authors have contributed equally to this work.



the yet incipient production of renewable methanol derived from a variety of CO₂ sources, such as biogas,⁸ geothermal origins⁹ and steel plants.¹⁰

Among the diverse catalysts explored for CO₂ hydrogenation to methanol, ZnZrO_x-based materials have demonstrated notable potential as next-generation catalysts, given their excellent selectivity, stability and sulfur tolerance.^{11,12} On the other hand, their non-metallic character engenders limited hydrogen activation, leading to lower CO₂ conversion compared to commercial Cu/ZnO-based materials.¹³

In ZnZrO_x catalysts, the synergistic interaction between Zn²⁺ and ZrO₂ plays a vital role in promoting both catalytic activity and selectivity.¹¹ Specifically, the Zn²⁺–O–Zr⁴⁺ sites from the ZnZrO_x solid solution are identified as the active sites for CO₂-to-methanol hydrogenation,^{14,15} in order that Zn species are considered responsible for dissociating H₂ molecules, while Zr species facilitate the activation of CO₂.¹⁵ This catalytically active Zn²⁺–O–Zr⁴⁺ system has been mostly observed as a result of Zn²⁺ ions incorporated in the tetragonal ZrO₂ lattice (t-ZrO₂), while the monoclinic zirconia polymorph (m-ZrO₂) is considered less able to accommodate these species.¹⁶ Additionally, the recent evidence for ZnO clusters embedded in ZrO₂ as a key feature of ZnZrO_x catalysts indicates that ZnO/ZrO₂ systems should be also taken into account as possible active sites for CO₂ hydrogenation in these materials.^{17,18} In addition to the clear importance of Zn²⁺ species in ZnZrO_x, recent studies have emphasized the role of lattice oxygen on H₂ activation, suggesting a direct correlation between catalytic activity and surface oxygen content.¹⁹ In fact, experimental and computational studies indicate that Zn²⁺–O²⁻ pairs may be responsible for the heterolytic H₂ dissociation in ZnZrO_x catalysts for CO₂ hydrogenation to methanol.²⁰

In several previous studies, ZnZrO_x catalysts with a high content of t-ZrO₂ have been typically produced by coprecipitation approaches, followed by calcination at 500 °C.^{11,21,22} Although t-ZrO₂ is thermodynamically less stable than m-ZrO₂ at such temperatures, the presence of a hydrated surface²³ and small crystallites²⁴ may promote the formation of tetragonal zirconia in these cases. Alternatively, a hydrothermal approach followed by calcination between 300 °C and 600 °C has been shown as an effective method to produce t-ZrO₂-based catalysts, and the presence of Na ions has been suggested as another important factor for the stabilization of the tetragonal phase.²⁵ Therefore, the hydrothermal synthesis method may deserve further exploration due to the possibility of obtaining nanostructured ZnZrO_x catalysts with high surface area²⁶ and suitable crystalline structure for CO₂ hydrogenation to methanol. However, achieving optimal catalytic performance requires a deeper understanding of the catalyst synthesis under varying parameters, such as pH values, which are often a key factor in the nucleation, growth, and crystal size of metal-oxide particles. In Zn and Zr aqueous solutions, basic pH was shown to accelerate the crystallization of Zn and Zr oxides.^{27,28} Thus, exploring the catalytic improvement of ZnZrO_x by systematically varying pH levels represents a promising strategy for enhancing the efficiency of CO₂ conversion to methanol in this catalyst.

This work presents an investigation into the catalytic performance and material properties of ZnZrO_x produced by hydrothermal synthesis. Herein, the effect of synthesis pH on structural and surface properties is investigated and the material is tested as a catalyst for CO₂ hydrogenation to methanol.

Experimental

Chemicals and materials

Zirconyl chloride octahydrate (ZrOCl₂·8H₂O, 98%, Sigma-Aldrich), zinc chloride (ZnCl₂, 98%, Fluka), sodium hydroxide (NaOH, 98%, Sigma-Aldrich), and ammonium hydroxide (NH₄OH, 25%, Donau Chem) were used for the catalyst synthesis.

Synthesis of ZnZrO_x

A series of ZnZrO_x catalysts were prepared at different pH values (7, 8, 9, and 10) using a hydrothermal treatment method based on a previously reported procedure for the preparation of t-ZrO₂.²⁵ Initially, 3.36 g of ZrOCl₂·8H₂O and ZnCl₂ with the Zn/(Zr + Zn) mole ratio of 20% were dissolved in 20 mL of deionized water under stirring. Subsequently, a 1.0 M NaOH solution was slowly added into the mixed metal solution to achieve the desired pH value. The mixture was then transferred into an autoclave with a Teflon liner and heated at 150 °C for 18 h. After the hydrothermal treatment, the autoclave was cooled down to room temperature. The white powder was filtered, washed with deionized water until neutral pH, dried, and calcined at 500 °C for 3 h. Alternatively, a similar procedure was followed for the production of ZnZrO_x at pH 10, using NH₄OH as a pH adjuster instead of NaOH.

Catalyst characterization

The crystalline structure of the samples was characterized by powder X-ray diffraction (XRD) on a Philips XPert diffractometer using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) at 45 kV and 40 mA operating in Bragg–Brentano reflection geometry. Transmission Electron Microscopy (TEM) and Energy-Dispersive X-ray Spectroscopy (EDX) were performed on a Thermo Scientific TALOS F200X operated at 200 kV. The morphologies of the samples were investigated by scanning electron microscopy (SEM) with a FEI Quanta 250 FEG microscope at a 5 kV voltage. N₂ adsorption–desorption analysis of the samples was determined using Micromeritics ASAP 2020 at –196 °C. Before the measurement, the sample was degassed at 350 °C for 8 h under vacuum. Specific surface areas were calculated using the Brunauer–Emmett–Teller (BET) method. Pore size distributions were determined by the Barrett–Joyner–Halenda (BJH) model.

The basicity and CO₂ adsorption capacity of the sample were investigated by temperature-programmed desorption of carbon dioxide (CO₂-TPD) using a BELCAT-B chemisorption analyzer with a thermal conductivity detector (TCD). Prior to analysis, the sample was pretreated at 350 °C for 1 h under flowing He gas with 30 mL min⁻¹. Then, the sample was cooled down to 50 °C and a gas mixture containing 10% CO₂ in He was adsorbed on the sample surface for 1 h. The sample was purged with



He and held for 30 min to remove non-adsorbed CO₂. The TPD process was performed in the temperature range from 50 to 350 °C with a heating rate of 10 °C min⁻¹ and held at 350 °C for 1 h under a He flow of 30 mL min⁻¹.

Chemical states of surface species were identified by X-ray photoelectron spectroscopy (XPS) with a SPECS u-Focus system (AlK α source, Phoibos 150 WAL detector). XPS data evaluation was carried out using the CasaXPS software,²⁹ considering spectra calibrated with the C 1s peak at 284.8 eV. Quantification of surface species was conducted by considering the areas of Zn 2p_{3/2}, O 1s, Zr 3p_{3/2}, Zr 3d and Zn 3p peaks with the respective Relative Sensitivity Factors (RSF) of 18.92, 2.93, 5.14, 7.04 and 2.83.

In situ diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) was carried out on a Bruker Vertex 70 spectrometer equipped with a mercury-cadmium-telluride detector cooled by liquid nitrogen. Before measurement, the sample was pretreated at 350 °C for 2 h under pure H₂ flow (7.7 mL min⁻¹) and then cooled to 250 °C under Ar flow (11.5 mL min⁻¹). After cooling down, the background spectrum was collected from 800–4000 cm⁻¹ with 256 scans at a resolution of 4 cm⁻¹. H₂ (7.7 mL min⁻¹) and CO₂ (2.6 mL min⁻¹) were introduced into the reaction cell and the spectra were collected at 250 °C.

Catalytic testing for CO₂ hydrogenation

The catalytic activity testing was performed in a tubular fixed-bed continuous-flow “micro effi” reactor from PID Eng&Tech. Prior to the test, 1 g of the ZnZrO_x catalyst was activated under H₂ flow at 350 °C for 2 h. After cooling to 250 °C, the reactant gas mixture of CO₂/H₂/He (20/60/20) was introduced into the reactor at a total flow of 5 mL_n/min under a pressure of 2.0 MPa. The reaction was conducted in steps of 10 °C between 250 to 290 °C during 6 h in each step. Detection of products in gas phase was carried out using an Inficon Micro GC 3000 equipped with a Plot Q column. The CO₂ conversion (*X*) and the selectivity (*S*) for CH₃OH, CO and CH₄ were calculated using the following equations:

$$X_{\text{CO}_2} = \frac{\text{mol CH}_4 + \text{mol CO} + \text{mol CH}_3\text{OH}}{\text{mol CH}_4 + \text{mol CO} + \text{mol CH}_3\text{OH} + \text{mol CO}_2} \times 100\% \quad (1)$$

$$S_{\text{CO}} = \frac{\text{mol CO}}{\text{mol CH}_4 + \text{mol CO} + \text{mol CH}_3\text{OH}} \times 100\% \quad (2)$$

$$S_{\text{CH}_4} = \frac{\text{mol CH}_4}{\text{mol CH}_4 + \text{mol CO} + \text{mol CH}_3\text{OH}} \times 100\% \quad (3)$$

$$S_{\text{CH}_3\text{OH}} = \frac{\text{mol CH}_3\text{OH}}{\text{mol CH}_4 + \text{mol CO} + \text{mol CH}_3\text{OH}} \times 100\% \quad (4)$$

Results and discussion

ZnZrO_x samples were produced by hydrothermal synthesis using NaOH to adjust pH values between 7 and 10. Considering that the saturation of t-ZrO₂ with Zn²⁺ has been previously

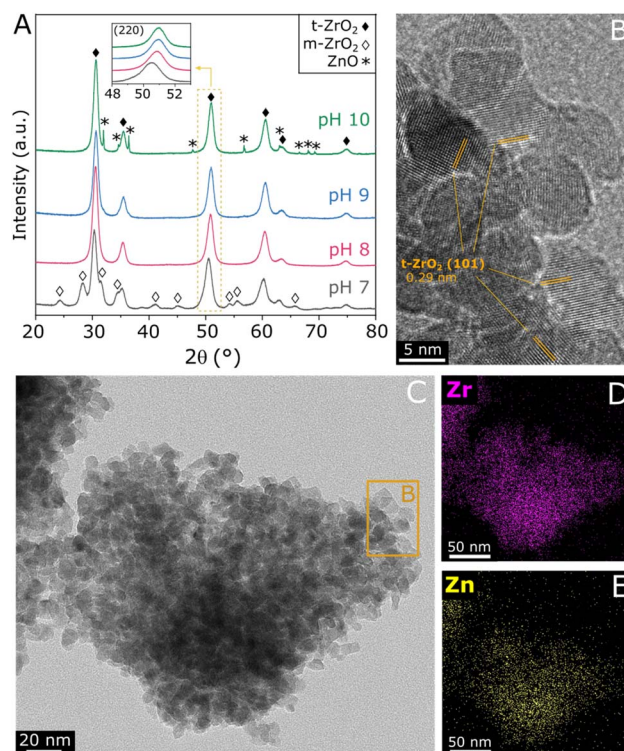


Fig. 1 XRD patterns of ZnZrO_x produced at different synthesis pH values and calcined at 500 °C (A), TEM image of ZnZrO_x produced at pH 8 (B and C) and TEM-EDX mapping images showing the Zr and Zn distribution in the same region covered by C (D and E).

reported at 25%,¹⁶ a Zn/(Zn + Zr) atomic ratio of 20% was chosen, seeking to obtain abundant and dispersed Zn²⁺ sites in a ZnZrO_x without the formation of segregated ZnO. In order to verify the crystalline structure of the material, XRD analysis was conducted, as shown in Fig. 1A. The XRD pattern of ZnZrO_x prepared at pH 7 presents evidence for the tetragonal ZrO₂ (t-ZrO₂) phase (JCPDS 68-0200) mixed with a monoclinic (m-ZrO₂) phase (JCPDS 65-0687).¹¹ However, more basic pH conditions completely attenuate the pattern related to m-ZrO₂, as observed for the pH 8 and pH 9 samples. Upon increasing pH during synthesis to 10, additional small features emerge at 31.9°, 34.6°, 36.4°, 47.8°, 56.8°, 63.0°, and 68.1°, which can be assigned to hexagonal ZnO phase (JCPDS 01-083-6338). This result indicates that the material produced at pH 10 presents both the t-ZrO₂ phase and a secondary contribution of hexagonal zirconia, which is observed in more detail by TEM in Fig. 1B and C, showing the characteristic (101) interplanar spacing of 0.29 nm from t-ZrO₂. As shown by TEM-EDS analysis in Fig. 1D and E, this phase presents a homogeneous distribution of Zr and Zn, giving evidence for the incorporation of Zn atoms into the t-ZrO₂ structure. Furthermore, as shown in the insert of Fig. 1A, the diffraction feature corresponding to t-ZrO₂ shifts by approximately 0.5° towards higher angles as the pH during synthesis increases from 7 to 9, but no changes are verified between pH 9 and 10. The observed shift can be attributed to the incorporation of Zn²⁺ ions (ionic radius 0.74 Å) into the t-



ZrO₂ lattice, leading to a reduction in interplanar spacing due to the substitution of Zr⁴⁺ (ionic radius, 0.82 Å) by smaller radius size of Zn²⁺ ions.^{11,30} Therefore, these findings indicate that basic hydrothermal conditions facilitate the formation of the Zn–ZrO₂ solid solution. However, above pH 9 this phase may be already saturated with Zn²⁺, which leads to the formation of segregated ZnO crystallites at higher pH.

Following the verification of clear influences of synthesis pH on the crystalline structure of ZnZrO_x, surface properties of the material have been evaluated by SEM, N₂ physisorption, XPS and CO₂-TPD. According to the SEM micrographs shown in Fig. 2 and S1–S3,† all samples exhibit predominantly agglomerated particles with a similarly rough surface regardless of synthesis pH, which can be associated with the zirconia structure given its dominance in XRD results. As shown in Fig. 2A and B, such morphology is largely present in the pH10 sample, although here it also coexists with the characteristic rod-like ZnO particles³¹ shown in Fig. 2C. Fig. 2D illustrates the N₂ sorption isotherms and pore size distributions of all the samples. All samples exhibit type-VI isotherms along with a type-H2 hysteresis loop. This characteristic behavior indicates the aggregation of ZrO₂ particles, leading to the creation of interparticle voids within the materials.³² Elevating the pH synthesis values from 7 to 10 induced a noticeable shift in the position of the hysteresis loop towards higher relative pressures, suggesting a subtle enlargement in mesopore sizes within the material structure. Nevertheless, only limited changes in surface area are observed, as it gradually decreases from 70 m² g⁻¹ at pH 7 to 63 m² g⁻¹ at pH 10. As shown in Fig. 2E, all samples display narrow distributions of pore size, suggesting that a uniformity of pore sizes was achieved through the hydrothermal synthesis method.

In order to assess the surface composition of the investigated materials, XPS analysis was performed. According to high-resolution spectra in Fig. S4,† all samples present similar Zr 3d doublets with Zr 3d_{5/2} and Zr 3d_{3/2} in the region of 183.1 and 185.5 eV, corresponding to Zr⁴⁺ in tetragonal ZrO₂.³³ Accordingly, O 1s located at approximately 530.4 eV indicates that lattice oxygen³³ is by far more abundant than adsorbed oxygen

species.³⁴ Moreover, the Zn 2p_{3/2} peak is verified at 1022.0 eV, as typically observed for Zn²⁺ species.³⁵ Due to the severe differential charging³⁶ experienced by the ZnZrO_x samples as a result of their insulating character and surface roughness, the tailing observed in the high-resolution XPS spectra prevents fitting or precise quantification in these spectra. For this reason, quantification of Zn/Zr and O/Zr surface atomic ratios was conducted in the survey spectra, considering O 1s, the average of Zn 2p_{3/2} and Zn 3p, as well as the average of Zr 3d and Zr 3p_{3/2} for higher precision. Accordingly, Fig. 3A presents these selected regions in the survey spectra, with the respective Zn/Zr and O/Zr surface molar ratios shown in Fig. 3B. Hydrothermal synthesis under neutral pH conditions results in a low surface Zn/Zr ratio of 0.05, which can be correlated with the observation of abundant monoclinic ZrO₂ by XRD, as this phase is less likely to accommodate Zn²⁺.¹⁶ In contrast, the pH 8 sample shows a greatly increased Zn/Zr ratio of 0.72, which is slightly decreased to 0.71 and 0.69 upon increasing pH to 9 and 10, respectively. Despite the observed differences in crystal structure upon increasing synthesis pH from 8 to 10, these results suggest that the surface has a similar content of surface Zn²⁺ within this basic pH range. Also in Fig. 3B, the surface O/Zr ratio presents a steady increase from 1.30 to 1.44 between pH 7 and 10, giving an indication that hydrothermal conditions with abundant OH⁻ may provide more surface oxygen for the ZnZrO_x solid solution during calcination. Furthermore, even though Na⁺ from NaOH has been previously suggested to stabilize the t-ZrO₂ structure, surface Na was not observed by XPS, as shown in Fig. S5.† However, the Cl 2p peak at 198 eV indicates surface chlorine species in all samples, as a residue from the metal chloride precursors utilized in the hydrothermal synthesis.³⁷ Although the effect of such species has not been deeply explored in ZnZrO_x catalysts for CO₂ hydrogenation to methanol, surface chlorine in Pd/ZnO was suggested to block some active sites and

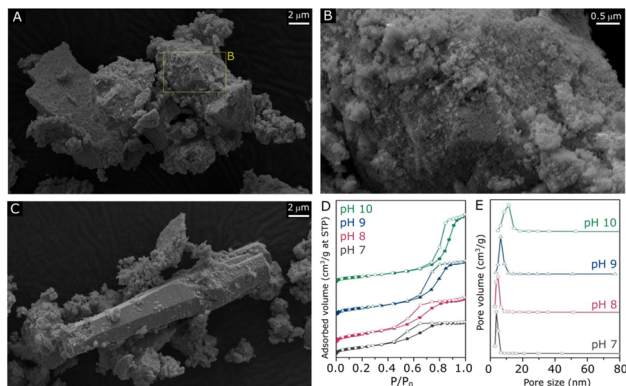


Fig. 2 SEM micrographs of ZnZrO_x produced at pH10 under different magnifications (A and B) and the region including rod-like particles (C). N₂ sorption isotherms (D) with respective pore size distributions of ZnZrO_x produced at pH 7, 8, 9 and 10 (E).

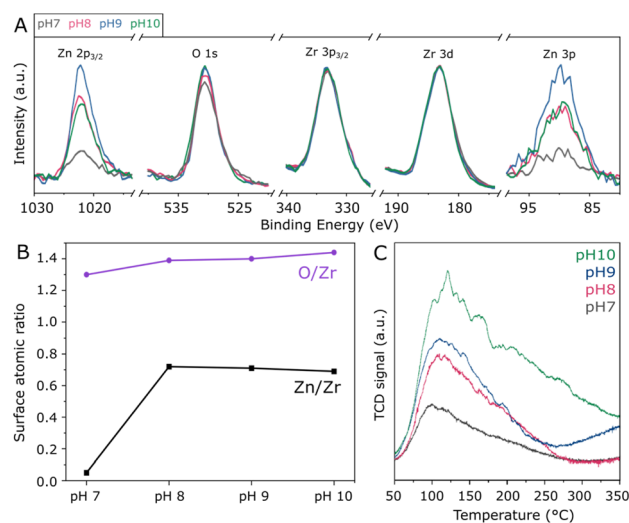


Fig. 3 Survey XPS spectra of ZnZrO_x normalized by the Zr 3d peak, showing the Zn 2p_{3/2}, O 1s, Zr 3p_{3/2}, Zr 3d and Zn 3p regions (A) with the respective quantification of the Zn/Zr and O/Zr surface molar ratios (B); CO₂-TPD profiles of the samples produced at pH 7 to 10 (C).



therefore offer a detrimental effect to catalytic activity in comparison to chlorine-free catalysts.³⁸

Given the pivotal role of CO₂ activation in its catalytic conversion, the CO₂-TPD profiles of all ZnZrO_x samples are investigated, as shown in Fig. 3C. In all cases, a main desorption peak is observed below 200 °C, corresponding to the desorption of CO₂ from weakly basic sites.³² Interestingly, the material produced at pH 7 presents the lowest CO₂ adsorption capacity despite having the highest surface area among the investigated samples. This observation cannot be directly associated with the presence of m-ZrO₂, as this phase typically interacts more strongly with CO₂ than t-ZrO₂.³⁹ As the synthesis pH rises from 7 to 10, this desorption peak position becomes more intense and is gradually shifted from 100 to 120 °C, indicating an increase in its basicity. Concurrently, higher synthesis pH values lead to increased desorption between 200 and 350 °C, indicating higher densities of moderately basic sites. This can be considered more relevant for CO₂ hydrogenation to methanol,²¹ as this reaction is typically conducted around 250 °C. Such positive correlation between synthesis pH and CO₂ adsorption capacity could be connected with the formation of the ZnZrO_x solid solution, which may show higher CO₂ adsorption with respect to pure ZrO₂.⁴⁰

The catalytic hydrogenation of CO₂ to methanol over the ZnZrO_x samples was tested in a fixed-bed reactor at various temperatures (250–290 °C), as summarized in Fig. 4. The material produced under pH 7 exhibits poor catalytic activity with CO₂ conversion below 1%, as a possible result of the low surface Zn content observed by XPS, since the Zn²⁺–O–Zr⁴⁺ linkages have been widely recognized as the active sites in ZnZrO_x catalysts. However, the pH 8 sample shows a sharply enhanced catalytic activity over the entire temperature range, as a likely effect of the improved incorporation of Zn²⁺ in the tetragonal zirconia phase. In this case, a CO₂ conversion of 1.5% and a methanol selectivity of 84% are achieved at 250 °C, and

increasing the reaction temperature to 290 °C results in a CO₂ conversion of 4.5% and a methanol selectivity of 65%, as higher temperatures simultaneously favor the kinetics for CO₂ hydrogenation to methanol and the endothermic production of CO *via* Reverse Water-Gas Shift reaction. Interestingly, increasing synthesis pH to 9 and 10 leads to progressively higher CO₂ conversions. As shown in Fig. 4D, at the highest pH value a CO₂ conversion of 3.4% is obtained along with a methanol selectivity of 95% at 250 °C. Such value is in a similar range to the previously reported performance at 260 °C/2.0 MPa using ZnZrO_x produced by co-precipitation.¹¹ Accordingly, an expressive increase in CO₂ conversion to 8.1% is observed at 290 °C, although this coincides with a decreased methanol selectivity of 40%.

In view of the catalytic performance of ZnZrO_x produced *via* hydrothermal synthesis at distinct pH values between 7 and 10, a clearly positive correlation between synthesis pH and CO₂ conversion is verified. As pH values increase, catalytic activity at 250 °C is enhanced with high methanol selectivity, while at higher temperatures this also coexists with an enhanced production of CO. At pH 10, the higher CO production above 250 °C could be associated with the additional contribution of ZnO, similarly as previously observed when ZnZrO_x is produced with an exceedingly high Zn content.¹¹ Although the formation of abundant Zn²⁺/t-ZrO₂ sites is important in this catalyst, surface characterization suggests that in this study, catalytic activity cannot be simply associated with surface area and the Zn surface content, as these parameters do not increase between pH 8 and 10. This is consistent with the observation that H₂ activation may not simply require Zn²⁺ atoms but rather Zn²⁺–O^{2–} pairs, as suggested by previous studies.^{19,20} Therefore, the enhanced CO₂ conversion to methanol may be related to the stronger CO₂ adsorption capacity²¹ and with the slightly higher lattice oxygen content at the catalyst surface, which may in turn benefit H₂ dissociation.^{19,20} Despite the correlation of synthesis pH with catalytic activity for CO₂ hydrogenation to methanol, the observed trends indicate that further increasing pH beyond 10 could lead to a ZnZrO_x/ZnO system with lower selectivity due to the production of CO as a byproduct.

To obtain further insights into the hydrothermal synthesis of ZnZrO_x catalysts, an analogous preparation procedure was followed using NH₄OH to achieve pH 10, as an alternative to NaOH. A comparison of such materials, shown in Fig. 5A and B, shows similar catalytic activities at 250 °C, as the catalyst produced with NH₄OH presents an unchanged CO₂ conversion of 3.4% with a slightly lower methanol selectivity of 90%. At reaction temperatures higher than 250 °C, the material shows similar methanol production but improved selectivity due to the lower production of CO. Corresponding to such similarities, ZnZrO_x produced at pH 10 with NH₄OH and NaOH show similarly high O/Zr ratios of 1.47 and 1.44, calculated from the XPS spectra in Fig. 5C. Furthermore, the comparable CO₂-TPD profiles in Fig. 5D indicate a similarly high density of weakly and moderately basic sites, with respect to ZnZrO_x produced at lower pH. Interestingly, the XRD patterns in Fig. 5E indicate that the main contribution consists of t-ZrO₂ in both catalysts, but when NH₄OH is used, m-ZrO₂ appears as a minor phase

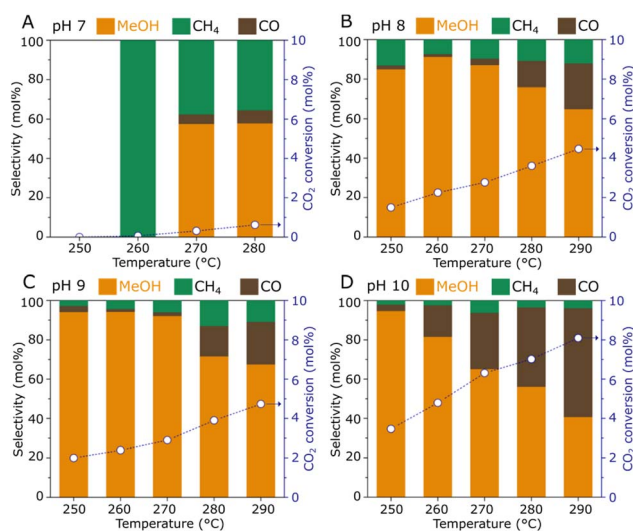


Fig. 4 CO₂ hydrogenation performance of ZnZrO_x catalysts produced under synthesis pH 7 (A), 8 (B), 9 (C), and 10 (D). Reaction conditions: 0.5 g catalyst, 2.0 MPa, CO₂/H₂ = 1/3, 5 mL min⁻¹.



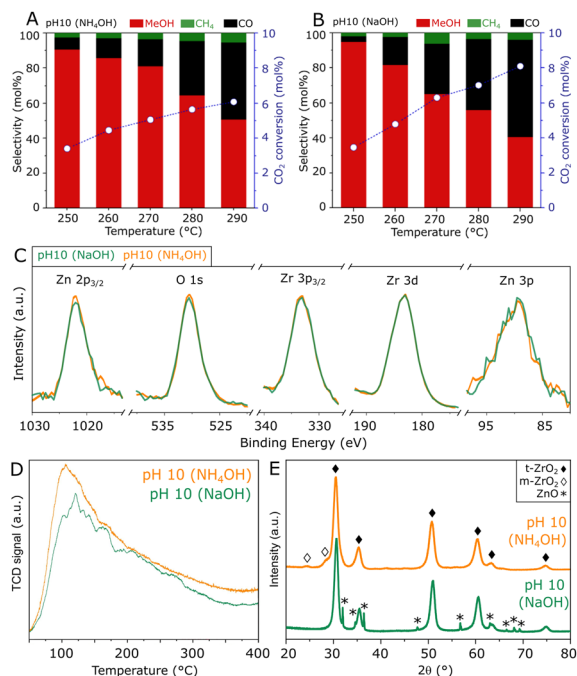


Fig. 5 Comparison of ZnZrO_x catalysts produced under synthesis pH 10 with the distinct additives NH_4OH and NaOH , in terms of CO_2 hydrogenation performance (A and B), $\text{Zn } 2p_{3/2}$, $\text{O } 1s$, $\text{Zr } 3p_{3/2}$, $\text{Zr } 3d$ and $\text{Zn } 3p$ XPS spectra (C), CO_2 -TPD profiles (D) and XRD patterns (E).

instead of ZnO . Given the most likely negative effect of ZnO , such differences in crystallinity suggest that the absence of ZnO may explain the higher methanol selectivity above 250°C in the catalyst produced with NH_4OH . Although this finding hints at a possible improvement by further increasing synthesis pH using NH_4OH , reaching values above 10 was not feasible without drastically altering the content of the remaining reactants involved in the hydrothermal synthesis of ZnZrO_x .

In summary, these results emphasize that high surface oxygen content and basicity for CO_2 activation are key features behind the high catalytic activity of ZnZrO_x produced *via* hydrothermal synthesis at pH 10. As expected, these findings confirm that the Zn^{2+} - ZrO_2 solid solution is the active phase in the catalyst, and the presence of bulk ZnO may not contribute to methanol production in this case, even though the presence of ZnO_x clusters within the solid solution cannot be ruled out.^{17,18} In fact, bulk ZnO is shown to have a detrimental effect on methanol selectivity as it promotes the formation of CO as a byproduct.

In order to obtain insights on the reaction mechanism of CO_2 hydrogenation to methanol over the ZnZrO_x catalyst produced at pH 10, the surface intermediates involved in the reaction were monitored by an *in situ* DRIFTS experiment. Spectra were collected at 250°C under CO_2/H_2 flow at ambient pressure, as shown in Fig. 6A. Specifically, the peaks observed at 2978, 2881, 2737, 1385, and 1373 cm^{-1} , which appear in the initial 2 minutes of the experiment, can be ascribed to formate species (HCOO^*). Subsequently, after approximately 25 min, additional peaks corresponding to CH_3O^* are observed at 2935, 2823, and 1049 cm^{-1} , with progressively increased intensity

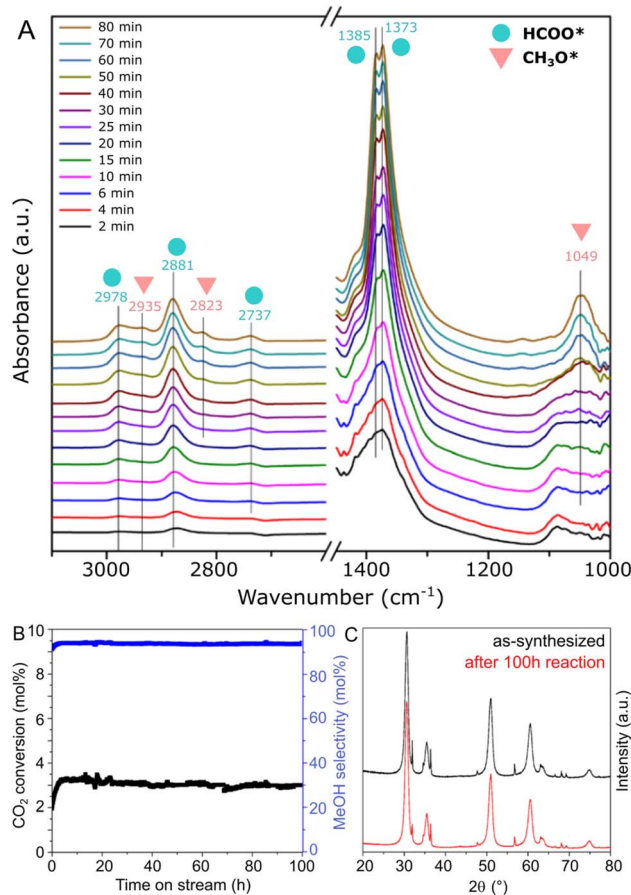


Fig. 6 *In situ* DRIFTS results of CO_2 hydrogenation conditions at 250°C (A) and catalytic stability test at 250°C using the ZnZrO_x catalyst produced at pH 10 with NaOH (B), with the respective XRD patterns of as synthesized and spent material (C).

over the reaction time. These results suggest that CH_3O^* species are generated through the stepwise hydrogenation of HCOO^* species, as part of a formate reaction pathway previously suggested in other ZnZrO_x catalysts.^{11,22,41}

In Fig. 6B, the stability of the ZnZrO_x catalyst is evaluated through a 250°C reaction carried out during 100 h. The material demonstrates remarkable stability over the test period, with no deactivation trend observed in both CO_2 conversion and methanol selectivity over the 100 hours duration. Correspondingly, Fig. 6C shows that the XRD patterns of spent and fresh catalyst are highly similar, apart from a minor decrease in the peak intensities of ZnO . This change might be attributed to a slight amorphization of ZnO facilitated by the reducing reaction conditions. Nevertheless, given the key role of the $\text{Zn}^{2+}/\text{t-ZrO}_2$ solid solution for CO_2 hydrogenation to methanol, these patterns suggest high catalyst robustness under reaction conditions.

Conclusions

In the hydrothermal synthesis of ZnZrO_x catalysts for CO_2 hydrogenation to methanol, altering synthesis pH significantly impacts both the structural and catalytic properties of the



material. Basic pH conditions promote the formation of tetragonal ZrO_2 and facilitate the incorporation of Zn^{2+} into this phase. As synthesis pH is increased from 8 to 10, the catalysts show a marked improvement in methanol production at 250 °C, while higher temperatures favor CO production. The correlation between hydrothermal synthesis pH and catalytic activity may be associated with the improved surface basicity verified by CO_2 -TPD and the slight increase in the surface oxygen content observed by XPS, given the decisive effect of Zn^{2+} - O^{2-} pairs on H_2 activation.²⁰ At reaction temperatures above 250 °C, the selectivity of CO_2 hydrogenation to methanol can be improved by utilizing NH_4OH as an alternative to NaOH in the hydrothermal synthesis at pH 10, thus suppressing the formation of bulk ZnO . In summary, these findings suggest that the hydrothermal approach is an effective and versatile method for producing ZnZrO_x catalysts for CO_2 hydrogenation to methanol. Nevertheless, given the inherently limited hydrogen activation in ZnZrO_x , achieving catalytic activity superior to commercial Cu-based catalysts will likely require further strategies, such as the optimization of Zn^{2+} dispersion⁴² or the addition of metallic nanoparticles^{13,43} and promoters,²² which could offer new concepts for the hydrothermal synthesis of ZnZrO_x -based catalysts.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

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