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Effect of Support on Steam Reforming of Ethanol for H_2 Production with Copper-Based Catalysts

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Abstract: Catalytic studies for hydrogen production via steam reforming of ethanol (SRE) are essential for process optimization. Likewise, selecting the ideal support for the active phase can be critical to achieve high conversion rates during the catalytic steam reforming. In this work, copper-based catalysts were synthesized using two different supports, NaY zeolite and Nb_2O_5/Al_2O_3 mixed oxides. The materials were prepared using wet impregnation and characterized for their physicochemical properties using different analytical techniques. Differences in catalyst morphologies were readily attributed to the characteristics of the support. The Cu/NaY catalyst showed better textural properties than $Cu/Nb_2O_5/Al_2O_3$, resulting in a homogeneous metal dispersion over the support surface. Both catalytic systems were active in SRE, but Cu/NaY resulted in higher ethanol conversions compared to $Cu/Nb_2O_5/Al_2O_3$. Hence, the performance of copper-based catalysts was influenced significantly by the textural properties of the support.

Keywords: ethanol steam reforming; hydrogen production; copper-based catalysts; zeolite; mixed oxides

1. Introduction

The increasing global demand for energy, coupled with the socioenvironmental impacts of an energy matrix that is still heavily reliant on traditional fossil fuels such as coal, crude oil, and natural gas [1,2], are crying out for the development of sustainable production processes to support the transition to a new and more diversified energy matrix. Among the sustainable alternatives for this energy transition, hydrogen (H_2) stands out as one of the most prominent.

H_2 can be obtained through different pathways such as electrolysis [3,4], biological reactions [5], biomass gasification [6], steam reforming [7,8], and partial oxidation of both hydrocarbons and alcohols [9]. Among these possibilities, the use of ethanol as feedstock for H_2 production in fuel cells has considerable advantages. These include easier storage, handling, and safe transportation due to its low toxicity and volatility. Additionally, ethanol is a renewable feedstock when obtained through biomass fermentation, is rich in H_2, and has a nearly closed carbon cycle that helps in the abatement of greenhouse gas emissions [10,11]. Thus, the steam reforming of ethanol (SRE) emerges as an attractive solution for H_2 production due to its high H_2 yield and thermodynamic feasibility [12].

SRE for H_2 production is a catalytic process. Therefore, H_2 yield depends on the properties of the catalyst to be employed [13]. This includes the catalytic support for the active phase [14] and the method used for catalyst preparation [15]. In general, the catalyst design is crucial for a successful SRE process. Different catalytic systems have been investigated for SRE using noble and non-noble metal-based catalysts [16]. Among them, copper-based catalysts [17–19] have the advantage of being

 doi:10.20944/preprints202405.2026.v1

cost-effective and widely available compared to other metals. Additionally, the presence of copper active sites promotes ethanol steam reforming to produce H_2 and CO or its dehydrogenation to acetaldehyde followed by decarbonylation, producing CH_4 and CO [20–22]. Hence, copper-based catalysts have potential for SRE applications.

The choice of support for the active phase is extremely important for SRE because it plays a significant role in H_2 selectivity and catalyst stability [23,24]. In general, efficient SRE supports must have favorable textural properties and moderate acidity, in addition to being relatively cheap, readily available, and easily accessible. In this study, two supports were selected and evaluated for their effect on H_2 production by SRE using copper as the catalytic active phase.

The first selected support was NaY, a commercially available zeolite that is known for its high heat resistance, unique ordered three-dimensional porous structure, and larger pores compared to the dimensions of the ethanol molecule, as well as low production costs [25,26]. For instance, NaY can be synthesized from alternative, abundant, and inexpensive materials such as rice husks [27,28] and wheat straw [29] ashes. Several studies have already demonstrated the application of NaY as a catalyst support for SER [30–32]. The other selected support was a Nb_2O_5/Al_2O_3 mixed oxide. Alumina is a widely used as a support in heterogeneous catalysis [33–37] due to its large surface area, good stability, and wide commercial availability [38]. Nb_2O_5 is also a notable material in the field of catalysis, known for its non-toxic nature, suitable acid properties [39,40], excellent chemical stability, high thermodynamic stability, low cost, and high commercial availability [41,42]. The combination of Nb_2O_5 with alumina is favorable because, being an n-type semiconductor, Nb_2O_5 can interact with copper in catalytic active reaction sites [43,44]. Additionally, Nb_2O_5 is structurally similar to commercial catalysts for methanol reforming ($Cu/ZnO/Al_2O_3$). Since ZnO is also an n-type semiconductor oxide, Nb_2O_5 may have similar catalytic properties.

This study aimed to evaluate the effect of both NaY and Nb_2O_5/Al_2O_3 supports on H_2 production by SRE using copper as the catalytic active phase. Copper was anchored on the support surface by wet impregnation. Then, the obtained catalysts were characterized using several analytical techniques and subjected to SRE using an experimental reaction module.

2. Materials and Methods

2.1. Material

Materials were synthesized using copper nitrate ($Cu(NO_3)2{\cdot}3H_2O$, 98%) from Sigma-Aldrich, commercial alumina (Al_2O_3, 90%) from Merck, NaY zeolite from Sigma-Aldrich, and niobic acid (HY-340) from the Brazilian Metallurgy and Mining Company (CBMM). HY-340 was heat-treated to obtain niobium pentoxide (Nb_2O_5).

2.2. Methods

2.2.1. Catalyst Preparation

The catalysts were prepared using a simple wet impregnation methodology under solvent excess, consisting of the following steps: initially, appropriate quantities of the copper precursor ($Cu(NO_3)2{\cdot}3H_2O$) were dissolved in water and mixed with the support (NaY or Nb_2O_5/Al_2O_3) in a rotary evaporator. The mixture was evaporated for 2 h at 343 K for complete water evaporation. After this, the materials were placed in an oven at 353 K for about 10 h. Then, the dried materials were crushed and subjected to a thermal treatment in a muffle furnace at 773.15 K for 5 h, using a heating rate of 10 K min^{-1}. At the end of the process, two catalysts named Cu/NaY and Cu/ Nb_2O_5/Al_2O_3 were obtained.

2.2.2. Catalyst Characterization

Scanning Electron Microscopy (SEM) was performed using a Zeiss EVO MA15 microscope coupled with an X-Max 20 mm^2 Energy Dispersive Spectrometer (EDS). X-ray Diffraction (XRD) analyses were conducted on a Shimadzu XDR-7000 diffractometer using CuKα radiation.

 doi:10.20944/preprints202405.2026.v1

Measurements were taken at 40 kV and 30 mA using a Cu tube with a wavelength of 1.54 nm, with a scan rate of 2° min^{-1} and an interval of $5 \leq º 2\theta \leq 80$. The FWHM of the XRD peaks was used to estimate the average particle size using the Scherrer equation (Eq. 1).

$$D_{(hkl)} = \frac{0.9 \times \lambda}{\beta_{(hkl)} \times \theta'} \quad (1)$$

The textural properties of the catalysts were determined by N_2 adsorption/desorption at 77 K using a NOVA-4000-Quantachrome adsorption analyzer. Infrared spectroscopy analyses (FTIR) were performed using a Varian 640-IR spectrometer with potassium bromide (KBr) as the dispersing agent in the region from 4000 to 400 cm^{-1}. Temperature-programmed desorption of NH_3 (TPD-NH_3) and Temperature-programmed reduction (TPR) were carried out using a Quantachrome Chembet-3000 multi-use unit coupled with a ThermoStar-GSD 301 mass spectrometer. In both analyses, 0.1 g sample was placed in a "U"-shaped quartz reactor, which was first subjected to a 20 cm^3/min N_2 flow at 300°C for 1 h to remove humidity and possibly adsorbed materials. For TPD-NH_3 analysis, the samples were reduced with 1.75% H_2 diluted in N_2 for 1 h using a heating rate of 10°C/min from room temperature to 500°C and remaining at this temperature for another 1 h. NH_3 adsorption was performed at 100°C for 30 min with a flow rate of 15 cm^3/min of 5% NH_3 diluted in N_2. Subsequently, the system was purged for 2 h with a flow rate of 20 cm^3/min N_2. Finally, the sample was heated to 700°C at a heating rate of 10°C/min under N_2 flow for NH_3 desorption. TPR was performed with a reducing gas feed containing 1.75% H_2 in N_2 at a flow rate of 20 cm^3/min, from room temperature to 1000°C with a heating rate of 10°C/min.

2.2.3. Catalytic Performance Evaluation

SRE was carried out using two catalysts, Cu/NaY and Cu/Nb_2O_5/Al_2O_3. Tests were performed in an experimental unit consisting of a preheating system, a 20 cm long stainless-steel reactor with an internal diameter of 2.54 cm, a condenser, and a phase collector/separator. The reactant mixture was introduced through the system inlet using a peristaltic pump.

Before the catalytic tests, the catalysts were activated *in situ* with an 85 cm^3/min N_2 flow rate containing 40% H_2 by volume using the following heating steps: 30 min at 100°C, 1 h at 200°C, and 4 h at 500°C. After this, the H_2 flow was stopped, and the N_2 flow was adjusted to 85 mL/min for 4 h to purge H_2 from the entire reaction system. Subsequently, catalytic tests were conducted at 300°C and 450°C using a mass hourly space velocity of 40 $dm^3/h.g_{cat}$, 5 g catalyst (40 mesh, positioned at the center with the reactor ends filled with silica of the same particle size), and a H_2O/C_2H_5OH molar ratio of 10/1 without the presence of an inert. The gaseous products were analyzed in a Trace GC ThermoQuest gas chromatograph with a Carboxen 1010 PLOT column, with argon as carrier gas, detection by TCD, and the following temperature programming: 7 min at 45°C; 25°C/min to 180°C; and 5 min at 180°C. The liquid phase was analyzed using a Varian 3300 gas chromatograph, with a 10% Carbowax 20M CHR W HP column, helium as carrier gas, detection by TCD, and the following temperature programming: 2 min at 50°C; 25°C/min to 100°C; and 2 min at 100°C.

Evaluation of catalytic performance for H_2 production and product selectivity (dry basis) were based on ethanol conversion following Eqs. (2) and (3),

$$C_{EtOH}(\%) = \left(\frac{F_{in}^{EtOH} - F_{out}^{EtOH}}{F_{in}^{EtOH}}\right) \times 100, \quad (2)$$

$$S_i(\%) = \sum_i \left(\frac{n_i}{n_t}\right) \times 100 \quad (3)$$

where F is the molar flow rate, n_i is the average molar flow rate of the product component, i is the component of the mixture, and n_t is the average molar flow rate of the products, excluding water.

3. Results and Discussion

3.1. Catalyst Characterization

 doi:10.20944/preprints202405.2026.v1

3.1.1. Morphology

SEM was used to analyze the microstructural morphology of the catalysts. Figure 1a shows the NaY support, and Figure 1b the synthesized Cu/NaY catalyst. Even after the wet impregnation of copper on the NaY support, the polyhedral shapes of the zeolite remained regular and homogeneous, indicating no change in its morphological structure. By contrast, Figure 1c shows the Nb_2O_5 support while Figure 1d shows the synthesized $Cu/Nb_2O_5/Al_2O_3$ catalyst. Unlike Cu/NaY, the particles are randomly distributed with various geometries and distinct sizes. These morphological properties were attributed to the nature of the support used, which does not present a well-defined microstructural morphology and evenly distributed particle sizes.

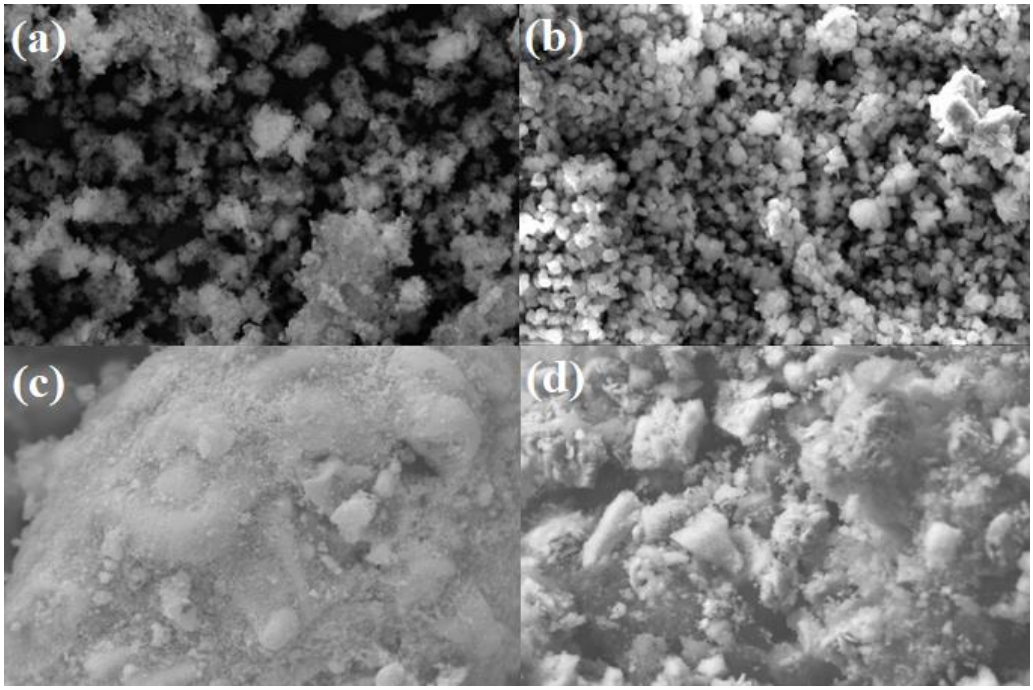

Figure 1. SEM at 4000x of (a) NaY, (b) Cu/NaY, (c) Nb_2O_5 and (d) $Cu/Nb_2O_5/Al_2O_3$.

Elemental mapping was performed by EDS to identify chemical elements at the catalyst surface, using a magnification of 4,000x. Figure 2 shows that all proposed elements were detected, indicating the effectiveness of the proposed wet impregnation process. Additionally, Cu seemed to be better dispersed on NaY compared to Nb_2O_5/Al_2O_3, which presented higher Cu concentration in some regions. This is strongly linked to the superior textural properties of the zeolite, which allowed for a better distribution of the metal particles.

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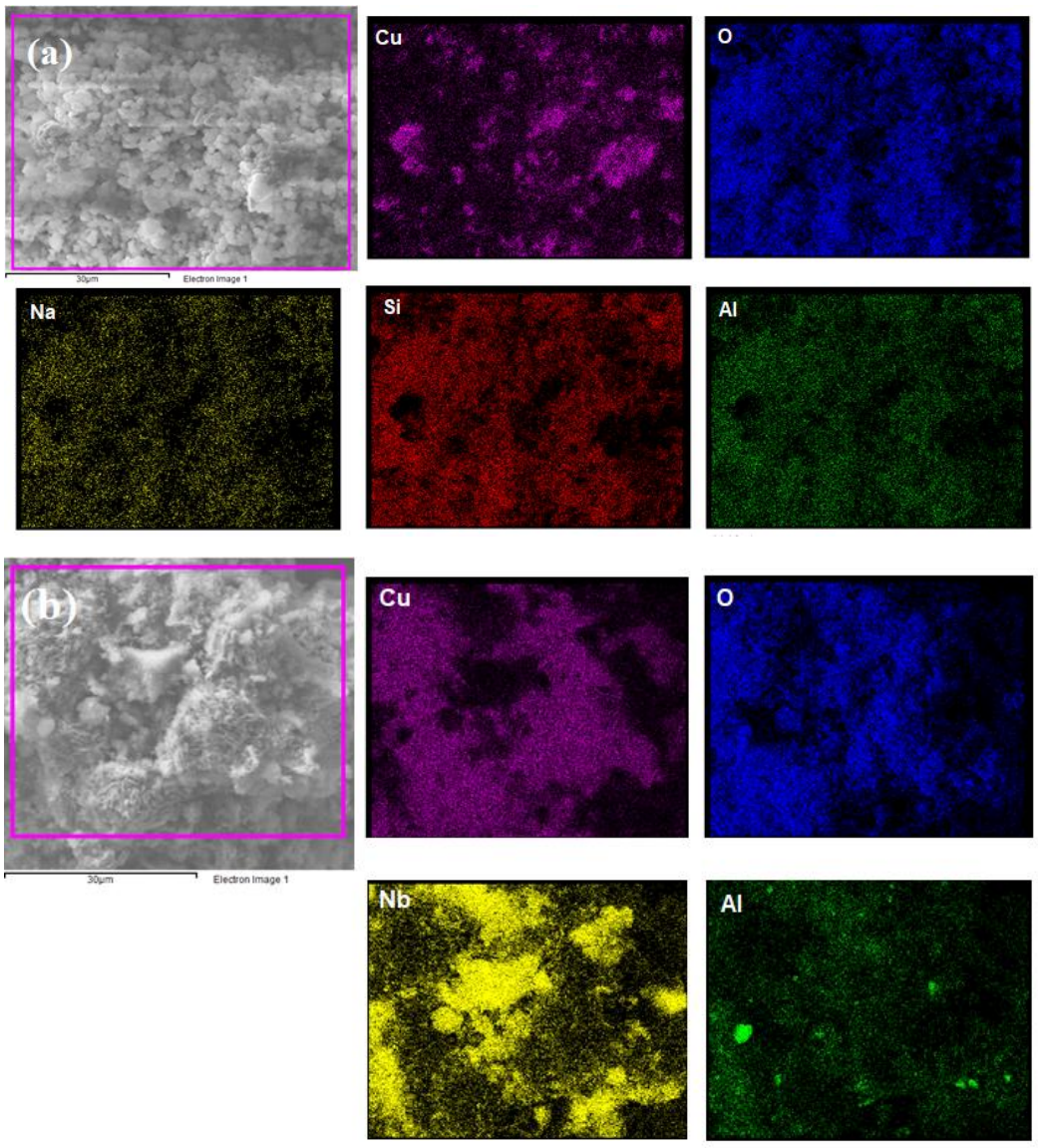

Figure 2. Elemental mapping of (a) Cu/NaY and (b) Cu/Nb_2O_5/Al_2O_3.

Table 1 presents the EDS mass composition of the catalysts. Cu was present in both catalysts in very similar percentages. Furthermore, a Si/Al ratio of 2.58 confirmed the presence of unmodified NaY zeolite after the wet impregnation synthesis.

Table 1. Elemental analysis of Cu/NaY and Cu/Nb_2O_5/Al_2O_3.

Sample	Element (%)						
	Cu	Na	Al	Si	O	Nb	C
Cu/NAY	11.90	3.87	3.00	7.76	26.75	-	3.01
Cu/Nb_2O_5/Al_2O_3	11.17	-	2.84	-	15.72	10.82	0.88

3.1.2. Crystallinity

The XRD technique was employed to determine the crystallinity and purity of the synthesized catalysts. The experimental XRD patterns obtained for Cu/NaY and Cu/Nb_2O_5/Al_2O_3 are shown in Figure 3. For the Cu/NaY catalyst, the diffraction peaks at 2θ = 6.18°, 15.61°, 18.66°, 23.64°, 26.98°, and 31.36° are indexed to the cubic crystal structure of NaY, which corresponds to the Fd-3m space group in card #00-039-1380. The diffraction peaks at 2θ = 35.57°, 38.72°, 48.81°, 58.30°, 61.60°, 66.32°, and 68.12° are indexed to the monoclinic crystal system of CuO, referring to card #01-089-5895. The X-ray

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diffractogram of the Cu/NaY catalyst indicated that there were no modifications in the original crystal structure of the zeolite, probably due to the fine distribution of copper on the zeolite structure [45].

The $Cu/Nb_2O_5/Al_2O_3$ catalyst presented diffraction peaks at 2θ = 35.57°, 38.72°, 48.81°, and 56.72°, which are indexed to the monoclinic crystal system of CuO in card #01-089-5895. The diffraction peak at 2θ = 67.03° is indexed to the hexagonal crystal system of Al_2O_3 in card #00-013-0373, while the diffraction peaks at 2θ = 22.60°, 28.58°, 36.71°, and 46.23° are indexed to the hexagonal crystal system of Nb_2O_5 in card #00-028-0317. Both copper oxide and niobium pentoxide are present in the diffractogram with significant intensities, indicating that the precursors maintained their defined crystal lattice even after the catalyst synthesis. Also, alumina diffraction peaks are almost imperceptible, indicating a high dispersion of alumina in niobium oxide [46].

The crystallite size has important implications for the rate of molecular diffusion and the contribution of the external surface area to adsorption and desorption rates. For the calculation of the crystallite size of the active phase in both catalysts, the (-111) diffraction peak at 2θ = 35.57° of copper oxide was considered. The result was approximately 55 nm for both catalysts, indicating that the change of support did not cause alteration in the crystallite size of the active phase. For the calculation of the support crystallite sizes, the (533) diffraction peak at 2θ = 23.64° of NaY and the (100) diffraction peak at 2θ = 28.58° of Nb_2O_5 were considered, resulting in 114 nm and 43 nm, respectively. Kugai et al. [47] concluded that the smaller the crystallite size of the support, the greater the dispersion of the active phase and consequently the higher the catalytic activity, indicating that the catalyst performance strongly depends on surface area and crystallite sizes.

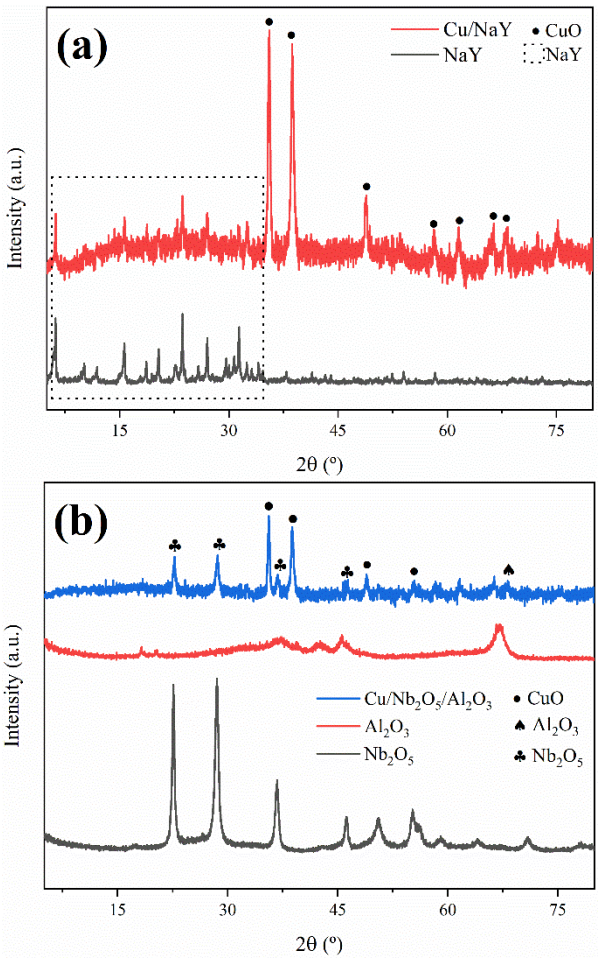

Figure 3. DRX patterns of (a) Cu/NaY and (b) $Cu/Nb_2O_5/Al_2O_3$.

3.1.3. Textural Parameters

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The determination of textural parameters of the synthesized materials and their precursors is relevant to understand their SRE catalytic performance. The parameters obtained through N_2 physisorption are presented in Table 2, while the N_2 adsorption/desorption isotherms are shown in Figure 4. For the Cu/NaY catalyst, the isotherm exhibits characteristics of type IV according to I.U.P.A.C. [48], which is attributed to the presence of micropores associated with mesopores. The formation of a round knee-like feature at the beginning of the isotherm is related to the formation of adsorbed N_2 monolayers inside micropores [49], while the increase in relative pressure improves adsorption as the material mesopores are filled. For the Cu/Nb_2O_5/Al_2O_3 catalyst, the obtained isotherm is of type V, which is also associated with mesoporous materials with weak adsorbate-adsorbent interactions. In both isotherms, there was hysteresis in N_2 desorption, which is characteristic of capillary condensation in mesoporous materials [50]. For Cu/NaY, the hysteresis of type H4 is associated with narrow slit-like pores, while for Cu/Nb_2O_5/Al_2O_3, the hysteresis of type H3 refers to non-rigid aggregates of plate-like particles forming slit pores, typical of non-uniform pore sizes and shapes as observed by SEM.

Concerning the obtained values for textural parameters, the surface areas of the catalytic supports were similar to other studies involving NaY [51,52], Nb_2O_5 [10,42] and Al_2O_3 [53,54]. For the catalysts, a noticeable reduction in surface area and pore volume was observed, compared to their corresponding precursors. This effect is strongly associated with the possible obstruction of smaller pore diameters (micropores) by deposition of copper oxides inside the catalyst structure, as evidenced by the reduction in micropore volume. However, despite this reduction, a significant variation in textural properties was detected among our catalysts. This reinforces the possible influence of the support type on the catalyst performance, as it plays a fundamental role in the reaction. Cu/NaY has a significantly higher surface area than Cu/Nb_2O_5/Al_2O_3, which is expected to result in a superior catalytic performance of the former compared to the latter. This advantageous characteristic of Cu/NaY has been attributed to the three-dimensional pore structure of zeolite NaY [55].

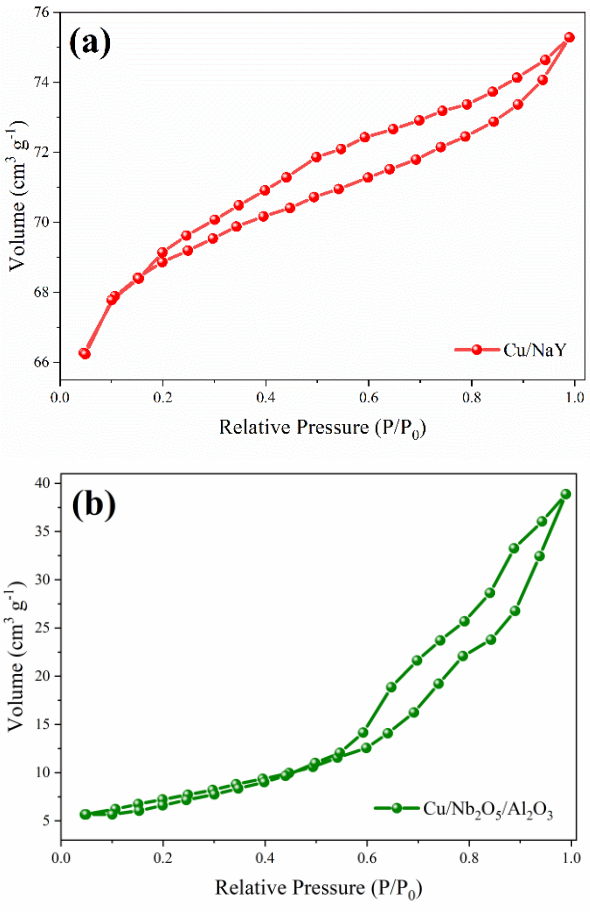

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Figure 4. N_2 adsorption/desorption isotherms of the catalysts (a) Cu/NaY and (b) $Cu/Nb_2O_5/Al_2O_3$.

Table 2. Textural parameters of the catalysts and precursors.

Sample	Surface area ($m^2\ g^{-1}$)	Pore volume ($cm^3\ g^{-1}$)	Micropore volume ($cm^3\ g^{-1}$)	Pore diameter (nm)
Nb_2O_5	71.73	0.37	0.32	8.24
NaY	588.49	0.1479	0.0281	1.74
Al_2O_3	99.26	0.1799	0,0389	7.24
Cu/NaY	210.4	0.118	0.1114	2.24
$Cu/Nb_2O_5/Al_2O_3$	26	0.0617	0.0106	9.56

The FTIR spectra of the synthesized catalysts and both Nb_2O_5 and NaY supports are shown in Figure 5a,b, respectively. The band at approximately 3500 cm^{-1}, observed in all spectra, reveals the presence of surface hydroxyl groups in these materials [26,56]. The main NaY vibration modes were identified as the strong band located at 1029 cm^{-1} and the lower intensity band at 469 cm^{-1}, which correspond to the internal vibrations of the tetrahedral units of the zeolite, while the bands identified at 1150, 794, and 570 cm^{-1} were attributed to the external linkages between the $(Si/Al)O_4$ tetrahedra [57]. Sensitive bands did not show significant changes in the Cu/NaY spectrum compared to those of NaY. On the other hand, the band at 570 cm^{-1}, attributed to the polyhedral ring in the zeolite structure, showed a slight alteration that may be associated with the binding of copper. According to previous studies, copper oxide (CuO) bands are present between the wavenumbers of 610 and 500 cm^{-1} [57,58].

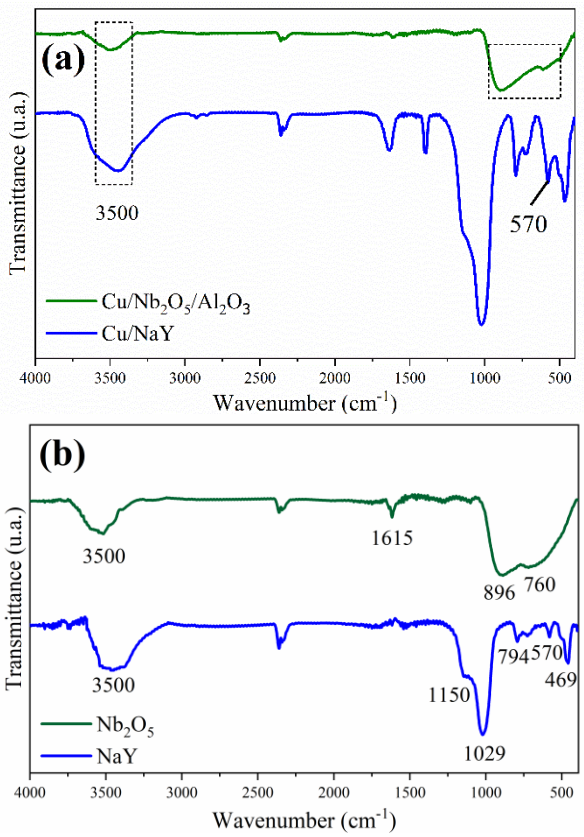

Figure 5. Infrared spectra of the catalysts (a) Cu/NaY and $Cu/Nb_2O_5/Al_2O_3$ and of the precursors (b) NaY and Nb_2O_5.

The FTIR spectrum of Nb_2O_5 (Figure 5b) shows strong and broad bands in the region between 500 and 900 cm^{-1}. The band centered at 896 cm^{-1} is attributed to the Nb-O stretching vibration and the band at 760 cm^{-1} to the Nb-O-Nb vibration [59]. The narrower band at 1622 cm^{-1} is attributed to water molecules adsorbed on the Nb_2O_5 surface [60]. The presence of niobium pentoxide was confirmed by

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the presence of its main vibration modes in the FTIR spectrum of the $Cu/Nb_2O_5/Al_2O_3$ catalyst (Figure 5a). Alterations were also noted in the intensity of the two bands between 500 and 900 cm^{-1}, and in the resolution between them, when compared to the Nb_2O_5 spectrum. These changes are associated to the binding with copper, as we are once again referring to the region of copper oxide bands.

3.1.4. Temperature-Programmed Desorption (TPD)

Analyses of both catalysts by TPD-NH_3 are shown in Figure 6. The NH_3 desorption profiles for Cu/NaY and $Cu/Nb_2O_5/Al_2O_3$ were confined to the 140°C to 460°C and 150°C to 620°C temperatures ranges, respectively, showing that the support type influenced the acidity of the catalyst. The peak location and wide temperature range for Cu/NaY suggest the presence of sites of weak and intermediate acid strength. By contrast, the higher temperature range for $Cu/Nb_2O_5/Al_2O_3$ is attributable to the presence of intermediate to strong acid sites. Also, Cu/NaY had a higher concentration of acid sites compared to $Cu/Nb_2O_5/Al_2O_3$ (Table 3). In general, the higher acidity of Cu/NaY may be justified by its higher surface area.

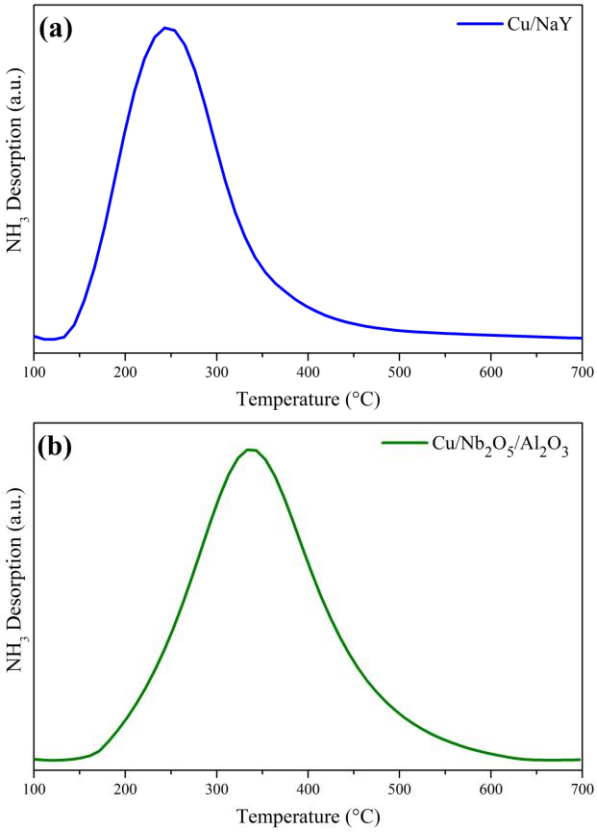

Figure 6. NH_3 desorption curves of the catalysts (a) Cu/NaY and (b) $Cu/Nb_2O_5/Al_2O_3$.

Table 3. Acidity of the synthesized catalysts by TPD-NH_3.

Sample	Chemisorbed NH_3 (mmol/g)	Temperature (°C)
Cu/NaY	1.598	247
$Cu/Nb_2O_5/Al_2O_3$	0.059	336

The maximum NH_3 desorption temperature for the Cu/NaY catalyst was slightly higher than that for NaY alone, which typically ranges between 150°C and 250°C [61–63]. This is an indication that the incorporation of Cu into the zeolite structure increased the strength of its acid sites. On the other hand, the impregnation of Cu onto Nb_2O_5/Al_2O_3 did not have a significant influence on the desorption temperature range.

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3.1.5. Temperature-Programmed Reduction (TPR)

Both catalysts displayed a wide reduction range in their TPR profiles (Figure 7). However, the position of the maximum reduction temperature of CuO for $Cu/Nb_2O_5/Al_2O_3$ was shifted to higher values compared to Cu/NaY, which may indicate a greater interaction of Cu with Nb_2O_5/Al_2O_3 compared to NaY. Reduction at temperatures below 300°C indicated that CuO was dispersed on the catalyst surface with little interaction with the support. Above this temperature, total copper reduction was prevented in both catalytic systems by the interaction between CuO and the support surface [17,64]. Additionally, $Cu/Nb_2O_5/Al_2O_3$ showed a reduction peak with a maximum around 928°C, which was attributed to the partial reduction of Nb_2O_5 to NbO_2 [43,65]. The hydrogen consumption of the Cu/NaY catalyst was 6.16 mmol/g_{cat}, while that of $Cu/Nb_2O_5/Al_2O_3$ was 6.38 mmol/g_{cat}, a slightly higher value due to the partial reduction of Nb_2O_5.

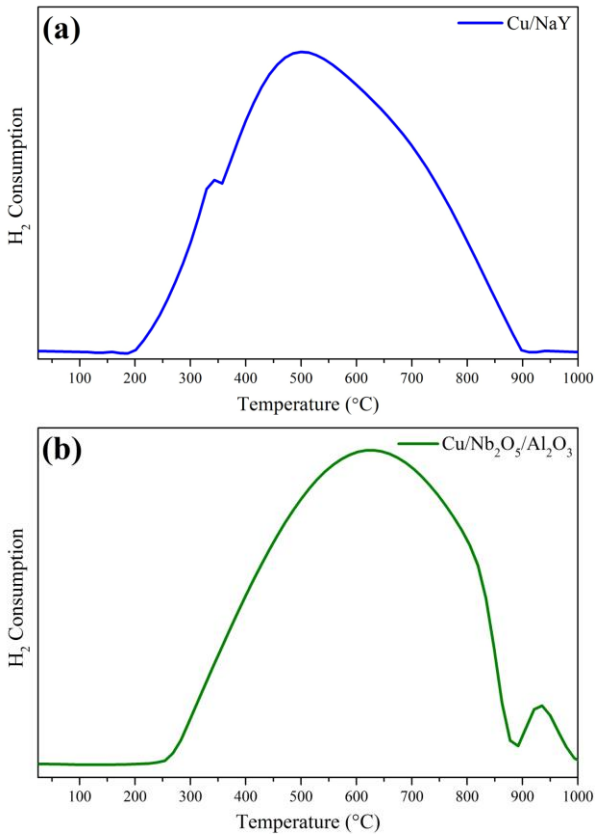

Figure 7. TPR profiles of (a) Cu/NaY and (b) $Cu/Nb_2O_5/Al_2O_3$ catalysts.

3.2. Catalytic Performance Evaluation

Figure 8 shows the selectivity data for both $Cu/Nb_2O_5/Al_2O_3$ and Cu/NaY at 300°C and 450°C. The differences between catalytic performances show that both support and temperature influenced the reaction efficiency. Conversion increased with increasing temperature for both catalysts, but the effect was more pronounced for the $Cu/Nb_2O_5/Al_2O_3$ catalyst. On the other hand, the selectivity for H_2 and acetaldehyde decreased with increasing temperature, and the quantity of by-products (especially ethylene) increased, with this effect being greater for the $Cu/Nb_2O_5/Al_2O_3$ catalyst.

For both catalysts at 300°C, the main reaction was ethanol dehydrogenation (Eq. 4) forming acetaldehyde and H_2, while higher temperatures favored dehydration forming ethylene (Eq. 5). Also, the use of NaY at 450°C favored parallel reactions forming CO and CH_4 [30]. This is probably due to the presence of more pronounced acid sites in the zeolyte at lower temperatures, as observed by TPD-NH_3 analysis of the Cu/NaY catalyst, where acid sites are found between 100 and 450°C (Figure 6). Also, the high surface area of this catalyst contributed to the greater exposure of acid sites, as well as the catalytically active copper sites on the catalyst surface, promoting parallel reactions that are part

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of the ethanol reforming reaction pathway. This explains the detection of reaction intermediates such as acetaldehyde.

$$C_2H_5OH \rightarrow C_2H_4O + H_2 \quad (4)$$

$$C_2H_5OH \rightarrow C_2H_4 + H_2O \quad (5)$$

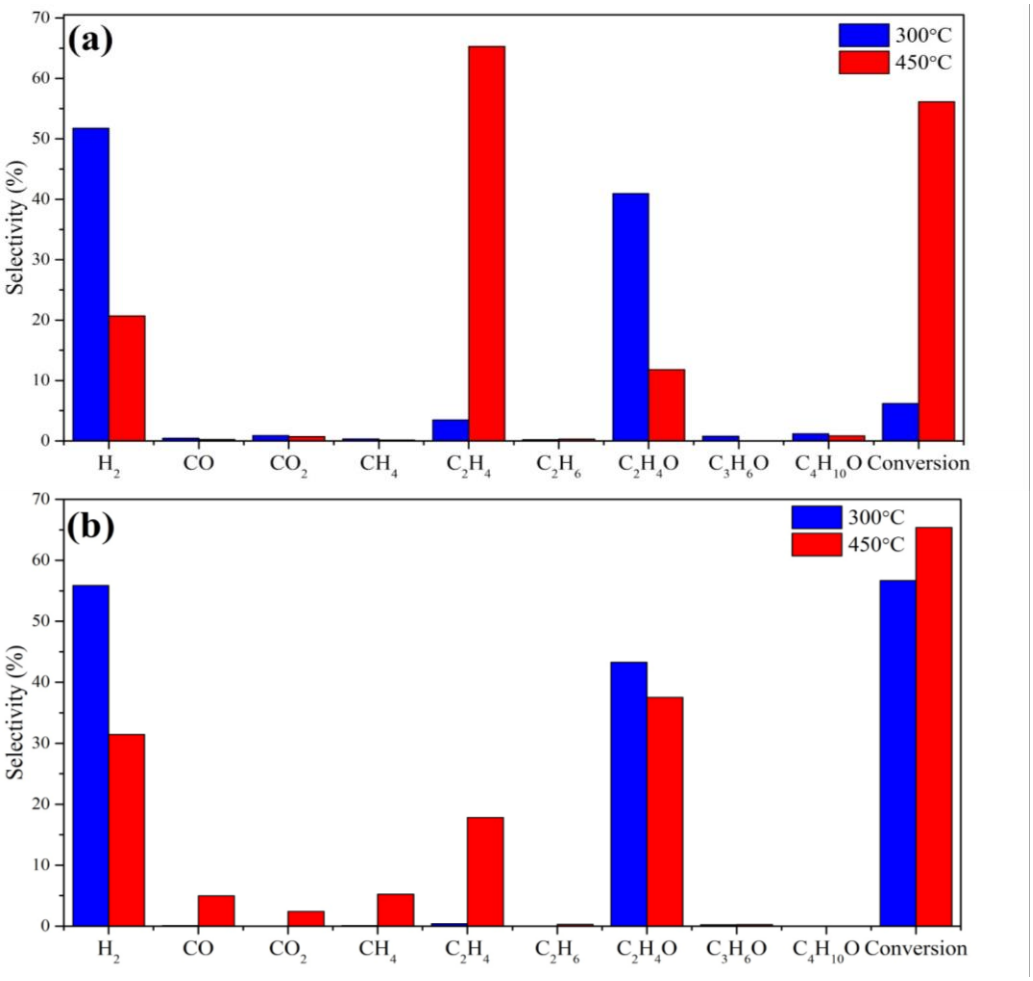

Figure 8. Average selectivity of (a) $Cu/Nb_2O_5/Al_2O_3$ and (b) Cu/NaY at 300°C and 450°C.

The selectivity of $Cu/Nb_2O_5/Al_2O_3$ to C_2H_4 was higher than that of Cu/NaY. The TPD-NH_3 of this catalyst showed acid sites of greater strength due to the desorption of NH_3 at higher temperatures, which may be connected to the higher formation of C_2H_4 [65]. Lorenzut et al. [66] observed the same low selectivity behavior for Cu catalysts supported on ZnO/Al_2O_3. Also, the support seemed to have influenced the reaction pathway, since Nb_2O_5 is an n-type semiconductor that may have driven the selectivity toward ethanol and water. For the $Cu/Nb_2O_5/Al_2O_3$ catalyst, the formation of CO_2 was limited at both temperatures, while for Cu/NaY, CO_2 formation was more pronounced at 450°C, indicating the occurrence of ethanol reforming.

Both catalysts exhibited more stability at 300°C (Figure 9) because, at 450°C, C_2H_4 formation accelerated deactivation by coke deposition [67]. Overall, the results highlight the strong influence of the catalytic support on the steam reforming of ethanol for H_2 production. The Cu/NaY catalyst showed higher ethanol conversion compared to $Cu/Nb_2O_5/Al_2O_3$, suggesting that support properties such as surface area, pore volume, and pore size significantly influenced the catalytic performance. The porous structure and higher surface area of NaY may have facilitated copper dispersion and interaction with the reactants, enhancing the catalytic activity. Additionally, zeolites have a structure with a regular arrangement of uniform micropores that promote greater selectivity for H_2 formation.

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Furthermore, the acidity measurements revealed that the incorporation of copper into NaY increases the strength of the acid sites, as indicated by the higher desorption temperature found for Cu/NaY compared to pure NaY in other studies [68–70]. This increased acidity may have contributed to the improvement of the catalytic activity by influencing the adsorption and breakdown of ethanol molecules. Therefore, a careful selection of the support is crucial for optimizing the performance of copper catalysts in H_2 production by SRE.

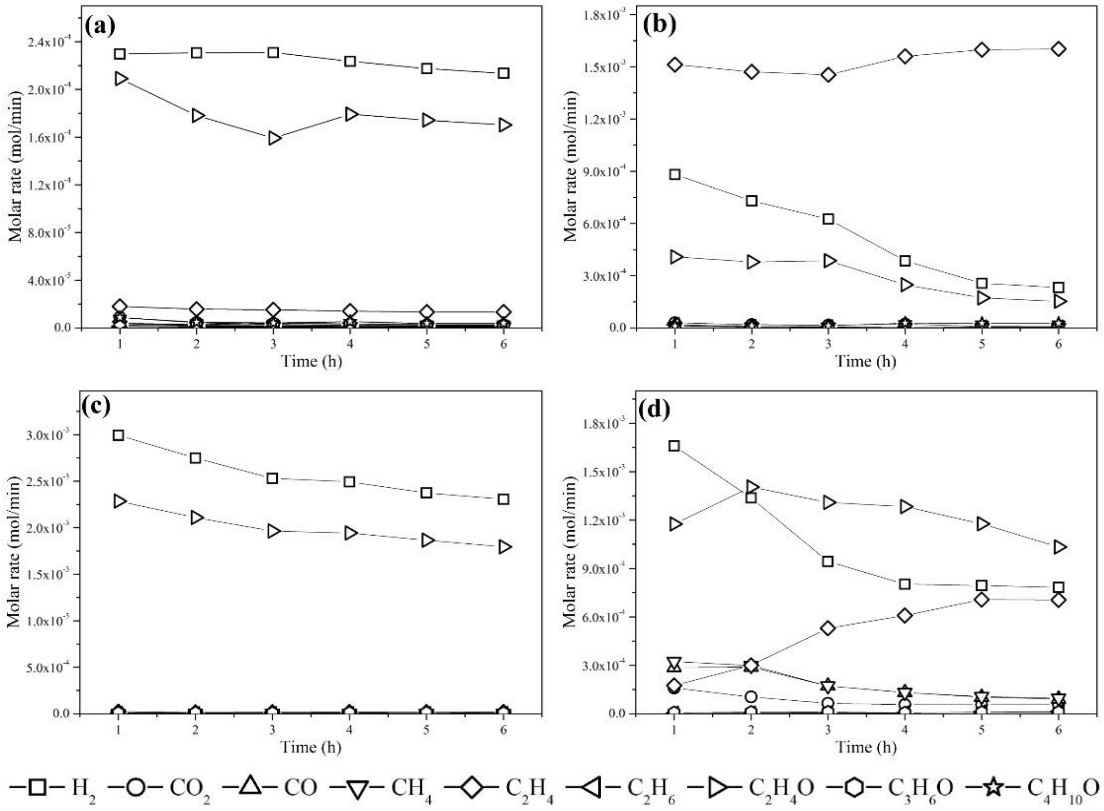

Figure 9. Molar rate as a function of time for $Cu/Nb_2O_5/Al_2O_3$ at (a) 300°C and (b) 450°C and Cu/NaY at (c) 300°C and (d) 450°C.

The maximum H_2 production with the Cu/NaY catalyst, considering the average H_2 production rate of 0.57 mL/s at 450°C, was 4.7 x 10^{-5} g/s, regardless of the reaction pathway whereby H_2 was formed. Since the calorific value of H_2 is 142 kJ/g, this H_2 production represents 6.6 W for a catalyst mass of 5 g, or 1.33 W/g_{cat}. Hence, 1.5 kg Cu/NaY would be required to power a 1 kW cell with an efficiency of 50%.

4. Conclusions

The steam reforming of ethanol was viable using copper-based catalysts supported on NaY zeolite (Cu/NaY) and niobium-aluminum oxides ($Cu/Nb_2O_5/Al_2O_3$). The physicochemical properties of the two catalysts were different due to differences in the support properties. Nevertheless, copper particles were well dispersed in both catalysts, contributing to achieving better catalytic performances. Both catalysts were active in the steam reforming of ethanol, but Cu/NaY was best for H_2 production at 450°C, with CO_2 formation remaining constant throughout the reaction course. Therefore, this catalyst has potential for large-scale operations and, with the addition of a small amount of acidity dopants, it may become even more selective for H_2 production by ethanol reforming. Finally, the support effect was demonstrated as a relevant parameter for optimal SER catalytic performance.

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