



# Article CoCuMgAl-Mixed-Oxide-Based Catalysts with Fine-Tunable Composition for the Hydrogenation of Furan Compounds

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Abstract: Catalysts based on CoCuMgAl mixed oxides were synthesized and studied in the hydrogenations of furfural and 5-hydroxymethylfurfural under different conditions. The changes in the structural properties of the catalysts at different stages of their preparation were studied using a set of physical methods (XRD, SEM, and TEM). It was shown that the fine regulation of the chemical compositions of the mixed oxides (i.e., changes in the Co/Cu ratio) made it possible to vary the structure, morphology, and catalytic properties of the samples. The phase composition of catalysts with Co/Cu = 1 did not change during the catalytic reaction, although the initial catalysts had a less-homogeneous morphology. 5-hydroxymethylfurfural conversion was higher for the samples with Co/Cu = 1. Furfural conversion increased when raising the Co/Cu ratio. The selectivity toward furfuryl alcohol for the catalyst with Co/Cu = 2 under mild conditions of furfural hydrogenation was more than 99%. The results obtained are important for the development of the scientific foundations of the preparation of hydrogenation catalysts with a fine-tunable composition in order to obtain the desired hydrogenation products.

**Keywords:** cobalt; copper; layered hydroxides; mixed oxides; hydrogenation; furfural; 5-hydroxymethylfurfural

## 1. Introduction

The development of environmentally friendly alternative energy sources is one of the key challenges of our time. Biomass is the only renewable source of carbon-neutral energy. It can be used for the production of fuels and value-added chemicals [1]. Among the wide variety of biomass sources, lignocellulosic biomass has emerged as a relevant sustainable source since it does not interfere with the food chain. Moreover, biomass is very abundant, and the products of its processing are valuable chemicals used in many fields. Biomass is mainly composed of cellulose, hemicellulose, and lignin. 5-Hydroxymethylfurfural (5-HMF) and furfural (FAL) are the most important platform chemicals derived from plant biomass [2,3]. FAL can be obtained through the acidic hydrolysis of hemicellulose, while 5-HMF is obtained through the acid-catalyzed hydrolysis and dehydration of cellulose. FAL and 5-HMF are used as the starting compounds in different reactions, such as hydrogenation, oxidation, esterification, condensation, and many others. Among them, the hydrogenations of FAL and 5-HMF are the reactions that attract the greatest commercial interest [4,5]. Due to the variety of possible reaction products, the selection of suitable catalysts is an important task.

Furfuryl alcohol (FOL) is one of the most desirable products derived from the selective hydrogenation of FAL. The applications of FOL in the chemical industry include the synthesis of lubricants, lysine, plasticizers, dispersing agents, adhesives, and thermostatic resins [6]. 2,5-Bis(hydroxymethyl)furan (BHMF) obtained through 5-HMF hydrogenation



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**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). can be used as an intermediate for various potential industrial applications, such as the production of polymers, polyurethane foams, and different drugs [7]. A great number of catalysts for the hydrogenation of FAL and 5-HMF have been proposed. They include noble (Pt, Pd, Au, Ru, and Ir) and non-noble (Cu, Co, Ni, and Fe) metals deposited on various supports [8–10]. High dispersion of active metal and the basic properties of the support are among the main features that a catalyst should have. Two or more active metals can be combined to achieve high selectivity in hydrogenations of FAL and 5-HMF.

The development of new inexpensive catalysts based on layered hydroxides (LHs) whose compositions are finely regulated to achieve distinctive physicochemical properties and high catalytic performance in the hydrogenation of furan compounds is a challenging task. The introduction of active metals into the structures of LHs can provide the desired activity and selectivity [11]. Mixed oxides with a high specific surface area are obtained during the high-temperature treatment of LHs. Cu- and Co-containing catalysts show excellent catalytic performance (activity and selectivity) in hydrogenations of FAL to FOL and 5-HMF to BHMF, respectively [12–15]. Bimetallic CoCu-systems based on LHs are intensively studied as composites for activating  $H_2O_2$  to degrade ciprofloxacin [16], three-dimensional (3-D) urchin-architectured electrode materials [17], catalyst precursors for higher-alcohol synthesis [18], bifunctional catalysts for rechargeable lithium–air batteries [19], catalysts for low-temperature CO-SCR denitration [20], etc. At the same time, CoCu-catalysts based on LHs remain poorly studied in these reactions. Research in this direction has already been started by our scientific group [21,22]. However, there is very little information about the changes in morphology (which affects the diffusion of reagents) and microstructure (which determines the catalytic properties of active centers) of LH-based catalysts during a catalyst's preparation and function in a catalytic reaction. It is well known that surface structure determines the properties of Cu-containing catalysts [23]. Therefore, such studies are of great scientific and practical interest.

The aim of this work was to demonstrate the possibility of changing the properties of catalysts based on CoCu-containing mixed oxides and derived from the corresponding LHs in the hydrogenations of FAL and 5-HMF through the regulation of their compositions (Co/Cu = 1 and 2 at constant values of (Co + Cu + Mg)/Al = 2 and (Co + Cu)/Mg = 2). For this purpose, the structures and morphologies of the catalysts during their preparation and after hydrogenation were studied in detail.

## 2. Materials and Methods

## 2.1. Catalyst Preparation

CoCuMgAl-layered hydroxides (CoCuMgAl-LHs) were prepared through coprecipitation. Aqueous solution containing a mixture of  $Co(NO_3)_2$  (>99%, Omskreaktiv, Omsk, Russia), Cu(NO<sub>3</sub>)<sub>2</sub> (>99%, Lenreaktiv, Saint-Petersburg, Russia), Mg(NO<sub>3</sub>)<sub>2</sub> (>99%, Omskreaktiv, Omsk, Russia), and Al(NO<sub>3</sub>)<sub>3</sub> (>98%, Omskreaktiv, Omsk, Russia) (total concentration of metals 1 mol/L) was gradually added to Na<sub>2</sub>CO<sub>3</sub> (>99.9%, SeverReakhim, Vologda, Russia) solution (1 mol/L) at a temperature of 60 °C and pH 9.5. Aging was carried out at 60 °C for 18 h. Then, washing, filtration, and drying at 80 °C for 18 h were performed. CoCuMgAlO<sub>x</sub> mixed oxides were obtained through the calcination of CoCuMgAl-LHs in an air atmosphere at 550 °C for 3 h. The reductive treatment of CoCuMgAlO<sub>x</sub> samples was carried out in a hydrogen flow at 800 °C for 2 h. The catalyst samples obtained in this reduction step are denoted as CoCuMgAlO<sub>x</sub>-R. The designations, compositions, and preparation conditions of the catalyst samples are listed in Table 1.

The deviation of the metal ratio in the finished catalysts from the theoretically set one (1 or 2) was no more than 5%, as controlled by three replicate ICP-AES measurements of Co and Cu concentrations in the solutions obtained through the catalysts' dissolution.

No.	Co/Cu Molar Ratio	Sample	Preparation Conditions	
1	1	CoCuMaALLH	Coprecipitation from an aqueous solution of $Co(NO_3)_2$ ,	
2	2	CoCumgAI-LIT	$Cu(NO_3)_2$ , $Mg(NO_3)_2$ , and $Al(NO_3)_3$ with $Na_2CO_3$	
3	1	CoCuMaAlO	Calcination of CoCuMgAl-LH at 550 $^\circ \rm C$	
4	2	CoCumgAlOx		
5	1	$C_{0}C_{1}M_{\alpha}AlO_{\alpha}R$	Calcination of CoCuMgAl-LH at 550 °C and subsequent	
6	2	CocurvigAlO <sub>x</sub> -K	reductive treatment of CoCuMgAlOx with H2 at 800 $^\circ\text{C}$	

Table 1. The list of synthesized catalysts <sup>a</sup>.

<sup>a</sup> (Co + Cu + Mg)/Al = 2 and (Co + Cu)/Mg = 2 for all the samples.

## 2.2. Structural Characterization of the Catalysts

The structures of the as-prepared CoCuMgAl-LH, final catalysts (after calcination and reduction stages), and catalysts after the reaction were studied via X-ray diffraction (XRD) using a D8 Advance diffractometer (Bruker, Billerica, MA, USA) employing Cu-K $\alpha$  source in the 2 $\theta$  range from 5° to 80°. The scanning step was 0.02°, and the signal integration time was 5 s/step. The phase composition of samples was identified using the international diffraction database ICDD PDF-2. Crystal sizes of hydroxide phases were calculated using the following equations:

$$L_a = 1.84 \cdot \lambda / (\beta_{110} \cdot \cos \theta_{110}) \tag{1}$$

$$L_c = 0.89 \cdot \lambda / (\beta_{006} \cdot \cos \theta_{006}) \tag{2}$$

The surface morphology of the samples was investigated using scanning electron microscopy (SEM) conducted via a JSM-6460 LV instrument (JEOL Ltd., Tokyo, Japan) with a tungsten cathode and an accelerating voltage of 19 and 24 kV. Each catalyst sample was ground in an agate mortar and fixed on a conducting double-sided carbon Scotch tape. To prevent re-charging effects, a conducting gold film was sputtered on the fixed samples. Prior to each measurement, the samples were evacuated in the microscope chamber for 15–20 min to remove volatile compounds from the surface, as these could exert a detrimental effect on the secondary electron emission and thus deteriorate quality of the image.

Transmission electron microscopy (TEM) images were obtained using a JEM-2100 electron microscope (JEOL Ltd., Tokyo, Japan) at an accelerating voltage of 200 kV. The instrument was equipped with an energy-dispersive X-ray (EDX) spectrometer, INCA-250 (Oxford Instruments, Abingdon, UK). The analysis and computer processing of electron microscopic images were performed using the Digital Micrograph program (Gatan Inc., Pleasanton, CA, USA).

## 2.3. Catalyst Testing

Aqueous-phase hydrogenations of FAL (>99%, Vekton, Saint-Petersburg, Russia) and 5-HMF were performed in a Miniclave drive batch-type reactor (Büchi AG, Flawil, Switzerland). The reaction vessel was loaded with preliminary reduced catalyst and a solution of FAL or 5-HMF in distilled water. The reactor was flushed with argon and hydrogen to remove air. Then, the reactor was heated to a reaction temperature (90 or 150 °C) and simultaneously filled with hydrogen gas until reaching the necessary pressure (20 or 30 bar). The experiments were conducted under vigorous stirring of the reaction mixture at 1000 or 750 rpm for 1 h. After completion of the reaction and cooling, the aqueous phase was separated from the catalyst via filtering. The reaction products were identified through <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy using an Avance-400 NMR spectrometer (Bruker, Fällanden, Switzerland). The quantitative determination of the reaction products was carried out using gas chromatography (GC) conducted by means of a GKh-1000 instrument (Khromos, Moscow, Russia) equipped with a flame ionization detector and a ValcoBond VB-Wax capillary column (60 m  $\times$  0.32 mm, polyethylene glycol, stationary phase thickness: 0.50 µm). The relative error of GC measurements did not exceed 7%.

## 3. Results and Discussion

#### 3.1. Structure and Morphology of the Catalysts Based on CoCuMgAl-LHs

According to the XRD results, all of the synthesized LH samples contained a hydrotalcitetype phase (Figure 1, patterns 1, Table 2). The typical reflections indexed to the lattice planes (003), (006), (012), (015), (018), (110), and (113) can be observed in the corresponding XRD patterns. The cell parameters of the samples with different Co/Cu molar ratios are very close to each other since there was little change in the metal content. Lattice parameter *a*, which corresponds to the distance of octahedral O-O in a layer and depends on the type of cations in the layer, is 3.059 and 3.058 Å for the samples with Co/Cu = 1 and 2, respectively. Lattice parameter *c*, corresponding to the interlayer distance, is 22.79 and 22.82 Å for the samples with Co/Cu = 1 and 2, respectively. The crystallite sizes in the *a* and *c* directions are as follows:  $L_a = 88$  (Co/Cu = 1) and 96 Å (Co/Cu = 2);  $L_c = 160$  (Co/Cu = 1) and 166 Å (Co/Cu = 2).



**Figure 1.** XRD patterns of the samples with Co/Cu = 1 (a) and Co/Cu = 2 (b): 1—as-synthesized CoCuMgAl-LHs; 2—CoCuMgAlO<sub>x</sub>-R; 3—CoCuMgAlO<sub>x</sub>-R after FAL hydrogenation.

Sample	Co/Cu	Phase Composition	
CoC::MaALLH	1	- hydrotalcite-type phase	
CoCulvigAI-LH	2		
	1	- Co <sub>3</sub> O <sub>4</sub> , α-Co, Cu	
CoCumgAlO <sub>x</sub> -R	2		
CoCuMgAlO <sub>x</sub> -R after the FAL	1	Co <sub>3</sub> O <sub>4</sub> , α-Co, Cu	
hydrogenation	2	X-ray amorphous	

Table 2. Phase composition of the CoCuMgAl-systems.

The morphology of a catalyst is an important characteristic related to porosity. Usually, but not always, a high specific surface area contributes to a more uniform distribution of the catalytically active component and, as a result, an increase in the efficiency of a catalyst in a reaction. The study of the structure/morphology transformation during the preparation of LH-based catalysts is an important task. An increase in the density of the morphology of LH-based catalysts may decrease their specific surface area [21]. Moreover, the rate of diffusion of reagents to the active centers of the catalyst is determined by surface morphology. In this regard, it was interesting to study the changes in the morphology of the CoCuMgAl systems during their high-temperature treatment (calcination in air

and reductive treatment in hydrogen) with slight variations of their chemical composition (Co/Cu = 1 and 2 at the constant values of (Co + Cu + Mg)/Al = 2 and (Co + Cu)/Mg = 2).

According to the SEM data, the as-prepared CoCuMgAl-LHs exhibited a randomly oriented hexagonal lamellar structure (Figure 2). A similar structure was revealed for  $Cu_xCo_{3-x}Al$ -LH catalysts without Mg in their composition [24]. The authors of this work pointed out that for the samples with higher Cu content, the edge of the hexagonal lamellar structure becomes obscured and close in resemblance to a filmy sphere. We did not observe a similar trend with an increasing Cu fraction (decreasing the Co/Cu ratio from 2 to 1) in the CoCuMgAl-LH system. This is likely due to the similar chemical compositions of the CoCuMgAl-LHs, having a different Co/Cu ratio but the same (Co + Cu)/Mg and (Co + Cu + Mg)/Al ratios. Consequently, such a slight variation in the composition did not lead to changes in the morphology of the CoCuMgAl-LH system.



**Figure 2.** SEM images of CoCuMgAl-LHs with Co/Cu = 1 (**a**–**c**) and Co/Cu = 2 (**d**–**f**) at different magnifications.

The phase composition of the CoCuMgAlO<sub>x</sub>-R catalysts prepared via consistent calcination and reductive treatment is different from that of the initial as-synthesized LHs (Figure 1, patterns 2). No XRD peaks that characterize the layered structure of initial hydroxide are observed. At the same time, the reflexes of cobalt oxide (Co<sub>3</sub>O<sub>4</sub>), metallic  $\alpha$ -Co, and Cu appear in the XRD patterns. Phases containing Mg or Al were not detected. It is probable that these metals are included in the composition of Mg (Co, Cu) Al-mixed oxides with a structure close to the structure of cobalt oxide. The exact composition of Mg (Co, Cu) Al-mixed oxide phases has not yet been fully clarified. Most researchers believe that the peaks of these mixed oxides may be in the angle regions corresponding to cobalt oxide [25,26]. Therefore, such phases cannot be uniquely identified. The intensity of metallic Cu peaks decreases when increasing the Co/Cu ratio (i.e., when decreasing the Cu fraction). However, the intensity of the peaks corresponding to metallic Co remains almost unchanged when increasing the Co/Cu ratio.

According to the SEM data, the high-temperature treatment (calcination in air and reductive treatment in hydrogen) promoted the sticking of plates and the formation of a smoother morphology (Figure 3). The initial morphology was preserved to a greater extent for the samples with a higher Co/Cu ratio. Moreover, these samples have a more

uniform morphology (Figure 3g-i). Two types of surface morphologies can be distinguished for the samples with Co/Cu = 1. In some images, a smooth surface consisting of barely discernible clumped aggregates is observed (Figure 3a-c). In other images, plates are clearly distinguishable (Figure 3d-f). Thus, a minor change in the composition of the CoCuMgAl systems facilitates the formation of catalysts with different morphologies.



**Figure 3.** SEM images of CoCuMgAlO<sub>x</sub>-R with Co/Cu = 1 ( $\mathbf{a}-\mathbf{f}$ ) and Co/Cu = 2 ( $\mathbf{g}-\mathbf{i}$ ) at different magnifications.

## 3.2. Performance of the CoCuMgAl-Mixed Oxide Catalysts in Hydrogenations of FAL and 5-HMF

In order to study the effect of the composition of CoCuMgAl mixed oxide catalysts on their catalytic properties in aqueous-phase hydrogenations of FAL and 5-HMF, catalytic experiments were carried out under mild (90 °C, 20 bar) and harsh conditions (150 °C, 30 bar). According to the obtained results, FAL conversion for 1 h increases when raising the Co/Cu ratio independently of the reaction conditions (Table 3). Under mild reaction conditions, the catalyst with Co/Cu = 2 was twice as active compared to the sample with Co/Cu = 1 (FAL conversion of 21 and 10 mol.%, respectively). FAL conversion increased up to 77 mol.% under more severe reaction conditions (150 °C, 30 bar), and the catalysts hardly differ in this parameter. FOL is the main product of FAL hydrogenation under any conditions and for all catalysts. The FOL selectivity was slightly higher for the sample with Co/Cu = 2. The increase in reaction temperature and pressure led to an intensification of the reaction along with the participation of water (Piancatelli rearrangement), resulting

in the formation of cyclopentanone, 2-cyclopentenone, and 4-hydroxy-2-cyclopentenone (Scheme 1).

**Table 3.** Results regarding FAL hydrogenation in the presence of CoCuMgAlO<sub>x</sub>-R catalysts with Co/Cu = 1 and 2.

Co/Cu Molar Ratio	Reaction Temperature and Total Pressure <sup>a</sup>	FAL Conversion, mol.%	Selectivity to FOL, mol.%
1	90 °C, 20 bar	10	95 <sup>b</sup>
1	150 °C, 30 bar	71	82 <sup>c</sup>
2	90 °C, 20 bar	21	>99
2	150 °C, 30 bar	77	86 <sup>c</sup>

<sup>a</sup> Other reaction conditions were the same: 500 mg of a catalyst, 5 mL of FAL, 95 mL of H<sub>2</sub>O, duration of 1 h, and stirring rate of 1000 rpm. <sup>b</sup> Other products were unidentified. <sup>c</sup> Except FOL, cyclopentanone (1 mol.%), 2-cyclopentenone (1–4 mol.%), and 4-hydroxy-2-cyclopentenone (7–9 mol.%) were identified using NMR spectroscopy.



**Scheme 1.** Reaction sequence realized during the aqueous-phase hydrogenation of FAL over the CoCuMgAlO<sub>x</sub>-R catalysts.

The activity (in terms of conversion) of CoCuMgAl catalysts in the hydrogenation of 5-HMF was much lower compared to that in FAL hydrogenation. This is likely due to the reduced reactivity of the 5-HMF molecule compared to FAL [27]. In contrast to FAL hydrogenation, the 5-HMF conversion increases upon decreasing the Co/Cu ratio (Table 4). Under more severe reaction conditions, 5-HMF conversion reaches 27 mol.%. Among the products of 5-HMF conversion, only BHMF was identified using NMR spectroscopy. Although the structures of the remaining products were not determined, it was reliably established that they are not products of reactions with water, as in the case of FAL hydrogenation. The catalyst with Co/Cu = 2 has negligible activity, which almost does not change with the increase in reaction temperature and pressure.

**Table 4.** Results of 5-HMF hydrogenation in the presence of CoCuMgAlO<sub>x</sub>-R catalysts with Co/Cu = 1 and 2.

Co/Cu Molar Ratio	Reaction Temperature and Total Pressure <sup>a</sup>	5-HMF Conversion, mol.%	Selectivity to BHMF, mol.% <sup>b</sup>
1	90 °C, 20 bar	13	59
1	150 °C, 30 bar	27	63
2	90 °C, 20 bar	7	75
2	150 °C, 30 bar	9	61

<sup>a</sup> Other reaction conditions were the same: 50 mg of a catalyst, 500 mg of 5-HMF, 50 mL of H<sub>2</sub>O, duration of 1 h, and stirring rate of 750 rpm. <sup>b</sup> Other products were unidentified.

Since the CoCuMgAl-oxide catalysts possessed good activity regarding FAL hydrogenation, changes in their microstructure during the reaction were of particular interest. TEM images of the fresh CoCuMgAlO<sub>x</sub>-R catalysts with Co/Cu = 1 and 2, as well as the images of these samples after FAL hydrogenation (90 °C, 20 bar), can be seen in Figure 4. In accordance with the obtained data, clear agglomerates of metallic particles can be observed in all the fresh catalysts irrespective of their Co/Cu ratios (Figure 4a–d). These agglomerates have a "core–shell" structure. According to EDX spectroscopy, the metallic Co and Cu particles are in the "core". The average diameter of the "core" is 12.7 nm. Lattice fringes, which are difficult to attribute to a specific oxide phase, can be identified in the "shell". It is most likely that different types of non-stoichiometric CoCuMgAlO<sub>x</sub> mixed oxides can exist simultaneously. The XRD data obtained for these samples also confirm this assumption (Figure 1, patterns 2). Such a phenomenon is often observed for catalysts prepared via the high-temperature treatment of LHs [25]. The high selectivity toward FOL achieved by the CoCuMgAlO<sub>x</sub>-R catalysts may be due to their microstructures. The catalytically active metallic Co and Cu species located in the "core" have limited accessibility to reacting molecules. As a result, the reactions of deeper hydrogenation are suppressed, even under harsh reaction conditions.



**Figure 4.** TEM images of the fresh CoCuMgAlO<sub>x</sub>-R catalysts with Co/Cu = 1 (**a**,**b**) and Co/Cu = 2 (**c**,**d**) and the spent CoCuMgAlO<sub>x</sub>-R catalysts with Co/Cu = 1 (**e**,**f**) and Co/Cu = 2 (**g**,**h**) after FAL hydrogenation.

The "core–shell" structure of the samples became less obvious after FAL hydrogenation. Distinct round particles with an average size in the range of 20 nm were still observed for the catalyst with Co/Cu = 1 (Figure 4e,f). For the sample with Co/Cu = 2, the contours of the particles are more blurred, and the shapes of the particles are less defined (Figure 4g,h). Carbon-containing deposits formed on the surfaces of the catalysts during the reaction for both samples. According to the XRD data, the phase composition of the sample with Co/Cu = 1 did not change during the reaction (Figure 1a, pattern 3). Moreover, the intensity of the peaks attributed to metallic Cu increased for the spent catalyst. This is likely due to the increase in the crystallinity or size of Cu particles. The spent catalyst with Co/Cu = 2 is X-ray-amorphous (Figure 1b, pattern 3). Thus, the stability of the catalyst structure decreases when increasing the Co/Cu ratio. This phenomenon may be one of the reasons for the lower activity of this catalyst in 5-HMF hydrogenation.

#### 4. Conclusions

In summary, CoCuMgAl-mixed oxides were studied and employed as catalysts in FAL and 5-HMF hydrogenation. To finely regulate the chemical compositions of the catalysts, the Co/Cu molar ratio was changed (Co/Cu = 1 and 2), while the (Co + Cu + Mg)/Al and

(Co + Cu)/Mg ratios remained the same. It was shown that this change in the composition affects the properties of CoCuMgAl-LHs and corresponding mixed oxide catalysts. The phase compositions of the CoCuMgAl-LHs with different Co/Cu ratios were the same. The phase compositions of the corresponding catalysts after high-temperature treatment were also the same. The CoCuMgAl-LHs samples with Co/Cu = 1 and 2 were similar to each other in morphology and consisted of randomly oriented hexagonal plates. The hightemperature treatment of CoCuMgAl-LHs allowed for the alteration of their morphology depending on the Co/Cu ratio, and the catalyst with Co/Cu = 2 had a more uniform morphology. The CoCuMgAlOx-R catalysts obtained through the reductive treatment of mixed oxides contained agglomerates with a "core-shell" structure. The phase composition of the catalyst with Co/Cu = 1 did not change during FAL hydrogenation, while the spent catalyst with Co/Cu = 2 was X-ray-amorphous. Increasing the Co/Cu ratio led to an increase in FAL conversion and a decrease in 5-HMF conversion. Thus, the obtained results show that the properties of the CoCuMgAl mixed oxides can be fine-tuned through the variation of their chemical compositions, opening new possibilities for the development of effective catalysts for the hydrogenation of renewable biomass-derived furan compounds. However, further in-depth research in this field is undoubtedly needed.

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