Highly Efficient Nanosized Mesoporous CuMgAl Ternary Oxide Catalyst for Nitro-Alcohol Synthesis: Ultrasound-Assisted Sustainable Green Perspective for the Henry Reaction

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ABSTRACT: Nanosized mesoporous CuMgAl ternary oxide catalysts were prepared by thermal decomposition of CuMgAl-layered double hydroxides at 500 °C with nominal Cu/Mg/Al ratios of 1:1:1 (Cu-LDH-I), 1.5:0.5:1 (Cu-LDH-II), and 2:0:1 (Cu-LDH-III). The synthesized catalysts were characterized by inductively coupled plasma atomic emission spectroscopy (ICP-AES), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), high-resolution transmission electron microscopy (HRTEM), Fourier transform infrared (FTIR) spectroscopy, CO2-TPD, and N2 physisorption analysis techniques. The catalytic activity of the synthesized materials was investigated for the Henry reaction between nitromethane and numerous aldehyde derivatives under ultrasonic irradiation. The three CuMgAl ternary oxide catalysts exhibited a high catalytic activity, forming nitro alcohol products with 100% atom economy. The CuMgAl-I catalyst derived from Cu-LDH-I offered high turnover frequencies (TOFs in the synthesis of all of the nitro alcohols in shorter reaction times). The superior catalytic activity of the CuMgAl-I sample is attributed to the synergistic effect between the physicochemical properties of the catalysts and ultrasonic irradiation. The HRTEM analysis of the used CuMgAl-I catalyst revealed the evidence for the cavitation collapse, which causes localized deformation and surface erosion. Moreover, the synthesized catalysts also exhibited robust sustainable activity that resisted deactivation over repeated usage. The present example of ultrasonic-assisted catalyzed organic synthesis represents a novel strategy for the solvent-free green synthesis of nitro-alcohols by the Henry reaction with 100% atom economy.

1. INTRODUCTION

The Henry reaction continues to attract attention in synthetic organic chemistry research.1−3 With the development of suitable chiral catalysts, the reaction was established as a viable approach in asymmetric organic molecules synthesis, particularly in the field of pharmaceuticals and experimental therapeutics, in which the biological activities of compounds depend on their relative chirality.2 Traditional approaches for C−C coupling in the Henry reaction involving soluble inorganic bases such as alkali-metal/alkaline-earth-metal hydroxides, carbonates, bicarbonates, alkoxides, ethoxides, and organic bases such as primary, secondary, and tertiary amines frequently produce dehydration products.1 Moreover, control of the basicity of the reaction medium is vital to obtain higher yields of β-nitro alcohols. However, the reported methodologies in the literature suffer from the drawback of the production of moderate yields of alcohols over long reaction times.2,3

Stoichiometric organic synthetic methods, which have largely been applied so far, give rise to large quantities of inorganic salts as byproducts, disposal of which has serious consequences in the environment.4 The heterogeneous catalytic procedures described in the literature have many drawbacks, such as the removal of waste and the difficulty in recovering the catalyst from the products. Potentially, many byproducts can be formed during the selective synthesis of 2-nitroalkanols, such as aldol olefins and their polymers and Cannizzaro products, depending on the nature of the base.5 The Henry reaction has undergone significant developments, for example, silyl nitronates have been used in the presence of fluoride ions or alternatively α,α-doubly deprotonated primary nitroalkanes.6 These reactions are valued in the stereo-selective synthesis of vicinal amino alcohols, but are performed under severe conditions that reduce the diastereoselectivity of the reactions with aromatic aldehydes. Therefore, to achieve better yields and diastereoselectivity in the synthesis of 2-nitro
alcohols, it is vital to investigate the use of heterogeneous catalysts with basic sites.7

Although there have been outstanding advances in the development of heterogeneous catalysts for the Henry reaction,8,9 the development of an environmentally friendly process and a robust environmentally benign catalyst to synthesize novel Henry reaction products remains a challenge. Great progress has been made in the development of mesoporous solid bases in the last decade.10 They are extremely desirable in green catalytic processes owing to their advantages, including accelerated mass transfer, negligible corrosion, and easy separation. In addition to their widespread applications in the catalytic synthesis of biologically active organic molecules and fine chemicals, mesoporous solid bases have also been used as catalysts in the field of energy and environmental research.11 Nanosized metal oxides behave efficiently as they have unique features such as high specific surface area, electric conductivity, and thermal stability. The utilization of nanosized mesoporous solid-base catalysts is an alternative to the classical environmentally unfriendly homogeneous catalysts.

Metal oxides synthesized from hydrotalcite-like structures are considered as nanosized mesoporous solid-base catalysts, which have unique features with respect to crystallite size, morphology, and surface area, as well as high catalytic efficiency in various catalytic reactions.12,13 For example, in the last decade, CuO/Al2O3 obtained from hydrotalcites has been considered an efficient catalyst for the synthesis of alcohols.14 Furthermore, MgO has strong Lewis basic sites due to the presence of O2− ions and has been used as an efficient catalyst for the hydrogenation of alkyl ketones.15

Ultrasound irradiation has been proven to be an important tool in the arsenal of “green chemistry.”16−18 The utilization of ultrasound irradiation has become a common practice to overcome the disadvantages such as longer reaction times, unsatisfactory yields, usage of expensive reagents, and operation of reactions under high temperatures, and is commonly termed “sonochemistry.” In the present work, three nanosized mesoporous CuO/MgAl2O4 catalysts, CuMgAl-I, CuMgAl-II, and CuMgAl-III, have been prepared from CuMgAl-layered double hydroxides, CuLDH-I, CuLDH-II, and CuLDH-III catalysts were employed for the Henry reaction between nitromethane and a variety of benzaldehydes and CuLDH-I, CuLDH-II, and CuLDH-III catalysts were employed for the Henry reaction between nitromethane and a variety of benzaldehydes.

Table 1. Chemical Composition of As-Synthesized Cu-LDH Precursors

|            | CuLDH-I | CuLDH-II | CuLDH-III |
|------------|---------|----------|-----------|
| Cu/Al      | 0.95    | 1.40     | 1.90      |
| Mg/Al      | 0.97    | 0.57     |           |
| Cu + Mg/Al | 1.92    | 1.96     | 1.88      |

2. RESULTS AND DISCUSSION

2.1. Chemical Composition by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The ICP-AES analysis of the Cu-LDH precursor samples was carried out to determine their chemical composition. The Cu/Mg/Al molar ratios in the three solids are presented in Table 1, and are very close to the molar compositions used in the synthesis of the CuMgAl-layered double hydroxides. These results confirm the efficacy of the preparation procedure used in the present work.

2.2. X-ray Diffraction (XRD). The powder XRD patterns of the as-synthesized CuLDH precursor samples are shown in Figure 1A. The diffraction patterns reveal the typical crystalline phase of a carbonate-containing layered double hydroxide phase (JCPDS 22-700).19 The powder XRD (PXRD) patterns of three samples show sharp and intense diffraction peaks at 2θ = 11, 23, and 34° corresponding to (003), (006), and (009) reflections and broad diffraction peaks at 2θ = 39, 47, and 56° associated with (015) and (018) reflections, respectively. However, a poorly crystalline malachite phase [Cu2(OH)2CO3, JCPDS 10-0399] was also detected in the PXRD pattern of the CuLDH-III sample, which is mainly due to the high copper content in the material.

Figure 1B shows the PXRD patterns of the CuLDH samples calcined at 500 °C for 8 h. The formation of metal oxide of the predominant metallic cation was observed after thermal decomposition of layered double hydroxide below 700 °C.20 In the case of CuMgAl-I and CuMgAl-II samples, crystalline CuO phase (JCPD 01-078-0428) was observed along with the MgO periclase structure. Upon calcination, the CuMgAl-III sample, which is composed of the layered double hydroxide and malachite phases, yielded highly crystalline CuO and poorly crystalline γ-Al2O3 phases.21 The formation of CuO phase at low temperature can be ascribed to the well-known Jahn−Teller effect of copper ions22 and their behavior inside brucite-like layers.23 The crystallite size of the CuO phase, determined by using the Debye−Schererr equation, was calculated to be around 18, 21, and 25 nm for CuMgAl-I, CuMgAl-II, and CuMgAl-III samples, respectively. The gradual increase in CuO crystallite size can be attributed to the precipitation of copper particles within the LDH layers resulting in grain growth of platelets of the Cu-LDH samples,24 which in turn results in the formation of highly crystalline CuO phase after calcination in air at 500 °C.

Relatively intense XRD reflections due to γ-Al2O3 appeared in the CuMgAl-III sample, while CuMgAl-I and CuMgAl-II samples have not shown these reflections. This is mainly due to the Cu, Mg, and Al composition of the samples. The Cu/Mg/Al ratio for CuMgAl-III is 2:0:1, while it is 1:1:1 and 1.5:0.5:1.
for CuMgAl-I and CuMgAl-II samples, respectively. The CuMgAl-III sample does not contain any Mg; it contains only Cu and Al. The absence of Mg in the CuMgAl-III sample could be the reason for the dominance of $\gamma$-Al$_2$O$_3$ reflections. It is also well known that Al$_2$O$_3$ is present in the $\gamma$ phase structure at a relatively low temperature. The presence of MgO could suppress the formation of well-crystalline Al$_2$O$_3$ phase, which could be attributed to the more dominant appearance of the periclase structure than the amorphous-like structure of Al$_2$O$_3$ at 500 °C.

2.3. Morphology Studies by Scanning Electron Microscopy (SEM) and High-Resolution Transmission Electron Microscopy (HRTEM). The SEM images for the dried Cu-LDH precursors and calcined CuMgAl ternary oxide samples are shown in Figures S1 and S2, respectively. The SEM images of the LDH precursor samples clearly reveal that the LDH precursor materials form platelike agglomerated particles. The morphology of the LDH material was changed with an increase of Cu content or a decrease of the Mg content in LDH precursors. Most of the particles in the CuMgAl-III sample lost the best-defined platelet structure, and the platelet size decreased upon an increase of Cu inclusion. The calcined CuMgAl-I sample is composed of aggregated nanoparticles with undefined spongelike morphology. The morphology of the CuMgAl-II sample is very similar to that of the CuMgAl-I sample; however, relatively large particles were formed in this sample. In contrast, the CuMgAl-III sample shows individual isolated near-spherical-shaped aggregated particles with a larger size (approximately 2 μm) than in the other two samples. It is known that the decarbonation process that takes

Figure 2. HRTEM images of calcined CuMgAl samples.

Figure 3. (A) N$_2$ adsorption–desorption isotherms and (B) pore size distribution patterns of ternary CuMgAl oxide samples.
place during the calcination of the hydrotalcite samples is an exothermic process.\textsuperscript{26}

The destruction of the LDH layer structure to form Mg–Al oxides and the expulsion of copper oxide particles precipitated within the layered structure resulted in the formation of macropores. The growth of large particles of the CuLDH-III sample, which in turn resulted in the highly crystalline CuO phase after calcination is majorly due to high copper loading. These results are in accordance with the XRD data. The EDX profiles of the CuMgAl catalysts are also included in the Supporting Information of the revised manuscript. The chemical compositions are shown in Table S1, and the CuMgAl-III sample has the highest Cu content compared to the other two samples, as anticipated.

The HRTEM images of the CuMgAl-I and CuMgAl-II samples (Figure 2) are composed of small irregular sheets of Mg/Al/Cu oxides, which could be beneficial for a high exposure of active Cu\textsuperscript{2+} sites. The two samples with sheetlike morphology have size ranging from 10.5 to 24.5 nm. Large sheet particles are likely due to Mg–Al–O, whereas smaller particles are CuO. In the HRTEM image of the CuMgAl-II sample, several small-size CuO nanoparticles are clearly visible, while large sheets of MgO disappeared. The images clearly exhibit that lattice fringes correspond to the “d” spacing of MgO and CuO. The HRTEM images of CuMgAl-I and CuMgAl-II samples exhibited particles with lattice fringes by a distance of 0.243 nm, which could be attributed to the (111) plane of the cubic MgO phase. The lattice fringes of CuO particles, which could be confirmed by the high crystalline nature with a d-spacing of 0.254 nm, belong to the lattice plane of (111).\textsuperscript{27} The particle size distribution of CuO particles in the CuMgAl-III sample (Figure S3) was calculated from the HRTEM results, and the average particle size is about 13–15 nm.

2.4. \textit{N}_2 \textbf{Physisorption Studies.} The \textit{N}_2 adsorption–desorption isotherms obtained at −196 °C for all of the calcined samples are shown in Figure 3A. The CuMgAl-I sample exhibited type-IV isotherm with H4 hysteresis loop, which is characteristic of the presence of slitlike mesopores.\textsuperscript{28} The CuMgAl-II and CuMgAl-III samples show type-II isotherms with a clear H3 hysteresis loop according to the IUPAC classification.\textsuperscript{29}

The H3 hysteresis loops exhibited a delayed condensation in the adsorption branch of the isotherm and showed no limiting adsorption at high P/P\textsubscript{0} values. The hysteresis loops differ depending on the extent of Cu/Mg substitution in the layered hydrotalcite sheets. The hysteresis loop of the CuMgAl-II sample, with Cu/Mg ∝ 2 is narrower than that of the CuMgAl-I sample, with Cu/Mg ∝ 1, which indicates the possible precipitation of crystalline copper oxide particles with a different surface area and pore structure. The pore size distribution patterns for calcined CuMgAl ternary oxide samples were obtained from the adsorption branch of the isotherms by using the nonlocal density functional theory (NLDF) method (Figure 3B). A multimodal distribution in the micro-, meso-, and macrosizes was observed for CuMgAl-II and CuMgAl-III samples, whereas a bimodal distribution in the micro- and mesosizes is detected for the CuMgAl-I sample. The changes in the pore size distribution could be attributed to the different crystalline phases with different sizes.

The results from \textit{N}_2 adsorption–desorption measurements are consistent with SEM images (Figure S2). Table 2 shows the BET surface areas (S\textsubscript{BET}), total pore volumes (V\textsubscript{p}), and average pore sizes for all of the calcined samples. The CuMgAl-I sample has a higher surface area and pore volume (78 m\textsuperscript{2} g\textsuperscript{-1} and 0.210 cm\textsuperscript{3} g\textsuperscript{-1}) than the CuMgAl-II (70 m\textsuperscript{2} g\textsuperscript{-1} and 0.194 cm\textsuperscript{3} g\textsuperscript{-1}) and CuMgAl-III (20 m\textsuperscript{2} g\textsuperscript{-1} and 0.153 cm\textsuperscript{3} g\textsuperscript{-1}) samples. The notable decrease in the surface area with increasing copper concentration is linked to an increase in the particle sizes of the materials, as demonstrated by XRD and SEM analyses.

2.5. \textbf{X-ray Photoelectron Spectroscopy (XPS).} To gain insight into the location and nature of the Cu, Mg, Al, and O species present in CuMgAl samples, XPS studies were performed. The deconvoluted XPS spectra of the Cu 2p, Mg 2p, Al 2p, and O 1s core levels are shown in Figure 4A–D. The deconvoluted Cu 2p\textsubscript{3/2} X-ray photoelectron spectra for the CuMgAl-I, CuMgAl-II, and CuMgAl-III samples are shown in Figure 4A. The Cu 2p\textsubscript{3/2} peak position in the range of 933.5–933.9 eV and shape of the Cu 2p\textsubscript{3/2} spectral lines are consistent with the presence of Cu\textsuperscript{II} in the form of CuO phase.\textsuperscript{30–32} The assignment of binding energy is also corroborated by the presence of the satellite signals at 942.2 and 943.9 eV, which are characteristic of Cu\textsuperscript{II} species. The CuLMM Auger spectra for CuMgAl ternary oxide samples are shown in Figure S4. A minor difference was observed in the kinetic energy maximum of CuLMM Auger photoelectron spectra of the samples. The CuMgAl-I sample showed a kinetic energy maximum at 917.3 eV, and an increase in the Cu content resulted in an increase of the kinetic energy (CuMgAl-II: 917.5 eV, CuMgAl-III: 917.9 eV). Diaz-Drozgutt et al.\textsuperscript{33} reported that Cu\textsuperscript{II} species have a kinetic energy of the Auger transition at ca. 917–918 eV. These observations indicate that the three samples possessed Cu\textsuperscript{II} species, and the shift in kinetic energy maximum is most likely due to the difference in interaction between the CuO and other oxides.

The binding energy of the Mg 2p peak (Figure 4B) appeared around 49.3 eV for both CuMgAl-I and CuMgAl-II samples; the positions of the peaks are in accordance with the peak of XPS for Mg\textsuperscript{2+} in MgO phase. Similarly, the samples exhibited three different XP peaks of Al 2p at 73.2, 75.7, and 78.4 eV corresponding to the species in the Al\textsuperscript{3+} oxidation state. The observed results confirm that the Cu, Mg, and Al atoms are in bonding with oxygen atoms as they remained clustered during the thermal treatment, and these oxides might exist in the amorphous state or very small crystallites. The existence of a combination between Mg, Al, and Cu and oxygen atoms is also proved by the O 1s spectra shown in Figure 4D. The O 1s spectra of the samples showed two peaks; the peak at 530.4 eV could be attributed to the lattice oxygen of Mg–O, Cu–O, and Al–O species,\textsuperscript{34} while the second peak at 531.8 eV could be associated with the oxygen-adsorbed species, surface hydroxyl, or adsorbed water molecules.\textsuperscript{35} The ratio of the two peak intensities indicates that an increase of the Cu content in LDH resulted in an increase of more surface oxygen-adsorbed species. The decline in the intensity of the peaks of XPS

| Table 2. BET Surface Areas, Total Pore Volume, and Pore Sizes Derived from the N\textsubscript{2} Physisorption Data of the CuMgAl Samples |
|-----------------|-----------------|-----------------|
| sample          | S\textsubscript{BET} (m\textsuperscript{2} g\textsuperscript{-1}) | pore volume (cm\textsuperscript{3} g\textsuperscript{-1}) | half pore width (Å) |
| CuMgAl-I         | 78              | 0.210           | 16               |
| CuMgAl-II        | 70              | 0.194           | 14               |
| CuMgAl-III       | 20              | 0.153           | 19               |
detected with an increase of the Cu content (principally Mg 2p and O 1s) indicates the greater homogeneity of Cu species on the surface. The bulk atomic composition of materials (based on the precursor amounts) is in accordance with the surface atomic composition (Supporting Information Table S1).

2.6. Fourier Transform Infrared (FT-IR) Spectroscopy.
FT-IR spectroscopy was used further as a tool to investigate the structural feature of the synthesized CuO/MgAlO\textsubscript{x} catalysts (Figure 5). A broad band at 3420 cm\textsuperscript{-1} could be attributed to the O–H vibration of the structural –OH groups. It is interesting to observe a band at 1358 cm\textsuperscript{-1}, with a shoulder at 1530 cm\textsuperscript{-1}, due to the presence of [CO\textsubscript{3}]\textsuperscript{2–} species.\textsuperscript{36} The FT-IR bands in the 500–1000 cm\textsuperscript{-1} region could be assigned to M–O and M–OH species. It was reported that vibrations due to Cu–O appears around 530 and 590 cm\textsuperscript{-1}.\textsuperscript{37} And Cu–OH species show bands at 469 and 720 cm\textsuperscript{-1}.\textsuperscript{38} Hsu and Nacu reported a wide, strong absorption band at 430 cm\textsuperscript{-1} for the stretching vibration of Mg–O.\textsuperscript{39} It is interesting to note the $\gamma$-Al\textsubscript{2}O\textsubscript{3} phase yields IR absorption bands around 759, 630, 652, 617, 554, and 465 cm\textsuperscript{-1}.\textsuperscript{40} From all of these observations, it is possible to argue that the FT-IR bands observed at 850, 780, 630, and 430 cm\textsuperscript{-1} in the samples are due to lattice vibrations involving the Mg\textsuperscript{2+}, Cu\textsuperscript{2+}, and Al\textsuperscript{3+} cations. It is interesting to note that the intensity of the observed bands is strikingly high in the case of the CuMgAl-I sample compared to other two samples. An increase in the IR peak intensity is usually related to an increase in the amount (per unit volume) of the functional group associated with the molecular bond. A change in intensity could also be due to some changes corresponding to the sample composition related to the bonds, phase, crystallinity, etc. The synthesized samples clearly possessed different phases with different elemental compositions and sizes of the particles. The CuMgAl-I sample majorly contained nanosized crystalline MgO and CuO phases. This could be the major reason for the appearance of high-intense FT-IR bands corresponding to the M–O and M–OH species in this sample.
The deconvoluted CO$_2$ desorption profiles for the CuMgAl-I, CuMgAl-II, and CuMgAl-III samples are shown in Figure 6. It is generally accepted that weakly basic sites are correlated with OH structural groups (Bronsted basic sites), moderate basic sites are attributed to the metal-oxygen pairs in Mg–O (Lewis basic sites), and strong basic sites are associated with low-coordination oxygen atoms. The total number of basic sites, which are ascribed to the presence of –OH and Mg–O groups, decreased monotonically as the Cu content increased (FT-IR spectra). As shown in Figure 6, the CuMgAl-II sample exhibited three desorption peaks corresponding to weak, medium, and strong basic sites. The CuMgAl-II sample showed two peaks attributed to weak and strong basic sites. In contrast, relatively small desorption peaks centered at 150 and 200 °C (due to weak basic sites) were observed in the case of the CuMgAl-III sample. The quantitative data from the TPD-CO$_2$ experiments were obtained to understand the amount of basic sites. It is known that the presence of MgO increases the quantity of the basic sites, especially the medium-strength basic sites. The CuMgAl-III sample possessed less number of basic sites (86.3 mmol g$^{-1}$) compared to CuMgAl-II (220.5 mmol g$^{-1}$) and CuMgAl-I (292 mmol g$^{-1}$). The high surface area, presence of plenty of copper oxide species, and increase in the basicity in the CuMgAl-I catalyst could offer better catalyst activity in the Henry reaction.

2.8. Activity of Catalysts in the Henry Reaction. The Henry reaction is a base-catalyzed C=O bond-forming reaction between nitroalkanes and aldehydes or ketones (Scheme 1);

![Figure 6. CO$_2$-TPD profiles of the CuMgAl-I, CuMgAl-II, and CuMgAl-III samples.](https://dx.doi.org/10.1021/acsomega.9b04212)

The structure of the product 3a was elucidated by spectroscopic and analytical methods. The IR spectrum of 3a shows a band at 3447.02 cm$^{-1}$, which is a characteristic band for the alcoholic OH group, and two bands at 1514.35 and 1339.51 cm$^{-1}$ attributed to the presence of the NO$_2$ group. Additionally, the signals of the aromatic protons appear in the aromatic region of the spectrum. The $^{13}$C NMR spectrum shows two aliphatic saturated carbon atoms at 61.78 and 26.91 ppm, respectively. The results obtained from the catalytic test reactions are presented in Table 3. The performances of all the catalysts were studied by monitoring the formation of the product 3a. The target product was formed with 100% conversion of reactants in the case of CuMgAl catalysts; however, the yield of the catalysts differed considerably (Table 3).

The data in Table 3 show that all of the CuMgAl catalysts offered acceptable yields of the product. Among the bulk oxides, MgO exhibited considerable yield, but other two oxides CuO and γ-Al$_2$O$_3$ have not shown any conversion under studied reaction conditions. The ultrasonic-assisted catalytic reactions were completed in shorter reaction times with higher yields of the product compared to the reactions carried out by the conventional heating method. A discrepancy in the catalytic performance of the catalysts existed as CuMgAl-I required only 30 min to obtain 86% yield, whereas CuMgAl-II and CuMgAl-III needed 45 and 65 min to obtain 75 and 71%, respectively, under conventional heating. The CuMgAl-I catalyst offered a high turnover frequency in the Henry reaction due to the presence of more basic sites. However, under ultrasonic irradiation, the difference in activity between CuMgAl-I and CuMgAl-II is small, which is probably due to the fact that these two samples possessed majorly CuO and MgO phases. The synergy between the copper species and surface Lewis basic sites derived from MgO presented in the samples is responsible for the nucleophilic activity at the oxygen atom. In addition, the physical phenomenon known as acoustic cavitation at the solid–liquid interface under ultrasonic irradiation is suggested to enhance the activity of a catalyst. This effect might be equally contributing to improve the activity of both CuMgAl-I and CuMgAl-II catalysts in the Henry reaction. It was suggested that the microjet impact and shock wave damage at the surface of a solid (catalyst), along with the shock wave associated with the...
cavitation collapse, cause localized deformation and surface erosion, which increases the size of the possible reaction area.\textsuperscript{44} It is noteworthy that the intensity of cavitation depends on the type of solvent and frequency of ultrasonic waves used for the reaction. Therefore, the solvent used to perform the ultrasonic-assisted reaction must be carefully chosen. As a general rule, most reactions are performed in water; however, in this methodology, nitromethane was used as a solvent. It was found that nitromethane has a slightly high vapor pressure than water\textsuperscript{45} and cavitation is more difficult with a low-vapor-pressure liquid.

Recent advances in green chemistry principles drive chemists to strive to achieve maximum yield and also design a methodology that maximizes the incorporation of atoms of the reactants into the desired product (atom economy) to make reactions greener. In this context, the determination of the atom economy is important. The atom economies for the investigated catalysts in the Henry reaction were calculated by eq 1:\textsuperscript{46}

\[
\text{atom economy} = \frac{\text{mass of atoms of the desired product}}{\text{mass of atoms of the reactants}} \times 100
\]

It was observed that the atom economy for the reaction with CuMgAl-I (i.e., under the best conditions) to give compound 3a is 100\%. CuMgAl-I is the most efficient catalyst for the synthesis of 2-nitro-1-(4-nitrophenyl) ethanol (3a) because it offered the highest yields (99 and 86\%) in the shortest reaction times under both ultrasonic and conventional methods, respectively. Therefore, CuMgAl-I was selected to explore the substrate scope of the Henry reaction under ultrasound irradiation conditions; the results are summarized in Table 4.

The structures of the isolated products 3a–j were elucidated by IR, \(^1\)H, and \(^{13}\)C NMR spectroscopy techniques. The IR spectra show a characteristic band for the OH groups of the products 3a–j. It is clear from the data in Tables 3 and 4 that the CuMgAl-I catalyst displays efficient activity in all of the reactions, giving high yields in short reaction times (1–14 min). Furthermore, only one isolable alcohol product was synthesized using the CuMgAl-I catalyst in the reactions between nitromethane and various aldehyde derivatives.

The CuMgAl-I catalyst represents a mixture of nanosized CuO and MgO phases, as evidenced by the PXRD patterns. In addition, \(\gamma\)-Al\(_2\)O\(_3\) is usually formed in an amorphous phase in the presence of CuO at a low calcination temperature of around 500°C.\textsuperscript{14} The CuMgAl-I catalyst possessed a large surface area and pore volume compared to the other two synthesized catalysts (CuMgAl-II and CuMgAl-III). It is known that textural properties such as surface area and pore size have a significant impact on the catalyst performance. Results from \(\text{N}_2\) physisorption measurements of samples indicated that a multimodal distribution in the micro-, meso-, and macropores was presented in CuMgAl-II and CuMgAl-III samples, whereas a bimodal distribution in the micro- and mesopores is detected for the CuMgAl-I sample. It was also known that smaller or larger pores are not suitable for the catalysis, as larger pores could cause the formation of larger CuO crystallite and decrease its dispersion. The smaller pore size in the catalysts could cause diffusional limitations. Due to the moderate particle size and pore size, CuMgAl-I could offer better performance. The superior catalytic activity of the CuMgAl-I sample could be attributed to the combination of synergistic effects between the physicochemical properties of the catalysts and ultrasonic irradiation. It is also well known that the presence of MgO and \(\text{–OH}\) groups in the catalysts is responsible for the Lewis and Brønsted basic sites, respectively.\textsuperscript{47} The nitro-\(\)aldol reaction (Henry reaction) is usually carried out by adding small amounts of bases such as
ionic bases, alkali-metal hydroxides, alkoxides, carbonates, and sources of fluoride anion (e.g., TBAF) or nonionic organic amine. It was previously reported that the type of the base and solvent used do not have a significant effect on the overall result of the reaction. However, the presence of a strong alkali such as aqueous NaOH could lead to the dehydration of the nitro alcohol products to give nitroalkenes.

In the present system, MgO acts as a base and γ-Al₂O₃ acts as a moderate acidic site due to the Al³⁺ cation, and the Cu²⁺ species are widely accepted as an active species in the Henry reaction. Therefore, the dehydration of the nitro alcohol products could be ruled out in the studied methodology and the catalytic selectivity toward alcohol formation is directly related to the dispersed copper sites. The synergy between the copper species and surface Lewis basic sites derived from MgO presented in the samples led to the nucleophilic activity at the oxygen atom, thus improving the activity for the Henry reaction. The TON and TOF values were calculated and are presented in Table 5. Remarkably, high TON and TOF values were achieved with a small amount of copper in the CuMgAl-I catalyst. On the basis of the observed catalytic activity results, the synthesized CuMgAl-I catalyst can be considered to be a suitable efficient catalyst for the selective synthesis of nitro alcohol.

### Table 5. Henry Reaction Products Obtained from Different Aldehydes and Nitromethane Using CuMgAl-I Catalyst under Ultrasonic Irradiation

| Compound | Reactants | Henry Product Structure | Yield | Time | TON | TOF |
|----------|-----------|-------------------------|-------|------|-----|-----|
| 3a       | 1,2a      | ![Structure](image)      | 99%   | 1    | 12694 | 212 |
| 3b       | 1,2b      | ![Structure](image)      | 99%   | 1    | 12694 | 212 |
| 3c       | 1,2c      | ![Structure](image)      | 99%   | 1    | 12694 | 212 |
| 3d       | 1,2d      | ![Structure](image)      | 99%   | 3    | 12694 | 71  |
| 3e       | 1,2e      | ![Structure](image)      | 95%   | 7    | 12195 | 29  |
| 3f       | 1,2f      | ![Structure](image)      | 82%   | 3    | 10526 | 58  |
| 3g       | 1,2g      | ![Structure](image)      | 96%   | 1    | 12323 | 205 |
| 3h       | 1,2h      | ![Structure](image)      | 95%   | 14   | 12195 | 15  |
| 3i       | 1,2i      | ![Structure](image)      | 82%   | 7    | 10526 | 25  |
| 3j       | 1,2j      | ![Structure](image)      | 89%   | 3    | 11424 | 63  |

Figure 7. Recycling of the CuMgAl-I catalyst in the reaction between 1 and 2c.

Figure S5. HRTEM analysis of the spent CuMgAl-I catalyst showing the presence of agglomerated particles with very few lattice fringes, indicating that the ultrasonic waves caused the localized deformation and surface erosion resulted in an increased available interface for the reactions. Therefore, the HRTEM analysis of the spent catalyst provided an evidence for enhanced TOFs in the Henry reaction.

2.8.1. Recycling of the Catalyst. It was vitally important to study the stability of the CuMgAl-I catalyst under ultrasound conditions. Therefore, the reaction between 1 and 2c was repeated six times using a recovered catalyst. To recover the solid catalyst, it was filtered and washed with acetone after each catalytic cycle and then dried in vacuum before reuse. The catalytic activity was monitored for each reaction, and the results are presented in Figure 7. The results show that there was no apparent decline in the catalytic activity even after six runs, with the yields obtained in the recyclability test being within experimental error.

As described previously, the superior catalyst performance under ultrasound irradiation may be due to the microjet impact and shock wave damage occurring on the catalyst surface. The HRTEM analysis is used to study the effect of ultrasonic irradiation on the catalyst surface. The HRTEM image (Figure S5) of the spent CuMgAl-I sample shows the presence of agglomerated particles with very few lattice fringes, indicating that the ultrasonic waves caused the localized deformation and surface erosion resulted in an increased available interface for the reactions. Therefore, the HRTEM analysis of the spent catalyst provided an evidence for enhanced TOFs in the Henry reaction.
Based on the observed catalyst activity and characterization results, it is necessary to develop a proposed mechanism for this reaction utilizing CuMgAl-I, CuMgAl-II, and CuMgAl-III catalysts. From the FT-IR and CO₂-TPD results, it is clear that CuMgAl-I and CuMgAl-II catalysts possess Lewis basic sites as well as OH-Brønsted basic sites, while the CuMgAl-III catalyst does not possess any basic sites. Therefore, a plausible mechanism for the Henry reaction over synthesized CuMgAl catalysts was suggested mainly on the copper active sites and Lewis base centers, as presented in Figure 8. Initially, the nitromethane molecule is coordinated to the active Cu center on the surface of catalyst forming an intermediate. The hydrogen abstraction from the intermediate by the Lewis base sites yields the nitronate ion, and the nucleophilic carbon atom of the nitronate ion attacks the carbon of the carbonyl group in the aldehyde molecule to form β-nitro-alkoxide, as shown in Figure 8. Finally, the protonation of β-nitro-alkoxide affords β-nitro alcohol and catalyst, which are used for the next cycle.

3. CONCLUSIONS

The green reaction protocol described herein offers a rapid, atom-economic, and safe alternative to other methods for the Henry reaction to synthesize the nitro alcohol derivatives using the heterogeneous recyclable CuMgAl ternary oxide catalysts under ultrasonic irradiation. The CuMgAl ternary oxide catalysts were derived by the thermal decomposition of Cu:Mg:Al hydrotalcites with different Cu, Mg, and Al atomic ratios. The reactions were proceeded under mild reaction conditions and offered the products in excellent yields with 100% atom economy. The excellent catalytic activity could be attributed to the synergistic effect between the CuMgAl catalysts and ultrasonic irradiation. This remarkable synergistic effect between the ultrasound irradiation and the catalyst in the Henry reaction protocol was established according to the results obtained from HRTEM analysis of the used catalyst sample. The analysis showed that the presence of agglomerated particles with the cavitation collapse causes localized deformation and surface erosion enables an increase in the solid/liquid interface for the organic reactions. Other advantages of the present reaction protocol include simple separation and purification procedures. The excellent catalytic performance of the CuMgAl-I (Cu/Mg/Al = 1:1:1) catalyst is due to the combined effects of nanosized crystallites with a large surface area, mesoporosity, and superior basic properties, which provide a durable sustainable catalyst that can be reused over a long period of time.

4. EXPERIMENTAL SECTION

4.1. Reagents. The following chemical reagents were used for the synthesis of the catalysts: aluminum nitrate non-hydrate, magnesium nitrate hexahydrate, sodium carbonate, and sodium hydroxide (all from Sigma-Aldrich Laborchemikalien GmbH, Seelze, Germany), copper(II) nitrate trihydrate (Fluka AG, Chemische Fabrik, CH-9470 Buchs, Switzerland), and distilled/deionized water. The following chemical reagents were used for the Henry reaction: nitromethane, p-nitrobenzaldehyde (all from BDH Limited, Poole, England), m-nitrobenzaldehyde (Koch Light Research Laboratories, Gauteng, South Africa), o-nitrobenzaldehyde, p-bromo benaldehyde, 4-dimethylaminobenzaldehyde, 5-bromo-3-nitrosalicylaldehyde, vanillin, 3,5-dimethoxy benzaldehyde, 3,5-dibromobenzaldehyde, and 4-methoxybenzaldehyde (all from Sigma-Aldrich Laborchemikalien GmbH, Seelze, Germany).

4.2. Synthesis of the Cu-LDHs. The copper/magnesium/aluminum layered double hydroxides (Cu-LDHs) were prepared by the co-precipitation method. Two solutions, namely, solution A, containing the calculated amounts of metal (Cu, Mg, and Al) nitrates, and solution B, containing the
precipitating agents NaOH and Na₂CO₃ were added slowly and simultaneously by a peristatic pump to a flask containing distilled water at 50 °C to maintain the constant pH value (at around 10 ± 0.1). The total contents were stirred by using an overhead stirrer to ensure rapid and efficient mixing to obtain the precipitate. The obtained precipitate was filtered through Whatmann5 filter paper, and the resulted cake was washed with distilled water until the residual solution pH became neutral. The cake was then dried in an electric oven at 80 °C for 12 h. The theoretical Cu/Mg/Al ratios of the synthesized CuLDH materials are 1:1:1, 1:5:0:5:1, and 2:0:1 for Cu-LDH-I, Cu-LDH-II, and Cu-LDH-III, respectively.

4.3. Synthesis of CuMgAl Catalysts. The as-synthesized Cu-LDH materials were calcined in a muffle furnace in a flow of air at 500 °C for 8 h to obtain CuMgAl catalysts. The solids obtained from Cu-LDH-I, Cu-LDH-II, and Cu-LDH-III were labeled as CuMgAl-I, CuMgAl-II, and CuMgAl-III, respectively.

4.4. Catalyst Characterization Methods. The chemical composition of the samples was determined using Optima 4300 DV, PerkinElmer ICP-optical emission spectrometer. Powder X-ray diffraction (PXRD) studies were performed on all of the prepared solid samples by using a Bruker diffractometer (Bruker D8 advance target). The PXRD patterns were recorded with monochromatized Cu Kα irradiation (λ = 1.5405 Å) at 40 kV and 40 mA. The different crystalline phases in each of the samples were identified by comparing the data with those compiled by the Joint Committee for Powder Diffraction Standards (JCPDS). The sizes of the crystalline phases were calculated using the Scherrer equation: $D = \frac{K \lambda}{\beta \cos \theta}$, where “D” is the average crystallite size of the phase under investigation, “K” is the Scherrer constant (0.89), “λ” is the wavelength of the X-ray beam used (1.5405 Å), “β” is the full width at half-maximum (FWHM) of the diffraction peak, and “θ” is the diffraction angle.

The X-ray photoelectron spectroscopy (XPS) measurements were carried out by using an X-ray photoelectron spectrometer (SPECS GmbH, Berlin, Germany). Prior to the analysis, the samples were degassed under vacuum inside the load lock for 16 h. The binding energy of the adventitious carbon (C 1s) line at 284.6 eV was used for calibration, and the positions of the other peaks were corrected according to the position of the C 1s signal. For the measurements of high-resolution spectra, the analyzer was set to the large-area lens mode with energy steps of 25 meV and in the Fixed Analyzer Transmission (FAT) mode with a pass energy of 34 eV and dwell time of 100 ms.

A JEOL JSM840A scanning electron microscope and an FEI Tecnai F30 high-resolution transmission electron microscope were used to investigate the morphological characteristics of the solid samples. Prior to each measurement, the sample was placed on an aluminum block using carbon tape. The FT-IR spectra of the samples were obtained using a Bruker a-II FT-IR spectrometer. The CO₂-TPD analysis was performed using a CHEMBET-3000 instrument (Quantachrome). The samples were outgassed at 100 °C (1 h) by flowing helium gas over the sample. Then, the sample was saturated with CO₂ at 120 °C for 30 min. Subsequently, the sample was treated with helium gas to remove the physisorbed CO₂ gas. Finally, the TPD patterns of the samples were collected by ramping the sample temperature to 800 °C at a heating rate of 10 °C min⁻¹. N₂ physisorption experiments were carried out at −196 °C using a NOVA 3200E automated gas sorption system (Quantachrome) to investigate the textural properties of the solids. Before every measurement, the adsorbent was pretreated at 150 °C for 6 h. The Brunauer–Emmett–Teller (BET) equation was applied to determine the specific surface areas, and the average pore radii were deduced from the equation $Vp/SA = 0.98$.

4.5. Typical Procedure for the Henry Reaction. 4.5.1. Conventional Method. A mixture of 4-nitrobenzaldehyde (0.5 g), nitromethane (3 mL), and catalyst (150 mg) was heated together in a two-necked, round-bottom flask at 90 °C. The progress of the reaction was monitored by TLC (elucent:diethyl ether/chloroform in 1:1). Upon completion of the reaction, the mixture was cooled and the product was extracted by dissolution in hot ethanol. The catalyst was removed by filtration and washed with alcohol prior to drying and reuse. After evaporation of the volatile materials under vacuum, compound 3a was recrystallized from EtOH/DMF.

4.5.2. Ultrasonic Method. A mixture of aldehyde 2a–j (3.3 mmol), nitromethane 1a (3 mL), and the catalyst (150 mg) was added to a three-neck, round-bottom flask, and the reaction mixture was subjected to ultrasound irradiation for the time required to complete the reaction (Table 1). All reactions were kept at 25–30 °C; the temperature was maintained by the addition and removal of water from the bath (the temperature inside the reaction vessel was 27 °C, and the reaction flask was placed in the middle of the ultrasonicator bath to achieve effective cavitation). The progress of the reaction was monitored by TLC (elucent:diethyl ether/chloroform in 1:1). Then, the product mixture was cooled and extracted with acetone. The catalyst was then removed by filtration, and the products were purified by crystallization from EtOH/DMF to afford the pure crude β-nitro-alcohols 3a–j in excellent yields.

4.6. Characterization of the Reaction Products. All melting points were determined by using a Barnstead International 1002 melting point apparatus and are uncorrected. TLC was performed on aluminum silica gel 60 F254 (E-Merck). The spots were detected by UV light absorption. The IR spectra were recorded with a Thermo-Nicolet-6700 FT-IR spectrophotometer. ¹H and ¹³C NMR spectra were recorded on a Bruker WM 400 spectrometer at 850 MHz in deuterated chloroform (CDCl₃) or dimethyl sulfoxide (DMSO-d₆) using tetramethylsilane (TMS; 0.00 ppm) as internal standard. Chemical shifts (δ) are given in ppm relative to the signal for TMS as a standard, and coupling constants are given in hertz. The reactions performed under ultrasound irradiation were carried out in a Daihan (Wiseclean, 40–50 MHz) ultrasonic bath.

4.7. Physical and Spectral Data of the Titled Compounds. 3a–k. 2-Nitro-1-(4-nitrophenyl)ethan-1-ol (3a). Mp 83–86 °C. FTIR: $\nu_{\text{max}}$/cm⁻¹ 3447 (OH), 3114 (C–H), 1514–1339 (NO₂). ¹H NMR (850 MHz, CDCl₃): δH 8.29, 8.28 (2H, 2 d, Ar-H), 7.65, 7.64 (2H, 2 d, Ar-H), 6.65 (1H, br. s, –OH), 4.85 (1H, dd, 2-H), 4.60 (1H, dd, 2-H), 4.48 (1H, dd, 1-H). ¹³C NMR (850 MHz, CDCl₃): δC 148.18, 144.95, 128.72, 127.01, 124.27, 69.98.

2-Nitro-1-(3-nitrophenyl)ethan-1-ol (3b). Mp 59 °C. FTIR: $\nu_{\text{max}}$/cm⁻¹ 3517 (OH), 3080 (C–H), 1527 (NO₂). ¹H NMR (850 MHz, CDCl₃): δH 8.70 (1H, s, Ar-H), 8.48 (1H, d, Ar-H), 8.23 (1H, d, Ar-H), 7.89 (1H, t, Ar-H), 6.62.
1-(3,5-Dibromophenyl)-2-nitroethan-1-ol (3c). Mp 60 °C. FTIR: ν max/cm⁻¹ 3478 (OH), 3107 (C–H), 1511 (NO₂). ¹H NMR (850 MHz, CDCl₃): δ H 7.56 (2H, d, Ar-H), 6.03 (1H, br. s, OH), 4.86 (1H, dd, 2-H), 4.56 (1H, dd, 2-H), 4.47 (1H, d, 1-H). ¹³C NMR (850 MHz, CDCl₃): δ C 135.56, 134.76, 130.12, 128.96, 126.18, 125.01, 66.90.

1-(3-(Dibromophenyl)-2-nitroethan-1-ol (3d). Mp > 300 °C. FTIR: ν max/cm⁻¹ 3202 (OH), 3073 (C–H), 1548–1578 (NO₂), 684 (C–Br). ¹H NMR (850 MHz, CDCl₃): δ H 4.10 (1H, br. s, –OH), 8.49 (1H, Ar-H), 8.28 (1H, d, Ar-H), 7.28 (1H, br. s, –OH), 4.83 (1H, dd, 2-H), 4.52 (1H, dd, 2-H), 4.35 (1H, d, 1-H). ¹³C NMR (850 MHz, CDCl₃): δ C 150.18, 139.45, 138.06, 128.01, 127.40, 126.82, 111.87, 65.40.

1-(4-Dimethylamino)phenyl-2-nitroethan-1-ol (3f). Mp 70–72 °C. FTIR: ν max/cm⁻¹ 3317 (OH), 3048 (C–H), 1589–1568 (NO₂), 1125 (C–N). ¹H NMR (850 MHz, CDCl₃): δ H 7.26 (2H, d, Ar-H), 6.73 (2H, d, Ar-H), 5.39 (1H, br. s, OH), 4.75 (1H, dd, 2-H), 4.65 (1H, dd, 2-H), 4.50 (1H, dd, 1-H), 3.11 (6H, 2 s, –OCH₃). ¹³C NMR (850 MHz, CDCl₃): δ C 154.38, 131.50, 128.07, 125.14, 115.02, 71.11, 40.10, 40.08.

1-(4-Bromophenyl)-2-nitroethan-1-ol (3g). Mp 41 °C. FTIR: ν max/cm⁻¹ 3530 (OH), 3044 (C–H), 1548–1534 (NO₂), 660 (C–H). ¹H NMR (850 MHz, CDCl₃): δ H 7.57, 7.56 (2H, d, Ar-H), 7.31, 7.30 (2H, d, Ar-H), 5.44 (1H, br. s, –OH), 4.78 (1H, dd, 2-H), 4.59 (1H, dd, 2-H), 4.51 (1H, dd, 1-H). ¹³C NMR (850 MHz, CDCl₃): δ C 137.07, 132.48, 131.03, 129.08, 127.65, 123.09, 70.36.

1-(4-Methoxyphenyl)-2-nitroethan-1-ol (3h). Mp > 300 °C. FTIR: ν max/cm⁻¹ 3456 (OH), 3004 (C–H) 1550–1537 (C–O). ¹H NMR (850 MHz, CDCl₃): δ H 7.85, 7.84 (2H, d, Ar-H), 7.02, 7.01 (2H, d, Ar-H), 5.41 (1H, br. s, –OH), 4.77 (1H, dd, 2-H), 4.66 (1H, dd, 2-H), 4.50 (1H, dd, 1-H), 3.90 (3H, 1 s, –OCH₃). ¹³C NMR (850 MHz, CDCl₃): δ C 156.01, 132.05, 129.80, 127.31, 114.95, 67.78, 55.65.

1-(3,5-Dimethoxyphenyl)-2-nitroethan-1-ol (3i). Mp 86 °C. FTIR: ν max/cm⁻¹ 3504 (OH), 3081 (C–H), 1509–1398 (C–O). ¹H NMR (850 MHz, CDCl₃): δ H 7.68 (1H, br. s, Ar-H), 7.53 (2H, s, Ar-H), 5.41 (1H, br. s, OH), 4.77 (1H, dd, 2-H), 4.58 (1H, dd, 2-H), 4.54 (1H, dd, 1-H), 3.94, 3.97 (6H, 2 s, –OCH₃). ¹³C NMR (850 MHz, CDCl₃): δ C 154.50, 149.62, 130.11, 126.92, 111.27, 110.39, 108.93, 70.88, 56.19, 56.01.

4-(1-Hydroxy-2-nitroethyl)-2-methoxyphenol (3j). Mp 75 °C. FTIR: ν max/cm⁻¹ 3470–3181 (2 OH), 3030 (C–H), 1587–1373 (NO₂), 1150 (C–O). ¹H NMR (850 MHz, CDCl₃): δ H 9.85 (1H, br. s, –OH), 7.48, 7.44 (3H, d, Ar-H), 5.42 (1H, br. s, OH), 4.77 (1H, dd, 2-H), 4.63 (1H, dd, 2-H), 4.52 (1H, dd, 1-H), 3.99 (3H, s, –OCH₃). ¹³C NMR (850 MHz, CDCl₃): δ C 147.15, 146.97, 135.01, 127.58, 114.38, 108.76, 70.96, 56.41.

### ASSOCIATED CONTENT

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.9b04212.

SEM images of dried Cu-LDH samples (Figure S1); bulk and surface composition of the CuMgAl sample (Table S1); SEM and EDX profiles of CuMgAl samples (Figure S2); particle size distribution of CuMgAl-III samples (Figure S3); CuLMMA Auger spectra of the CuMgAl samples (Figure S4); and HRTEM images of used CuMgAl-I samples (Figure S5) (PDF)

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### Notes

The authors declare no competing financial interest.

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