Calcined Layered Double Hydroxides: Catalysts for Xanthene, 1,4-Dihydropyridine, and Polyhydroquinoline Derivative Synthesis

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ABSTRACT: This work is generally focused on the synthesis of NiFeTi-layered double hydroxides (LDHs) using a hydrothermal route, which were calcined at various temperatures (varying from 200 to 600 °C). The synthesized materials were physicochemically characterized. X-ray diffraction results revealed the loss of the layered structure on calcination resulting in the formation of layered double oxides (LDOs) or mixed metal oxides, which was also supported by Fourier transform infrared studies. Scanning electron microscopy results also show loss of the layered structure and the creation of LDOs on increasing the temperature. These LDOs were tested as the catalysts for the synthesis of biologically significant xanthene, 1,4-dihydropyridine, and polyhydroquinoline derivatives. Among all, NiFeTi LDH calcined at 600 °C proved to be the best catalyst for the synthesis of these derivative compounds under optimized conditions. The advantages obtained were excellent yields in a lesser reaction time. Stability and reusability were also assessed; the catalyst was stable even after five cycles. Furthermore, the memory effect of the obtained NiFeTi CLDH calcined at 600 °C confirms that the material so formed is a calcined state of LDH itself. High catalytic efficiency, easy fabrication, and recycling ability of NiFeTi CLDH calcined at 600 °C make it a potential catalyst for the synthesis of xanthene, 1,4-dihydropyridine, and polyhydroquinoline derivatives.

1. INTRODUCTION

Layered double hydroxides or LDHs (also named as hydrotalcite-like compounds) are anionic-clay materials. LDHs are made up of brucite-like layers comprising positive charge and intercalated anions (NO₃⁻, CO₃²⁻, SO₄²⁻, Cl⁻, etc.) and H₂O molecules. LDHs, so far, have been extensively represented by [M (M II + M III)]ₙ(OH)₂ (A⁻)ₓ/n·mH₂O, where M II represents divalent metallic cations (Mg²⁺, Cu²⁺, Fe²⁺, Ni²⁺, Ca²⁺, Co²⁺, Zn²⁺, etc.), M III (Fe³⁺, Al³⁺, Cr³⁺, Ga³⁺, etc.) and H₂O molecules. LDHs, so far, have been extensively employed in various fields, such as catalysis, adsorption, ion exchange, drug carriers, electrode materials, and anticorrosion agents. The general empirical formula of LDHs is represented by [M₁+x/ₙ]M₂-x/ₙ(OH)₂][A⁻]ₓ/n·mH₂O, where M II represents divalent metallic cations and M III represents trivalent metallic cations, x denotes the molar ratio (M II/(M II + M III)), and A represents the interlayered anions with n valency. To date, many different types of stacking arrangements have been designed, such as sheets stacked in hexagonal symmetry with two layers/unit cell (manasseite) and rhombohedral symmetry with three layers/unit cell (hydrotalcite) and in minor symmetrical stacking arrangements. The interlayer bonding in LDHs is relatively very weak, which makes them very efficient for capturing inorganic and organic anions. The properties of LDHs, which make them multifunctional materials, are their great ability for anion exchange, a high surface area, and a high thermal stability. Carbonate is the most common anion present in the interlayers of natural LDHs. However, a wide range of anions have been used for charge-balancing in various studies such as nitrates, oxyanions, halides, silicates, organic anions, complex anions, and polyoxometalate anions. Moreover, mixed metal oxides or layered double oxides (LDO) generated after thermally controlled calcination are efficient in showing large specific surface areas, high basic properties, greater adsorption capacity, elemental synergetic effects, thermal stability, and memory effects (ability to reconstruct their structure). Thus, nowadays, LDHs and their calcined form have attained significant attention.

Xanthene and its derivatives have become an important class of organic chemistry since last few decades because of their wide range of biological, pharmaceutical, and medicinal applicability such as antibacterial, antiviral, anti-inflammatory, antidepressants, antiplasmodial, and antimalarial agents. Furthermore, they have also been used as local dyes (examples: fluorescein, roamine, fluorescein, etc.), precursors for many useful organic compounds, in laser technologies, and for many useful organic compounds. The advantages obtained were excellent yields in a lesser reaction time. Stability and reusability were also assessed; the catalyst was stable even after five cycles. Furthermore, the memory effect of the obtained NiFeTi CLDH calcined at 600 °C confirms that the material so formed is a calcined state of LDH itself. High catalytic efficiency, easy fabrication, and recycling ability of NiFeTi CLDH calcined at 600 °C make it a potential catalyst for the synthesis of xanthene, 1,4-dihydropyridine, and polyhydroquinoline derivatives.

Received: April 25, 2020
Accepted: June 4, 2020
Published: June 16, 2020
(example-RO67-4853), pH-sensitive fluorescent materials for the visualization of biomolecules moieties, peptide synthesis, and antagonists for drug-resistant leukemia lines (Nguyen et al., 2009). Structures of some known xanthenes are depicted in Figure 1 with applications as fluorescent and dye materials (fluorone, rosamine, and fluorescein) and showing pharmacological activity (RO67-4853, rhodamine, and amsacrine). 1,4-Dihydropyridine (1,4-DHP) and polyhydroquinoline derivatives are also essential classes of organic chemistry significantly present in many synthetic drugs, biologically active natural products, and chemical intermediates.

To date, many methods have been employed for preparing many of these organic derivatives. Among all the methods, the simplest routes for synthesizing symmetrical and unsymmetrical xanthenes are the condensation of different aldehydes with cyclic 1,3-dicarbonyl compounds, β-naphthol, or with a 1:1 mixture of cyclic 1,3-dicarbonyl compounds and β-naphthol. So far, many catalysts are used for preparing various xanthenes, such as PVSA, nano-TiO₂, [Et₃NSO₃H]Cl, SbCl₅/SiO₂, core/shell Fe₃O₄@GA@isinglass, amberlyst-15, boric acid, and sulfamic acid. However, such catalysts suffer from various disadvantages such as low yields, extensive workup, harsh reaction conditions, toxic solvents, and use of excessive and expensive catalysts. Furthermore, only limited catalysts are capable of synthesizing different kinds of xanthenes. Therefore, it has become important to find an alternative route for an environment-friendly preparation of xanthenes derivatives. LDHs and calcined-LDHs (also named as LDOs) could be better alternatives for greener production of xanthenes, 1,4-DHP, and polyhydroquinoline derivatives because they can provide a large surface area as the catalytic support for catalyzing organic reactions. To the best of our knowledge, no such LDH or calcined LDH forms have been used so far for the preparation of these derivatives making this approach a novel one for such synthesis.

In this work, we have resynthesized a biocompatible NiFeTi LDH by using a hydrothermal method with urea as a template, which was previously used by our group for the water remediation. Because of the property of a high surface area; LDHs and calcined LDHs might act as the catalytic support for various organic transformations enhancing their applications in the heterogeneous catalysis field apart from their excellent efficiency for the water purification. Thus, we have calcined ternary LDHs at multiple temperatures. The obtained materials were characterized using different techniques such as X-ray diffraction (XRD), Fourier transform infrared (FTIR), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The so-obtained materials were tested for the one-pot synthesis of xanthenes, 1,4-DHP, and polyhydroquinoline derivatives for the very first time, under greener conditions.

2. RESULTS AND DISCUSSION

2.1. Characterization of NiFeTi CLDH6. The XRD patterns of regenerated NiFeTi LDH and its calcined forms are depicted in Figure 2. The XRD pattern of NiFeTi LDH was in a great correlation with that of the previously reported pure form of NiFeTi LDH. The XRD pattern of NiFeTi LDH (Figure 2a) shows sharp peaks at 10.63, 22.09, and 34.08° corresponding to the (003), (006), and (009) diffraction planes, respectively, which confirms the formation of CO₃²⁻-intercalated NiFeTi LDH. The obtained d-spacing for (003), (006), and (009) diffraction planes is 0.79, 0.39, and 0.26 nm, respectively. When calcination was carried out at 200 °C, the layered structure of the material starts collapsing, which can be
clearly understood from the illustration of the reduction of the peak intensity in the lower 2θ range (Figure 2a), because of the loss of water molecules from the material. When the calcination temperature was further increased (up to 600 °C), the complete destruction of the layered structure was observed, resulting in the formation of mixed metal oxides by the removal of all the intercalated carbonate ions and water molecules.30

High-resolution (HRTEM) images of NiFeTi CLDH6 depicted in Figure 3 show the existence of mixed metal oxide aggregates formed by the rupture of the layered structure of NiFeTi LDH.30 The obtained fringe widths of NiFeTi CLDH6 are 0.29 and 0.22 nm (depicted in Figure 3d). SEM images of NiFeTi CLDH1 to NiFeTi CLDH6 are depicted in Figure 4, which clearly show the distortion of the layered structure of LDH with the increase of temperature.

The FTIR spectra of the NiFeTi LDH and its calcined forms are illustrated in Figure 5. The FTIR spectrum of the NiFeTi LDH could be easily correlated with the previously synthesized NiFeTi LDH.7 The spectra of the NiFeTi LDH consist of a number of peaks around 3400 cm⁻¹, 1640 cm⁻¹, and 1380 cm⁻¹, which can be assigned to the stretching and bending vibrations of water molecules, CO₂, and carbonate ions, respectively. When the calcination temperature was increased, the intensity of these peaks decreased significantly, indicating the removal of water and carbonate ions from the material. Additionally, new peaks appeared around 1000 cm⁻¹ and 700 cm⁻¹, which can be assigned to the stretching and bending vibrations of metal-oxygen bonds in the mixed metal oxides.

Table 1. Optimization of Catalysts

| entry | catalyst | yield (%) |
|-------|----------|-----------|
| 1     | NiFeTi LDH | 60        |
| 2     | NiFeTi CLDH1 | 72       |
| 3     | NiFeTi CLDH2 | 78       |
| 4     | NiFeTi CLDH3 | 87       |
| 5     | NiFeTi CLDH4 | 89       |
| 6     | NiFeTi CLDH5 | 92       |
| 7     | NiFeTi CLDH6 | 96       |

“Reaction conditions—benzaldehyde/dimedone = 1:2 (mmol), solvent (ethanol) = 10 mL, the amount of catalyst = 30 mg, temperature = 80 °C, and time = 1 h.” Isolated yields.

Table 2. Optimization of Solvents

| entry | catalyst | solvent | temperature (°C) | time (min) | yield (%) |
|-------|----------|---------|------------------|------------|-----------|
| 1     | NiFeTi CLDH6 | acetonitrile | 85           | 60         | 65        |
| 2     | NiFeTi CLDH6 | methanol  | 70             | 60         | 76        |
| 3     | NiFeTi CLDH6 | water    | 100            | 60         | 30        |
| 4     | NiFeTi CLDH6 | ethanol  | 80             | 60         | 85        |

“Reaction conditions—benzaldehyde/dimedone = 1:2 (mmol), solvent = 10 mL.” Isolated yields.

Table 3. Optimization of Synthesis Conditions

| entry | catalyst | amount of catalyst (mg) | temperature (°C) | time (min) | yield (%) |
|-------|----------|-------------------------|------------------|------------|-----------|
| 1     | NiFeTi CLDH6 | 0           | 50             | 300        | 10        |
| 2     | NiFeTi CLDH6 | 5           | 50             | 60         | 40        |
| 3     | NiFeTi CLDH6 | 10          | 50             | 60         | 70        |
| 4     | NiFeTi CLDH6 | 20          | 50             | 60         | 85        |
| 5     | NiFeTi CLDH6 | 30          | 50             | 60         | 85        |
| 6     | NiFeTi CLDH6 | 20          | 25             | 90         | 50        |
| 7     | NiFeTi CLDH6 | 20          | 30             | 90         | 54        |
| 8     | NiFeTi CLDH6 | 20          | 40             | 90         | 59        |
| 9     | NiFeTi CLDH6 | 20          | 60             | 60         | 87        |
| 10    | NiFeTi CLDH6 | 20          | 60             | 70         | 60        |
| 11    | NiFeTi CLDH6 | 20          | 80             | 60         | 96        |

“Reaction conditions—benzaldehyde/dimedone = 1:2 (mmol), solvent (ethanol) = 10 mL.” Isolated yields.

High-resolution (HRTEM) images of NiFeTi CLDH6 depicted in Figure 3 show the existence of mixed metal oxide aggregates formed by the rupture of the layered structure of NiFeTi LDH.30 The obtained fringe widths of NiFeTi CLDH6 are 0.29 and 0.22 nm (depicted in Figure 3d). SEM images of NiFeTi CLDH1 to NiFeTi CLDH6 are depicted in Figure 4, which clearly show the distortion of the layered structure of LDH with the increase of temperature.

The FTIR spectra of the NiFeTi LDH and its calcined forms are illustrated in Figure 5. The FTIR spectrum of the NiFeTi LDH could be easily correlated with the previously synthesized NiFeTi LDH.7 The spectra of the NiFeTi LDH consist of a number of peaks around 3400 cm⁻¹, 1640 cm⁻¹, and 1380 cm⁻¹, which can be assigned to the stretching and bending vibrations of water molecules, CO₂, and carbonate ions, respectively. When the calcination temperature was increased, the intensity of these peaks decreased significantly, indicating the removal of water and carbonate ions from the material. Additionally, new peaks appeared around 1000 cm⁻¹ and 700 cm⁻¹, which can be assigned to the stretching and bending vibrations of metal-oxygen bonds in the mixed metal oxides.
broad band at 3423 cm\(^{-1}\) because of the interlayered OH group and H\(_2\)O molecules. Shoulders observed at 3241 and 2991 cm\(^{-1}\) could be assigned to the interaction (H-bonding) between the interlayered carbonate ions and the water molecules. Also, the presence of carbonate ions could be confirmed by the existence of an asymmetric band at 1363 cm\(^{-1}\). On calcination, the bands of the carbonate ions started diminishing with every temperature increase and finally disappeared in all the calcined forms above 300 °C because of the complete removal of all the intercalated carbonate ions. Shoulders observed at 1632 cm\(^{-1}\) might be attributed to the vibrational absorptions of reversibly sorbed water molecules on the oxide surfaces (illustrated in Figure 5).

2.2. Catalytic Activity of NiFeTi CLDH6.

The catalytic application of NiFeTi CLDH6 was investigated by synthesizing xanthene and 1,4-DHP derivatives. Preliminary, the best catalyst was selected from NiFeTi LDH and its calcined forms (NiFeTi CLDH1, NiFeTi CLDH2, NiFeTi CLDH3, NiFeTi CLDH4, NiFeTi CLDH5, and NiFeTi CLDH6) comparing the product yields (depicted in Table 1) acquired from the catalytic reaction between 1 mmol of benzaldehyde and 2 mmol of dimedone in 10 mL ethanol at 80 °C. Among all the catalysts, NiFeTi CLDH6, because of higher available active sites with temperature increase, showed the highest catalytic ability and was preferred for synthesis. Moreover, the best reaction conditions (ideal solvent, catalyst amount, and best temperature) were optimized by monitoring a model reaction between benzaldehyde and dimedone.

**Table 4. NiFeTi CLDH6-Catalyzed Synthesis of Xanthene Derivatives**

| product | R\(_1\) aldehyde   | time (min) | yield (%) |
|---------|-------------------|------------|-----------|
| 3a      | CH\(_3\) 4-nitrobenzaldehyde | 40         | 96        |
| 3b      | CH\(_3\) 2-nitrobenzaldehyde | 60         | 90        |
| 3c      | CH\(_3\) 3-nitrobenzaldehyde | 60         | 91        |
| 3d      | CH\(_3\) 2-bromobenzaldehyde | 60         | 89        |
| 3e      | CH\(_3\) 3-methoxybenzaldehyde | 80         | 88        |
| 3f      | CH\(_3\) 3-methylbenzaldehyde | 70         | 90        |
| 3g      | CH\(_3\) benzaldehyde         | 60         | 96        |
| 3h      | CH\(_3\) 4-methoxybenzaldehyde | 80         | 84        |
| 3i      | CH\(_3\) 3-Bromobenzaldehyde  | 50         | 90        |
| 3j      | CH\(_3\) 4-methylbenzaldehyde | 70         | 90        |
| 3k      | CH\(_3\) 4-cyanobenzaldehyde | 60         | 94        |
| 3l      | CH\(_3\) 3-chlorobenzaldehyde | 50         | 94        |
| 3m      | CH\(_3\) 4-chlorobenzaldehyde | 60         | 93        |
| 3n      | H benzaldehyde            | 60         | 95        |
| 3o      | H 3-Bromobenzaldehyde     | 50         | 94        |
| 3p      | H 2-methylbenzaldehyde    | 90         | 90        |
| 3q      | H 4-methylbenzaldehyde    | 70         | 89        |
| 3r      | H 4-hydroxybenzaldehyde   | 80         | 90        |
| 3s      | H 3-methoxybenzaldehyde   | 70         | 85        |
| 3t      | H 3-methylbenzaldehyde    | 70         | 89        |
| 3u      | H 4-nitrobenzaldehyde     | 40         | 93        |
| 3v      | H 4-methoxybenzaldehyde   | 70         | 83        |

**Table 5. NiFeTi CLDH6-Catalyzed Synthesis of 1,4-DHP and Polyhydroquinoline Derivatives**

| product aldehyde   | 1,3-dicarbonyl | time (min) | yield (%) |
|---------------------|---------------|------------|-----------|
| 8a                  | benzaldehyde  | 5          | 70        |
| 8b                  | 4-hydroxybenzaldehyde | 3          | 60        |
| 8c                  | cinnamaldehyde| 5          | 60        |
| 8d                  | propionaldehyde| 5          | 60        |
| 8e                  | 4-methylbenzaldehyde | 5         | 60        |
| 8f                  | 4-nitrobenzaldehyde | 5         | 50        |
| 8g                  | 4-chlorobenzaldehyde | 5         | 60        |
| 8h                  | 4-dimethylaminobenzaldehyde | 6       | 60        |
| 8i                  | cinnamaldehyde | 5          | 60        |
| 8j                  | 4-hydroxybenzaldehyde | 6         | 60        |
| 8k                  | propionaldehyde| 6          | 70        |
| 8l                  | 4-nitrobenzaldehyde | 6         | 40        |
| 8m                  | 2-nitrobenzaldehyde | 6         | 40        |
| 8n                  | benzaldehyde   | 6          | 60        |
| 8o                  | 4-methylbenzaldehyde | 6         | 60        |

**“Reaction conditions—Aldehyde/(5)/(6) = 1:2 (mmol), catalyst = 20 mg, solvent (ethanol) = 10 mL, and temperature = 80 °C.” Isolated yields. Products characterized by NMR spectroscopy.**
catalytic conversion, various solvents were tested, and the corresponding xanthene yields are summarized in Table 2. After scrutiny of the results, ethanol is chosen as an ideal solution for the catalytic synthesis of xanthene, 1,4-DHP, and polyhydroquinoline derivatives. Furthermore, altering the catalyst amount up to 20 mg indicated that with every amount increment, the yield percentage also increased. Still, when the amount was further increased to 30 mg, no further change in % yield was detected. This might be because of the achievement of the maximum catalytic conversion efficiency of NiFeTi CLDH6. Correspondingly, temperature also affects the reaction kinetics. Furthermore, to evaluate the effect of the temperature, the temperature was varied from 25 to 80 °C, and the results are summarized in Table 3. The refluxing temperature of ethanol, that is 80 °C, was obtained as the best temperature for achieving the maximum yield.

Using the above-optimized catalytic reaction conditions, a broad range of xanthene, 1,4-DHP, and polyhydroquinoline derivatives were synthesized by using benzaldehyde with electron-donating as well as electron-withdrawing groups (Tables 4 and 5). The obtained products were characterized using NMR spectroscopy and were compared with the previously reported spectra. A few 1H NMR spectra of synthesized xanthene, 1,4-DHP, and polyhydroquinoline derivatives are depicted in the Supporting Information (Figures S1–S11).

The plausible mechanisms are depicted in Figures 6 and 7. Calcined LDHs are supposed to show dual properties acidic as well as basic properties, acidic properties because of the positive charge on metal ions and basic properties because of the M–O⁻ oxides formed from the calcination of LDH. In the xanthene derivative synthesis (Figure 6), the reaction starts with the activation of the carbonyl group (aldehyde) by NiFeTi CLDH6, which leads to the formation of the intermediate (A) by the nucleophilic attack of dimedone on the activated carbonyl group, following Michael addition by the second dimedone molecule resulting in the formation of intermediate B. Furthermore, the elimination of water after intramolecular cyclization results in the formation of the desired product. Figure 7 illustrates two pathways (A and B) of the possible mechanism for 1,4-DHP and polyhydroquinoline synthesis. Similar to the xanthene synthesis, in the catalytic synthesis of 1,4-DHP and polyhydroquinoline derivatives (Figure 7), the reaction initiates by the activation of aldehyde and 1,3-dicarbonyl simultaneously by NiFeTi CLDH6. Then, these moieties react and result the Knoevenagel intermediate (I), which further reacts with a second 1,3-dicarbonyl molecule and produces the Michael addition intermediate (II). This intermediate further reacts with NH₄OAc to give enamine, which on intramolecular cyclization results in the elimination of water, giving the required product.
NiFeTi CLDH6 could be easily separated and recycled by using absolute ethanol. The recyclability and reusability of NiFeTi CLDH6 were evaluated by the model reaction. After the reaction completion, the catalyst was recovered using filtration, washed with ethanol and dried at 60 °C. The recovered catalyst was further used for five consecutive cycles, and the obtained yields (%) are illustrated in Figure 8. After every reusability stage, the FTIR spectrum of the recovered catalyst was recorded and summarized in Figure 9. From the results, it could be easily concluded that no appreciable change in the catalytic efficiency was recorded. Also, the FTIR spectra clearly illustrated that the recovered catalyst does not undergo any structural modifications. The elemental analysis of the recovered catalyst was also evaluated (reported in Table S1), and from the results, it could be inferred that no significant change in the elemental composition was reported. The SEM image of the recovered catalyst is illustrated in Figure S13.

Apart from the reusability test, the memory effect was also studied, for which NiFeTi CLDH6 was stirred in 0.1 M Na2CO3 aqueous solution for 24 h, and the obtained material was tested by FTIR spectroscopy. From the results (depicted in Figure S12), it could be inferred that the re-occurrence of the band at 1363 cm⁻¹ confirms the reformation of the layered structure because of the intercalation of carbonate ions. A comparative study of the catalytic ability of NiFeTi CLDH6 for catalytic synthesis of xanthene and 1,4-DHP derivatives with previously reported catalysts is illustrated in Table 6.

3. CONCLUSION

In summary, a novel and efficient NiFeTi CLDH6 was synthesized, characterized, and applied for the catalytic synthesis of xanthene, 1,4-DHP, and polyhydroquinoline derivatives in ethanol. This method is very much superior to previously known heterogeneous catalysts because of the various advantages such as no use of toxic solvents, great product yields, simple workup, less reaction time, and recyclable catalysts. NiFeTi CLDH6 showed significant recyclability up to 5 cycles. Therefore, it can be used as a potential catalyst for various sustainable syntheses.

4. EXPERIMENTAL SECTION

4.1. Synthesis of NiFeTi LDH and NiFeTi CLDH. NiFeTi LDH was resynthesized using the previously reported hydrothermal method. For NiFeTi LDH synthesis, Ni(NO3)2·6H2O, Fe(NO3)3·9H2O, and TiCl4 were weighed and further added to 70 mL of decarbonated water. 1.5 g of urea was added to the mixture, and the mixture was vigorously stirred. The mixture was further transferred to an autoclave and hydrothermally aged for 48 h at 160 °C. The obtained product was filtered, washed with degassed water, and dried in an oven at 60 °C. The obtained NiFeTi LDH was calcined at various temperatures by heating 1 g of NiFeTi LDH for 4 h in a furnace (at different temperatures: 200, 300, 350, 400, 500, and 600 °C). The obtained mixed oxides were labeled as NiFeTi CLDH1, NiFeTi CLDH2, NiFeTi CLDH3, NiFeTi CLDH4, NiFeTi CLDH5, and NiFeTi CLDH6, respectively.

Table 6. Comparative Study of the Catalytic Efficiency of NiFeTi CLDH6

| entry | catalyst & catalyst amount | derivative | solvent/condition | time | yield (%) | ref |
|-------|---------------------------|------------|-------------------|------|-----------|-----|
| 1     | Fe⁺⁺-montmorillonite, 85 mg | xanthene   | EtOH, 100 °C      | 6 h  | 94        | 33  |
| 2     | [bmmim]HSO₄, 100 mg        | xanthene   | solvent free/80 °C | 3 h  | 85        | 34  |
| 3     | Zr(DP)₂, 10 mol %          | xanthene   | EtOH/reflux       | 24 h | 98        | 35  |
| 4     | SO₄²⁻/ZrO₂, 15 wt %        | xanthene   | EtOH/70 °C        | 8 h  | 95        | 36  |
| 5     | NiFeTi CLDH6, 20 mg        | xanthene   | EtOH/reflux       | 1 h  | 96        | this study |
| 6     | Al₂(SO₄)₃, 10 mol %        | 1,4-DHP    | EtOH/reflux       | 8 h  | 92        | 37  |
| 7     | La₂O₃, 10 mol %            | 1,4-DHP    | TFE               | 1−1.5 h | 89 | 38  |
| 8     | BiBr₃, 2 mol %             | 1,4-DHP    | EtOH              | 2 h  | 86        | 39  |
| 9     | NiFeTi CLDH6, 20 mg        | 1,4-DHP    | EtOH/reflux       | 70 min | 85 | this study |

Abbreviations: bmmim = 1-butyl-3-methylimidazolium, dp = dodecylphosphonate.

4.2. Catalytic Activity. 4.2.1. Synthesis of 1,8-Dioxo-octahydroxanthene Derivatives. 1 mmol of aldehyde, 2 mmol of 5,5-dimethylcyclohexane-1,3-dione/1,3-cyclohexanedione, and 20 mg of NiFeTi CLDH6 were stirred in 10 mL ethanol at 50 °C for a suitable time as depicted in Table 4. The reaction progress was monitored by thin-layer chromatography (TLC) by using ethyl acetate/hexane as the eluent. After the reaction completion, the reaction mixture was diluted by the addition of 20 mL of hot ethanol, and the catalyst was separated by the filtration method. The crude product was dissolved in ethanol and kept for recrystallization. The crystals so obtained of the pure product were washed with absolute ethanol and further air-dried. All the derived crystallized products were confirmed by NMR spectroscopy.

4.2.2. Synthesis of 1,4-DHP and Polyhydroquinoline Derivatives. 1 mmol of aldehyde, 2 mmol of ethyl acetooacetate/dimedone, 1 mmol of ammonium acetate, and 20 mg of NiFeTi CLDH6 were stirred in 10 mL ethanol at 50 °C for a suitable time as depicted in Table 5. The reaction progress was detected by TLC by using ethyl acetate/hexane as the eluent. After the reaction completion, the reaction mixture was diluted by the addition of 20 mL of hot ethanol, and the catalyst was separated by the filtration method. The crude product was dissolved in ethanol and kept for recrystallization. The crystals so obtained of the pure products were washed with absolute ethanol and further air-dried. All the derived crystallized products were confirmed by NMR spectroscopy.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c01901.

Materials and characterization techniques, elemental analysis, 1H NMR spectra, FTIR spectra for the memory effect of NiFeTi CLDH6, and the SEM image of catalysts after the reaction (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

G.R. and R.C. are highly thankful to the University of Delhi for providing financial support.

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