

# Nanoceria Supported Copper Salophen Nanomaterial (Cu(II)Salophen@APTES/CeO<sub>2</sub>) for Catalytic Reduction of Organic Dye

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In this work, preparation of a heterojunction nano catalyst has been reported by the fabrication of Cu(II) Salophen complex to nano ceria (CeO<sub>2</sub>) through a silica linkage 3-Aminopropyl triethoxysilane (APTES), which is easily separable by centrifugation. The nanocatalyst was characterized by FTIR, XRD, HRTEM, and EDX analysis. The catalytic activity of the synthesized catalyst was examined for the reduction of organic dyes methyl orange

and methyl red in aqueous medium at room temperature. The dye solutions became colorless within a very short period of time in presence of synthesized catalyst and NaBH<sub>4</sub> as a source of hydride ions. The reduction process for both the dyes followed pseudo first-order reaction kinetics with a high catalytic efficiency.

## 1. Introduction

The modern era is dominated by nanomaterials with large dimensions for fabrication and application in potential fields. Fabrication of metal Schiff base complex with nanoparticles is also a trending dimension of nanomaterials.<sup>[1]</sup> Organic dyes have many applications in various industries such as textile, food, plastic, paper, cosmetics, leather, pharmaceuticals, etc. These industries release high amounts of wastewater drained into rivers or the environment and thus harm human health and the ecosystem of mother nature.<sup>[2–8]</sup> So removal of these dyes from industrial waste water is very much essential. Several techniques such as adsorption, membrane separation, ion exchange, ultra-filtration, biochemical methods, ozone treatment, etc. have been applied for the treatment of wastewater but the problem is still there.<sup>[9–13]</sup> These methods have many limitations including high price, high time-consuming process, generation of other secondary pollutants, difficulties of the techniques of removal, etc.<sup>[3,14]</sup> In this regard, catalytic reduction of the organic dyes by metal complexes or metal nanoparticles in the presence of NaBH<sub>4</sub> is a very promising and effective process.<sup>[15–17]</sup> Especially nanoparticles decorated Schiff base complexes are important heterogeneous catalysts for the catalytic reduction of organic dyes.<sup>[1,16,18]</sup> One of the main advantages of the decorated/fabricated nanomaterial is easy to remove from reaction media and reuse several times.<sup>[16,18,19]</sup> Both metal oxides and

Schiff base complexes can act as conventional catalysts but the combination of these two catalysts may increase the catalytic activity of the heterogeneous catalyst by increasing the interfacial area between metal oxide nanoparticles and the complex. Many Schiff base complexes of transition metals supported on Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, and SiO<sub>2</sub> have been reported for the catalytic reduction/degradation of organic dyes but CeO<sub>2</sub> decorated metal complexes are hardly reported.<sup>[20–22]</sup> In this work, we have synthesized Cu(II) salophen complex supported on CeO<sub>2</sub> nanoparticles through aminopropyl triethoxysilane (APTES) linkage and characterized by FTIR, XRD, HRTEM, and EDX analysis. In this connection, CeO<sub>2</sub> has been chosen for increasing its catalytic efficiency as CeO<sub>2</sub> itself is a potential catalyst. The low Ce<sup>3+</sup>/Ce<sup>4+</sup> ion ratios and increased surface area to volume ratio are the major reasons for the good catalytic activity of CeO<sub>2</sub> nanoparticles.<sup>[23]</sup> On the other hand, Cu is abundant and copper salts are inexpensive, nontoxic, and easily available compared to the other transition metals. So, Cu(II) Salophen complex has been chosen to fabricate with CeO<sub>2</sub>. The CeO<sub>2</sub> decorated Cu(II)-salophen has been employed as a heterogeneous catalyst for the reduction of organic dyes such as methyl orange(MO), and methyl red (MR). In this study we explored that, in the presence of NaBH<sub>4</sub>, the heterojunction catalyst created an important impact on the reduction process of dyes rather than the CeO<sub>2</sub> and Cu(II) complex. Here the novelty and originality of this work have appeared.

## 2. Experimental Section

### 2.1. Materials and Instruments

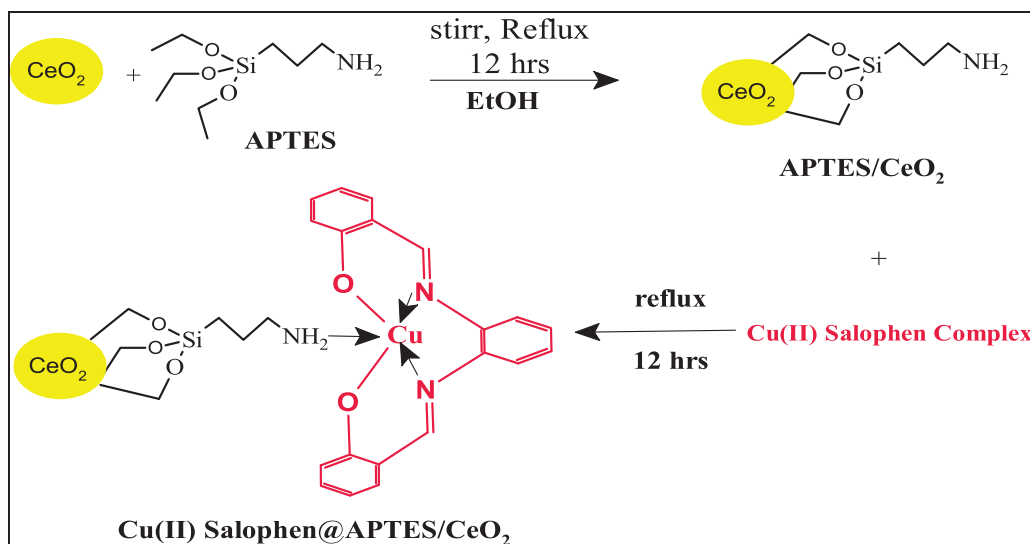
All the chemicals used for this paper work of analytical grade were commercially available and used without further purification. The chemicals have been kept in vacuum desiccators for minimum contamination, evaporation, and avoid the effect of sunlight.

UV-vis Spectrophotometer (Evaluation 201), Perkin Elmer Instrument, Waltham MA, USA was used for UV-vis spectra. FTIR spectra were reported by BRUKER-ALPHA-Platinum-ATR-IR instrument.

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 Supporting information for this article is available on the WWW under  
<https://doi.org/10.1002/slct.202405880>



Scheme 1. Preparation of Cu(II)Salophen@APTES/CeO<sub>2</sub> for catalytic reduction of dyes.

Powder XRD analysis were done by X-ray Diffractometer (Phillips X'pert Pro Powder X-ray Diffractometer). HRTEM images were recorded by JEM-2100 plus Electron Microscope.

## 2.2. Synthesis of Salophen Ligand (L) [C<sub>20</sub>H<sub>16</sub>N<sub>2</sub>O<sub>2</sub>] and Cu(II) Complex (CuL)

Salophen ligand was synthesized as per our previous experiment.<sup>[24]</sup> For the synthesis of complex, in a round bottom flask, 1 mmol of Salophen ligand (L) in 10 mL ethanol and 1 mmol of Cu(II) acetate salt in 20 mL ethanol were mixed homogeneously by keeping on a magnetic stirrer for 2 h. The reddish-brown solid was filtered, washed several times with ethanol, diethyl ether, dried at 60 °C (Scheme S1). The synthesized complex was soluble in DCM, DMF, and DMSO and characterized by UV-vis spectra, FT-IR spectra and <sup>1</sup>H-NMR analysis (Supporting Information).

## 2.3. Synthesis of CeO<sub>2</sub> Nanoparticles

Nano ceria was synthesized as per our previous work.<sup>[24]</sup>

## 2.4. Synthesis of APTES/CeO<sub>2</sub>

1.0 g of CeO<sub>2</sub> nanoparticles were mixed with 20 mL of ethanol followed by sonication of the mixture to produce a homogeneous solution. Then 1.0 g APTES was added drop wise to the CeO<sub>2</sub> suspension and the resulting mixture was allowed for sonication at 60 °C for 2 h (Scheme 1). Finally the mixture was refluxed for further 12 h. The resulting composition was isolated by centrifugation, washed several times with ethanol, dried under vacuum at 60 °C for 12 h.

## 2.5. Synthesis of Cu(II)Salophen@APTES/CeO<sub>2</sub>

1.0 g of the nanocomposite was mixed with 20 mL ethanol to produce a homogeneously mixed solution. 0.5 g of Cu(II) salophen complex was added to the solution followed by ultrasonication at 60 °C for 2 h. The resulting mixture was refluxed for another 12 h (Scheme 1). Finally, the product was collected by centrifugation, washed with ethanol, dried under vacuum for 12 h at 60 °C.

## 2.6. Procedure for Catalytic Reduction

Catalytic activity of the Cu(II)Salophen@APTES/CeO<sub>2</sub> for the reduction of methyl orange(MO) and methyl red (MR) was performed in aqueous medium with presence of NaBH<sub>4</sub> (1.0 M) as a reducing agent. At first, aqueous solution of the dyes (0.1 mM) was prepared with distilled water. To initiate the catalytic reduction process, a mixture of 3 mL of the dyes with 1 mL of NaBH<sub>4</sub> solution was prepared. Then 2 mg of the catalyst was added to the reaction mixture and the solution was added into a quartz cuvette. To investigate the reduction process, the absorption spectra of the dyes ( $\lambda_{\text{max}}$  at 463 nm for methyl orange,  $\lambda_{\text{max}}$  at 429 for methyl red) solutions was monitored at regular time interval at ambient temperature by UV-vis spectrophotometer within range 200–600 nm wavelength. To understand the influence of pH in reduction process, different sets of solution having pH 3,5,7, and 9 was prepared. Degradation efficiency was found to be maximum at pH 7 for both the dyes. So, pH of the reaction medium was maintained at 7.

## 2.7. Calculation of Percentage of Reduction/Conversion of Dyes

The percentage of reduction/conversion of dyes (*D*) were calculated by the following formula

$$D = \frac{A_0 - A_t}{A_0} \times 100\%$$

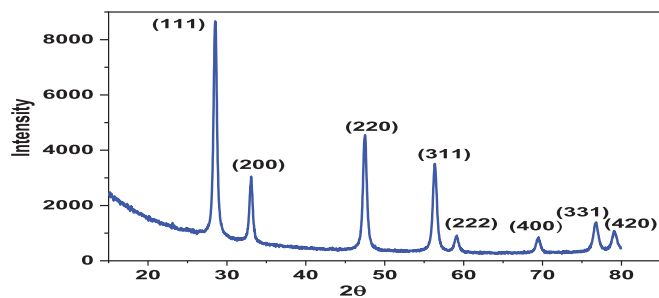
where *A*<sub>0</sub> is the absorbance of dye solution at *t* = 0 min and *A*<sub>*t*</sub> is the absorbance after *t* minutes.<sup>[17]</sup>

## 3. Results and Discussion

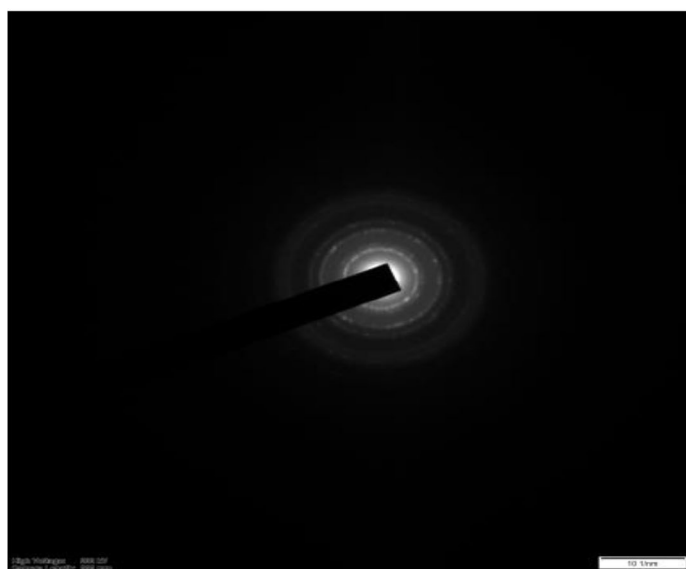
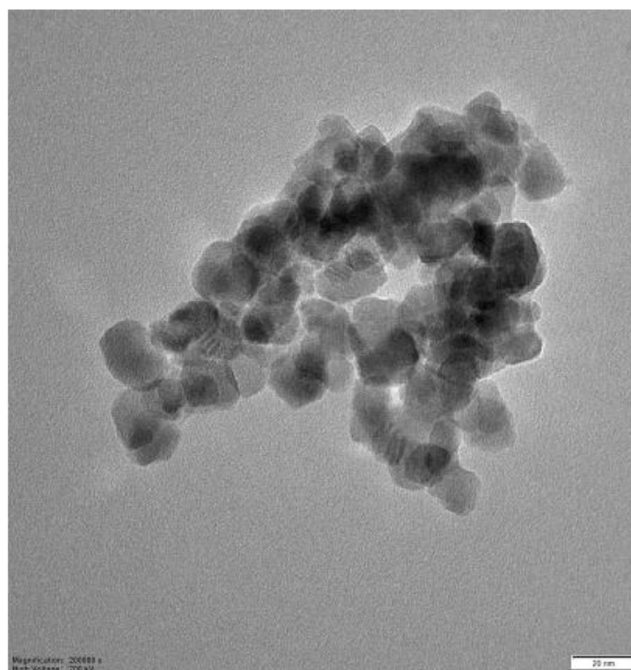
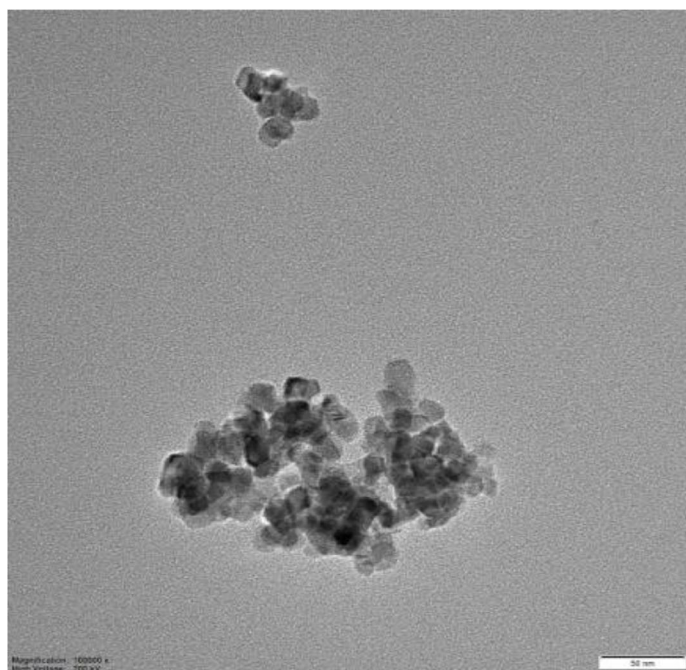
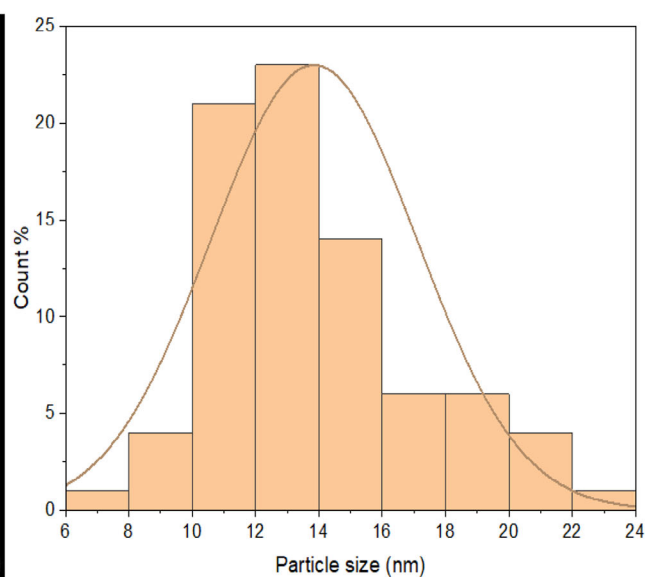
### 3.1. Characterization of Catalyst

#### 3.1.1. FT-IR Spectra

In the FT-IR spectra (Figure S4a,b) the bands appeared at 500–600 cm<sup>−1</sup> range for both CeO<sub>2</sub>/APTES and Cu(II)Salophen@

Figure 1. XRD plot of Cu(II)salophen@APTES/CeO<sub>2</sub>.

APTES/CeO<sub>2</sub> nano composite indicated the Ce–O stretching frequency which proved the successful fabrication of nanoceria in the synthesized compounds.<sup>[24]</sup> Figure S4a confirmed the linkage of silane through amine group of APTES on CeO<sub>2</sub>. The sharp band appeared at 3377 and 1616 cm<sup>−1</sup> indicated the stretching and bending vibrational mode of N–H bond respectively.<sup>[25,26,27]</sup> Band appeared at 2925 cm<sup>−1</sup> represented the stretching frequency of C–H bond of the propyl group.<sup>[25,28,29]</sup> The sharp band appeared at 1025 and 1067 cm<sup>−1</sup> was due to the Si–O bond stretching frequency.<sup>[22,25]</sup> Figure S4b indicated the successful coordination of CeO<sub>2</sub>/APTES to Cu(II)Salophen complex with a new band appeared at 1608 cm<sup>−1</sup>. This band

Figure 2. EDX Spectrum of Cu(II)salophen@APTES/CeO<sub>2</sub>.

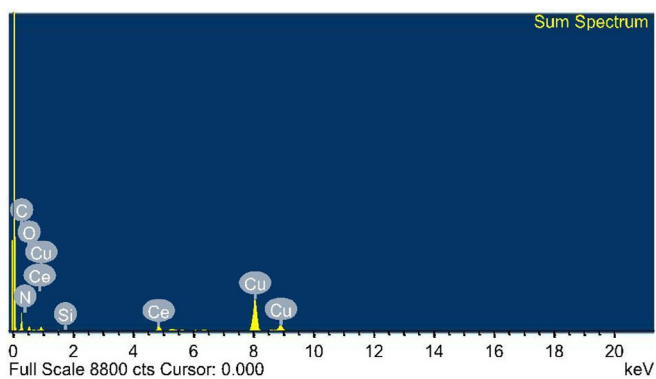


Figure 3. HRTEM images and particle size distribution histogram of Cu(II)salophen@APTES/CeO<sub>2</sub>.

represented the characteristic of the imine bonds (C=N) of salophen complex.<sup>[22,24]</sup> Other new bonds appeared at 700–900 cm<sup>−1</sup> range and 1200–1522 cm<sup>−1</sup> range compatible with that of Cu(II)Salophen complex (Figure S2).<sup>[24]</sup>

### 3.1.2. By XRD Plot

For Cu(II)Salophen@APTES/CeO<sub>2</sub>, characteristic diffraction peaks appeared at  $2\theta$  of 27.09°, 33.06°, 47.37°, 56.52°, 59.21°, 69.34°, 76.75°, and 79.20° which belongs to (111), (200), (220), (311), (222), (400), (331), and (420) miller indices respectively. The positions of the peaks matched well with the standard XRD pattern of CeO<sub>2</sub> nanoparticles reported one in JCPDS file no (34-0394) with no other peak for impurity.<sup>[30,31]</sup> This indicated that the face-centered cubic (fcc) crystalline phase of CeO<sub>2</sub> is not destroyed after the fabrication of Cu(II)Salophen complex. The broad peak in the XRD plot of the synthesized nanocomposite indicated the nanostructure nature of the product (Figure 1).

### 3.1.3. HRTEM and EDX Analysis

The successful fabrication of the Cu(II) salophen with CeO<sub>2</sub> nanoparticle was confirmed by HRTEM and EDX analysis. Presence of the composing elements (C, N, O, Si, Ce, and Cu) in

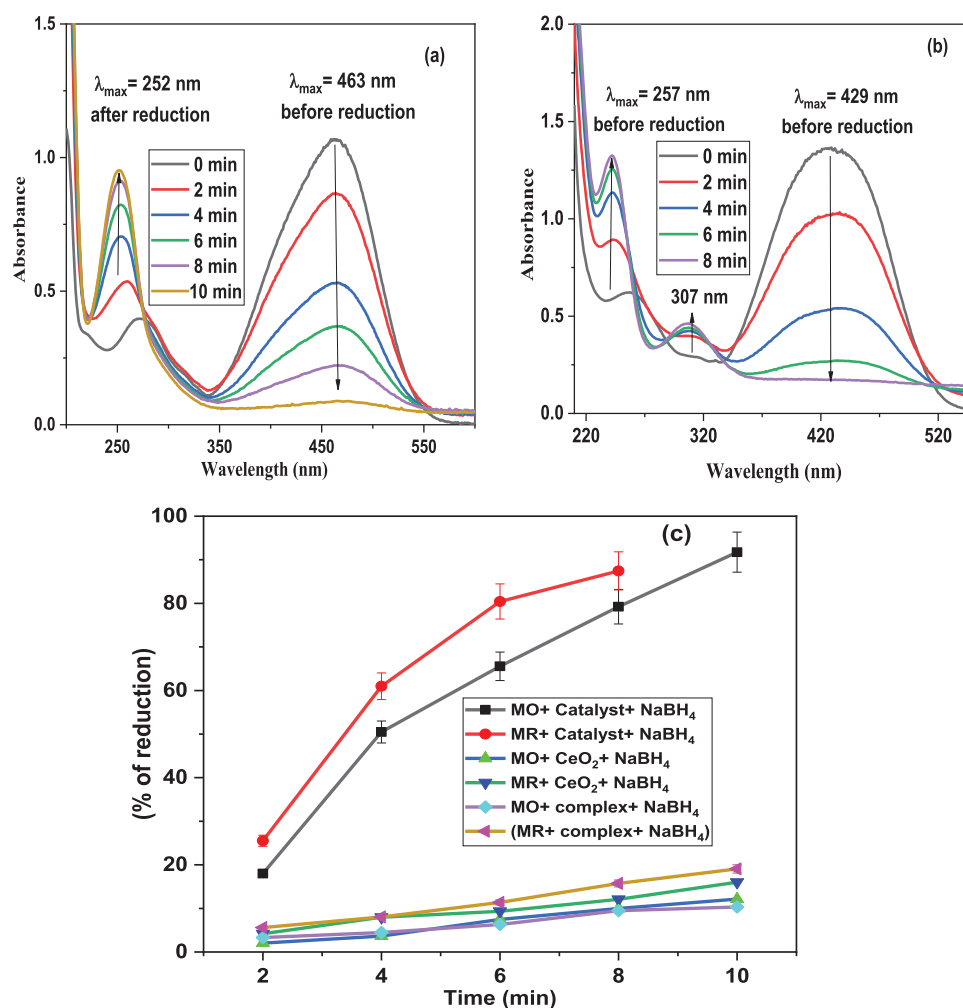


Figure 4. Time dependent UV-vis spectra for reduction of a) methyl orange and b) methyl red. c) Percentage of reduction with respect to time for the dyes in various condition.

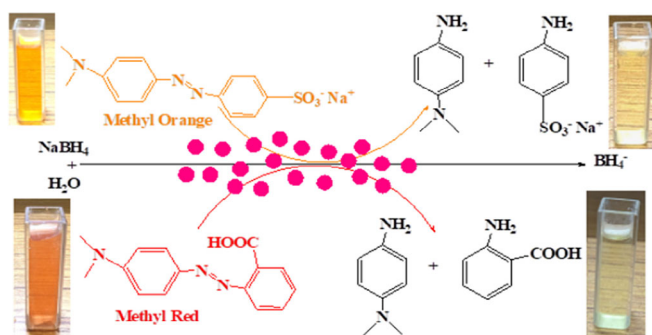


**Figure 5.** Schematic presentation of reduction of MO and MR dyes with possible reduced product.

the EDX spectrum with elemental mapping confirmed the synthesis of Cu(II)salophen@APTES/CeO<sub>2</sub> (Figures 2 and S5). The HRTEM image revealed the cubic shape of the particles for the nanocomposite with particle size 13 nm (Figure 3).

### 3.2. Catalytic Reduction of Methyl Orange (MO)

The UV–vis spectrum of azo dye methyl orange solution showed an absorption peak  $\lambda_{\text{max}}$  at 463 nm due to  $\pi \rightarrow \pi^*$  electronic transitions of azo group ( $-\text{N}=\text{N}-$ ). After addition of reducing agent ( $\text{NaBH}_4$ ) and catalyst the  $\lambda_{\text{max}}$  of methyl orange decreased and a new  $\lambda_{\text{max}}$  at 252 nm for reduced methyl orange increased gradually (Figure 4a). The catalyst showed maximum reduction up to 91.75% within only 10 min (Figure 4c). Within 10 min the orange color of methyl orange solution became colorless and  $\lambda_{\text{max}}$  at 463 nm totally disappeared. The sharp peak appeared at 252 nm range indicated the reduction of azo group and formation of aromatic ring with amino groups (Figure 5). The percentage of reduction was very low (10%–15%) when the dye was treated with CeO<sub>2</sub> and Cu(II) Salophen complex individually in presence of  $\text{NaBH}_4$  (Figure 4c). A comparative study on reduction of methyl orange with the other catalysts is given in Table 1.

### 3.3. Catalytic Reduction of Methyl Red (MR)

To investigate the catalytic reduction process of azo dye methyl red, UV–vis spectrum of methyl red solution was observed for a definite time interval. Before addition of  $\text{NaBH}_4$ , methyl red solution showed an absorption peak  $\lambda_{\text{max}}$  at 435 nm. After addition of  $\text{NaBH}_4$ , the color of methyl red solution became yellow from red and  $\lambda_{\text{max}}$  of methyl red solution shifted to 429 nm from 435 nm. The sharp peak appeared at 429 nm was due to the  $\pi \rightarrow \pi^*$  electronic transitions in the anionic form methyl red solution (Figure 4b). The reduction process was monitored from this point. After addition of catalyst in that solution (methyl red with  $\text{NaBH}_4$ ),  $\lambda_{\text{max}}$  of methyl red solution decreased and a new  $\lambda_{\text{max}}$  at 257 nm for reduced methyl red solution increased gradually. The peak at 257 nm indicated the formation of amino group containing aromatic ring by the reduction and destruction of the azo group ( $-\text{N}=\text{N}-$ ) of methyl red dye. Another new peak appeared in parallel way at 307 nm range due to the  $n \rightarrow \pi^*$  electronic transitions indicated the carboxylic acid containing aromatic ring which was also formed after reduction of methyl red (Figure 5). The reduction process was completed within only 8 min with maximum reduction up to 87.44% (Figure 4c). Within 8 min the yellow color of methyl red solution became colorless and  $\lambda_{\text{max}}$  at 429 nm totally disappeared (Figure 4b). A comparative study on reduction of methyl red with the other catalysts is given in Table 2. Here also the dye experienced a low reduction percentage when treated with CeO<sub>2</sub> and Cu(II) Salophen complex individually in presence of  $\text{NaBH}_4$  (Figure 4c).

### 3.4. Effect of pH

For reduction of dyes, pH of the solution has a significant impact on rate of reduction as pH can affect the molecular structure of dyes through degree of ionization and the nature of catalyst by affecting the surface charge. Therefore, determining the suitable pH of the medium for reduction of the dyes is an important task. Here in this work, we have investigated the reduction process

**Table 1.** Comparison of the reduction of methyl orange and the efficiency of the Cu(II)Salophen@APTES/CeO<sub>2</sub> nanocatalyst with other mentioned in literature (Symbol C stand as catalyst and S as substrate).

| Time (min) | Reaction Condition                                                  | pH | Temp. (°C) | Rate(min <sup>-1</sup> ) | References |
|------------|---------------------------------------------------------------------|----|------------|--------------------------|------------|
| 10         | S: 0.1 mM (3 mL)<br>C: Cu(II)Salophen@APTES/CeO <sub>2</sub> (2 mg) | 7  | room       | 0.2707                   | This study |
| 30         | S: 100 mg/L (100 mL)<br>C: CeO <sub>2</sub> (10 mg)                 | –  | –          | 0.1211                   | [32]       |
| 4          | S: 500 mg/L (100 mL)<br>C: Ag-AgCl (0.1 mg)                         | 6  | 60         | 1.0542                   | [17]       |
| 25         | S: 500 mg/L (5 mL)<br>C: Cu(0.02 mg)                                | 7  | 37         | 0.1266                   | [33]       |
| 70         | S: 500 mg/L (5 mL)<br>C: Fe(0.02 mg)                                | 7  | 37         | 0.0857                   | [32]       |
| 100        | S: 20 ppm (100 mL)<br>C: ZnO (1.5 g/dm <sup>3</sup> )               | –  | –          | –                        | [34]       |
| 60         | S: 100 mg/L (30 mL)<br>C: Fe <sub>3</sub> O <sub>4</sub>            | 6  | room       | –                        | [35]       |

**Table 2.** Comparison of the reduction of methyl red and the efficiency of the Cu(II)Salophen@APTES/CeO<sub>2</sub> nanocatalyst with other mentioned in literature (Symbol C stand as catalyst and S as substrate).

| Time (min) | Reaction Condition                                                          | pH | Temp. (°C) | Rate (min <sup>-1</sup> ) | References |
|------------|-----------------------------------------------------------------------------|----|------------|---------------------------|------------|
| 8          | S: 0.1 Mm (3 mL)<br>C: Cu(II)Salophen@APTES/CeO <sub>2</sub> (2 mg)         | 7  | room       | 0.3014                    | This study |
| 12         | S: 3 × 10 <sup>-4</sup> M<br>C: AuNP- <i>N.alata</i> (0.02 mg/ mL)          | –  | –          | 0.2975                    | [36]       |
| 19         | S: 3 × 10 <sup>-4</sup> M<br>C: AgNP- <i>N.alata</i> (0.02 mg/ mL)          | –  | –          | 0.0693                    | [36]       |
| 9          | S: 0.1 mM<br>(3 mL)<br>C: PdNC(60 μg)                                       | –  | –          | 0.2610                    | [37]       |
| 20 s       | S: 3 × 10 <sup>-5</sup> M<br>(20 mL)<br>C: ZnO@CuO@iron ore NCs(3 mg)       | –  | room       | –                         | [38]       |
| 85 s       | S: 1.3 × 10 <sup>-5</sup> M<br>(1 mL)<br>C: Pd/CS/γ-MnO <sub>2</sub> (8 mg) | –  | –          | –                         | [39]       |
| 16         | S: 0.03 mM (3 mL) C:<br>Ag/ZnO-CH(15 mg)                                    | –  | –          | 0.00157                   | [40]       |

at different pH (3, 5, 7, and 9). At pH 7, MO dye was degraded by 91.75% within 10 min and MR dye was degraded by 87.44% within 8 min. At pH 3, 5, and 9, MO dye was degraded by 25.65%, 30.09%, and 65.55% respectively within 10 min. The degradation efficiency of MR solution at pH 3, 5, and 9 was found to be 20.30%, 27.69%, and 57.45% respectively (Figure 6a,b).

### 3.5. Kinetic Study of the Reduction of Organic Dyes

The absorbance (A) of dye solutions is directly proportional to the concentration (C) of the solutions and it is expressed by Beer–Lambert's law, i.e.,

$$A = \epsilon bC$$

where,  $\epsilon$  (molar absorption coefficient) and  $b$  (thickness of absorption cell) are constant. Therefore  $A_t/A_0$  is proportional to  $C_t/C_0$ . (where  $A_t$  and  $A_0$  are absorbance at time  $t$  and  $t = 0$  respectively and  $C_t$  and  $C_0$  are the concentrations of the solution at time  $t$  and  $t = 0$  respectively).<sup>[41]</sup>

The changes of the concentrations of the dye solutions over a definite time interval was monitored by a UV–vis spectrometer

which followed the pseudo first order reaction kinetics,

$$\ln \left( \frac{C_0}{C_t} \right) = kt$$

As the concentration of NaBH<sub>4</sub> is higher than the concentration of dyes in the solution so the rate of reduction is considered to be independent on the concentration of NaBH<sub>4</sub>. From the slope of the plot  $\ln(C_0/C)$  versus time for both the dyes, the rate constant( $k$ ) of the reduction reaction was evaluated directly (Figure 7 and Table 3).

### 3.6. Catalytic Efficiency and Stability of Cu(II)Salophen@APTES/CeO<sub>2</sub> Catalyst

For a catalyst the catalytic efficiency or reusability of the catalyst is an important factor. In this experiment, for the reduction of organic dyes, we performed four consecutive cycles. After completion of one cycle of reduction, the catalyst was separated from reaction mixture by the centrifugation at 4500 rpm followed by washing with water and ethanol, and finally dried at 60°C on air oven. After drying up completely, the catalyst

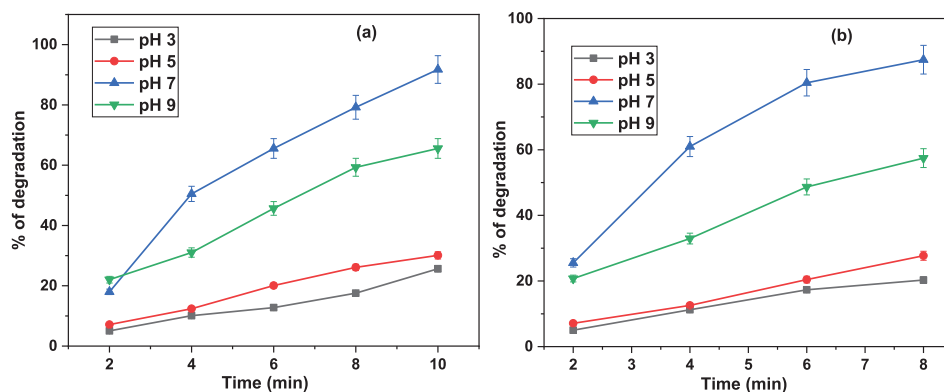


**Figure 6.** Effect of pH in the reduction of a) MO and b) MR in the presence of NaBH<sub>4</sub> (as reducing agent) and Cu(II)salophen@APTES/CeO<sub>2</sub> (as catalyst).

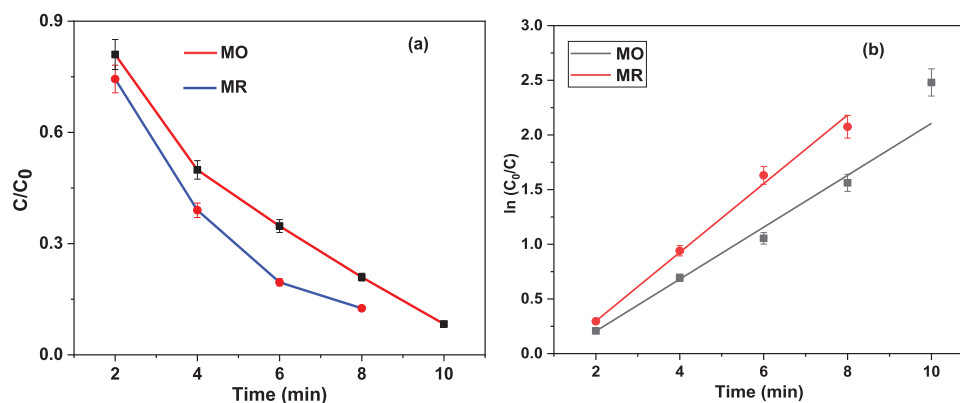


Figure 7. a) plot of  $C/C_0$  versus time and b) plot of  $\ln(C_0/C)$  versus time for pseudo first-order reaction kinetics of catalytic reduction of MO and MR dyes.

| Name of Dyes  | Pseudo First-Order Rate Constant $k$ ( $\text{min}^{-1}$ ) | Time (min) | Conversion (%) | $R^2$  |
|---------------|------------------------------------------------------------|------------|----------------|--------|
| Methyl Orange | 0.2707                                                     | 10         | 91.75          | 0.9665 |
| Methyl Red    | 0.3014                                                     | 8          | 87.44          | 0.9921 |

was used again for the next cycle of reduction step and thus the efficiency of the catalyst was checked for fourth cycle. The results of reusability study revealed a good catalytic efficiency of the synthesized  $\text{Cu(II)salophen@APTES/CeO}_2$  catalyst. While passing through the consecutive four cycle of reduction, the conversion rate reduces from 91.75% to 80% and 87.44% to 78% for methyl orange and methyl red respectively (Figure 8a). This

might be due to the discharge of Ce from the catalyst during the reduction process.<sup>[42]</sup>

To verify the stability of the catalyst, XRD and HRTEM analysis of the catalyst were performed again. The XRD data revealed that the crystalline phase of the catalyst did not change after the fourth cycle of reduction (Figure 8b). HRTEM analysis also proved that the morphology and nature of the catalyst also remain unchanged during the catalytic cycle (Figure 8c).

### 3.7. Mechanism of the Reduction of Organic Dyes

In this study we explored that there was no reduction of organic dyes in absence of  $\text{NaBH}_4$  or the catalyst by a UV-vis spectrum, which indicated that both  $\text{NaBH}_4$  and the catalyst are needed for the reduction of dyes. Because of the increased

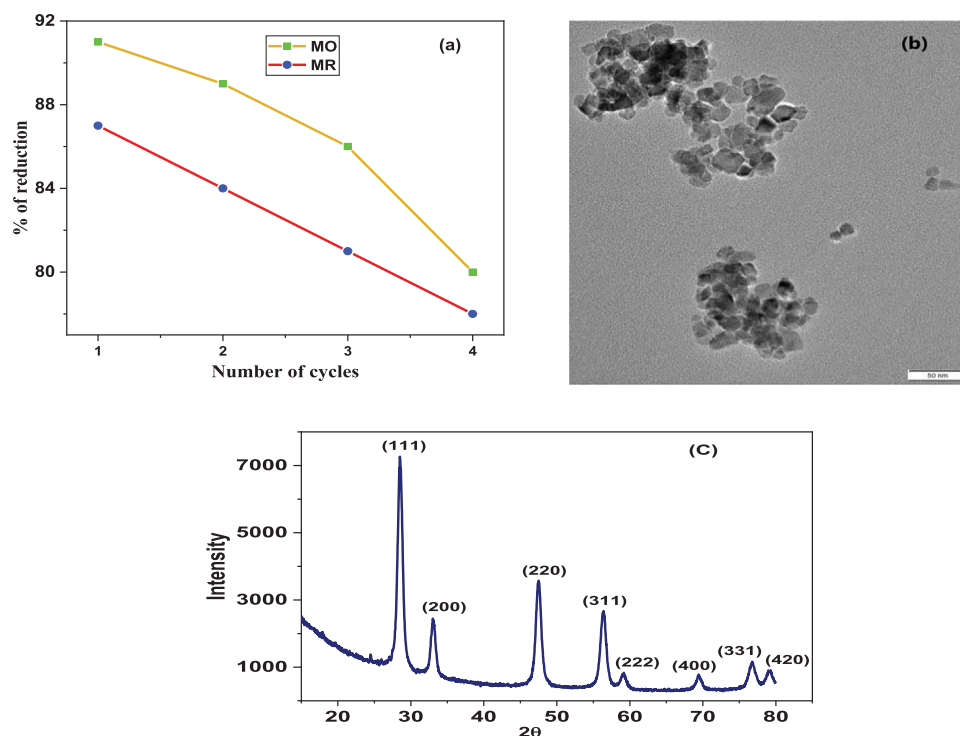


Figure 8. a) Catalytic efficiency of the catalyst for four cycle, b) Tem image, and c) XRD pattern of the catalyst after four cycle of reduction.

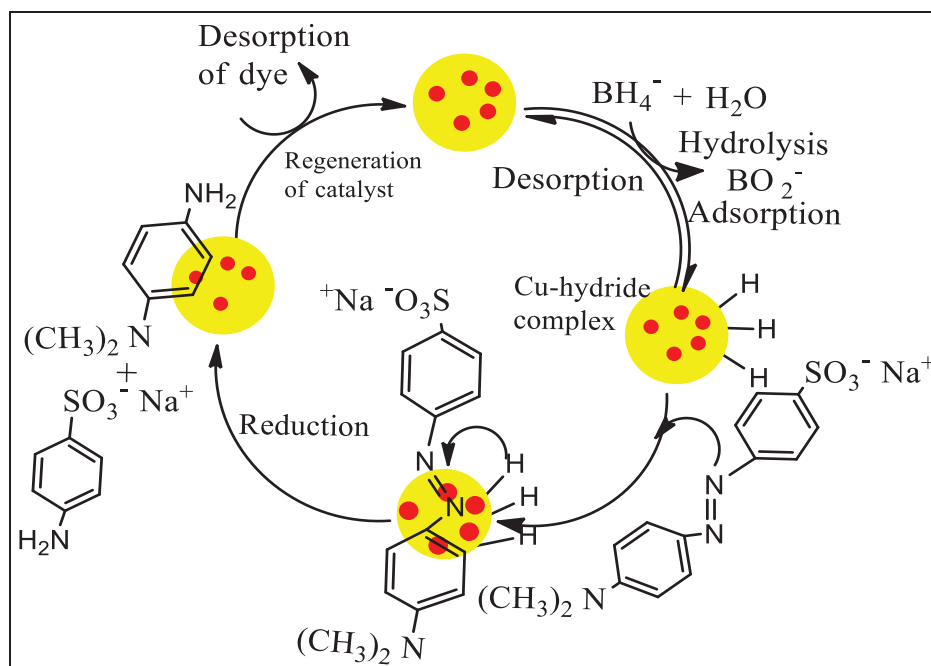


Figure 9. Plausible mechanism of reduction of organic dyes through a catalytic cycle.

surface area to volume ratio, the synthesized heterojunction catalyst showed good catalytic activity. In this regard Lewis acidity of the Cu(II) salophen complex immobilized nanocatalyst (Cu(II)salophen@APTES/CeO<sub>2</sub>) plays an important role. At first NaBH<sub>4</sub> in presence of aqueous medium ionizes to produce borohydride ions (BH<sub>4</sub><sup>-</sup>). This BH<sub>4</sub><sup>-</sup> ions and dye molecules both are adsorbed on the surface of catalyst (Figures 9 and 10). This adsorption of the BH<sub>4</sub><sup>-</sup> ions on the surface of Cu(II) com-

plex nanocomposite produce copper-hydride complex, which acts as an active hydrogen species and initiates the reduction reaction.<sup>[18,43]</sup> Now hydride ions transfer occurs from the active catalyst surface to the dye molecules. This is the rate determining step of the catalytic reduction. Dye molecules captured the hydride ions and then the reduction occurs through the azo bond (–N=N–). The reduced form of the dye molecules then desorbed from the surface of the catalyst and reac-

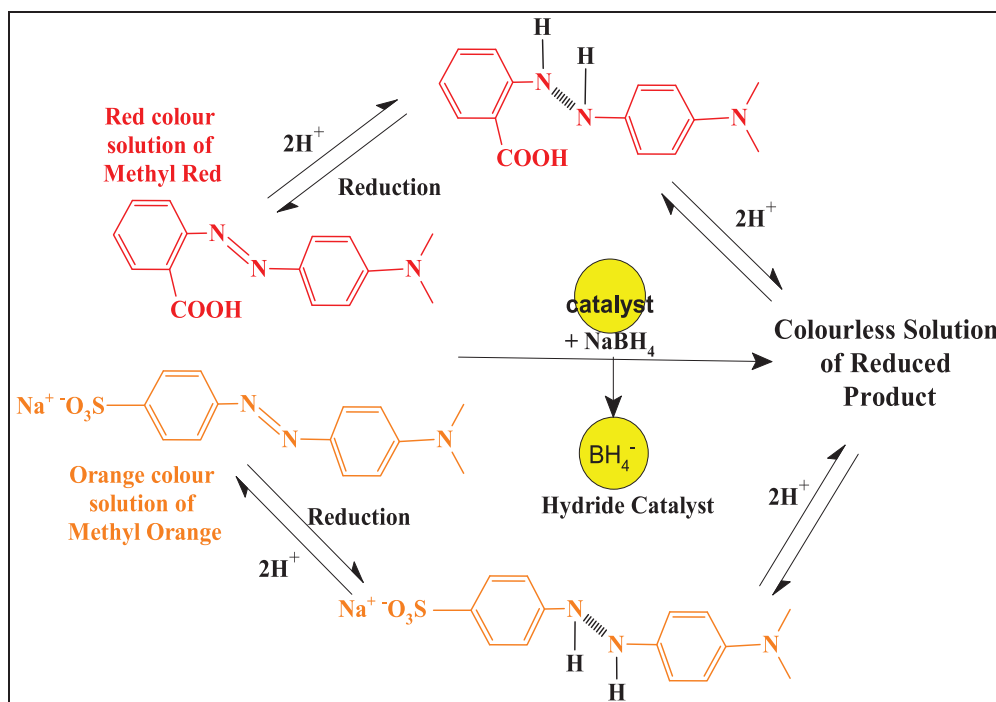


Figure 10. Schematic presentation of reduction mechanism of organic dyes.

tivated the catalyst again. These adsorption and desorption processes are reversible through the catalytic cycle (Figures 9 and 10).<sup>[18,43]</sup>

## 4. Conclusion

In summary, Cu(II) Salophen complex decorated nanoceria CeO<sub>2</sub> was synthesized via APTES linkage (Cu(II)Salophen@APTES/CeO<sub>2</sub>). This nanocomposite showed its nanostructured morphology in HRTEM analysis and acted as an effective catalyst for the reduction of organic dyes (MO, MR) with high catalytic efficiency up to four cycle. The reduction process was carried out in aqueous medium (pH = 7), in presence of NaBH<sub>4</sub> as a reducing agent at room temperature. The colored solution of the organic dyes became colorless within 10 and 8 min for MO and MR, respectively. The reduction process followed pseudo first-order reaction kinetics with high percentage of conversion.

## Acknowledgements

The authors are grateful to the department of Chemistry, Cooch Behar Panchanan Barma University for providing the space of research and financial support to carry out this work. The authors are also grateful to Gauhati University for providing the powder XRD data, IIT Palakkad for FT-IR data, CSIR-North East Institute of Science and Technology for providing us the HRTEM with EDX and Elemental Mapping data, North Bengal University for others instrumental support.

[Correction added on 22 February 2025, after first online publication: The figure call-ups have been updated in this version.]

## Conflict of Interests

The authors declare no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

**Keywords:** Dyes · Hybrid nanocatalyst · Nanoparticles · Schiff base complex · Silica linkage

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Manuscript received: December 16, 2024