Efficient Photoreduction of Hexavalent Chromium Using the Reduced Graphene Oxide–Sm$_2$MoO$_6$–TiO$_2$ Catalyst under Visible Light Illumination

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Cite This: ACS Omega 2020, 5, 6414–6422

ABSTRACT: In past years, the presence of toxic heavy metal ions in water and soil has caused major health problems. The ternary type semiconductor material, reduced graphene oxide (rGO)–Sm$_2$MoO$_6$–TiO$_2$, has been investigated as a photocatalyst for the reduction of soluble chromium(VI) into (III) for the first time. The as-synthesized rGO–Sm$_2$MoO$_6$–TiO$_2$ catalyst was analyzed by X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy, X-ray photoelectron spectroscopy, FT-Raman, Fourier transform infrared, and optical spectroscopy. The maximum Cr(VI) reduction of 96% was achieved within 70 min under visible light illumination. The powder XRD analysis confirmed the formation of anatase TiO$_2$. Field-emission SEM images depicted well-dispersed rGO sheets, and TiO$_2$ and Sm$_2$MoO$_6$ particles are randomly distributed onto rGO. The reduction of Cr(VI) by rGO–Sm$_2$MoO$_6$–TiO$_2$ was considerably greater than the reduction by Sm$_2$MoO$_6$, TiO$_2$, Sm$_2$MoO$_6$–rGO, TiO$_2$–rGO, and Sm$_2$MoO$_6$–TiO$_2$. Sm$_2$MoO$_6$ acts as an effective cocatalyst to TiO$_2$ to enhance the separation of photo-generated electron–holes. Even after six consecutive cycles, the photoreduction of Cr(VI) was more than 85%, which reveals that the excellent reusability performance of the catalyst for practical applications. The photogenerated electron plays an important role in the reduction of Cr(VI) into nontoxic Cr(III), and the synergistic effect of rGO greatly improved the separation of h$^+$ and e$^-$ pairs.

1. INTRODUCTION

Heavy metals in the aquatic system have adverse effects on the environment because of their high toxicity. Chromium has two general oxidation levels under relevant natural conditions: Cr(III) and Cr(VI). Chromium(III) is less mobile, less toxic, and easily precipitated as hydroxides, and Cr(III) is found in many vegetables, fruits, meats, grains, and yeast. Cr(VI) is highly active, dangerous, and toxic and present in the wastewater of chrome plating, electroplating, timber treatment, chilling plants, steel and alloy industries, leather tanning, automobiles, and mining industries. The release of Cr(VI) into the water sources can induce cancer, dermatitis, chronic ulcer, gastrointestinal tract damage, and kidney and lung damage. As a toxic environmental pollutant that induces harmful effects on human beings, the International Agency for Research on Cancer (IARC) has identified Cr(VI) as a type I carcinogen. Hence, the United States Environmental Protection Agency (USEPA) has optimized the limit on the amount of chromium in the drinking water to less than 0.1 mg L$^{-1}$. Because of the harmful nature of Cr(VI), the need for its reduction to Cr(III) from the waste is highly desired. The reduction of chromium(VI) into chromium(III) using chemicals such as sodium bisulfate, sodium thiosulfate, and ferrous sulfate is expensive. Recent strategies for the reduction of Cr(VI) into Cr(III) focus on different methods like chemical reduction, biological reduction, electroreduction, and photocatalytic reduction. In general, chemical routes have maximum reduction rates compared to the other mentioned methods.

In particular, semiconductor-based metal oxides such as TiO$_2$, ZnO, and WO$_3$ have received considerable attention under UV or visible light illumination. Among these semiconducting metal oxides, TiO$_2$ is an excellent material with low cost, high stability, and hypotonicity. Bare TiO$_2$ has been used for Cr(VI) reduction. Suppression of the photo-
generated hole–electron recombination in a semiconductor is needed to improve the efficiency as a photocatalyst. A small amount of foreign atoms added in the regular crystal lattice of the semiconductor oxide material makes dramatic changes in their electronic properties by increasing their electron or hole densities. Photocatalytic reduction of Cr(VI) with modified ZnO and TiO$_2$ was investigated by several authors. Rare-earth materials have received extensive attention because of their catalytic, luminescent, magnetic, optoelectronics, and chemical properties, which originate from their electronic properties by increasing their electron or hole densities. Sm$_2$MoO$_6$ was reported to be an effective photocatalyst to enhance the separation of photogenerated electron–holes and the efficiency of electron transfer. Samarium doping can efficiently improve the photocatalytic reduction rate of TiO$_2$ as a modified semiconducting metal oxide photocatalyst. Reduced graphene oxide (rGO) has a hexagonal honeycomb lattice structure made up of carbon atoms with sp$^2$ hybridization and has excellent electrical, optical, and mechanical properties and thermal stability. rGO is an ideal platform for various composites because of its uniform planar structure and excellent electron transport properties. Combining rGO with TiO$_2$ causes defects in the bandgap of TiO$_2$ and expands its sensitivity range to improve the photocatalytic activity. In this study, we report ternary type semiconductor material rGO–Sm$_2$MoO$_6$–TiO$_2$ for photocatalytic reduction of hexavalent chromium.

2. EXPERIMENTAL SECTION

2.1. Materials and Methods. Ti(OCH$_2$CH$_2$CH$_2$CH$_3$)$_4$, Sm(NO$_3$)$_3$·6H$_2$O, Na$_2$MoO$_4$·2H$_2$O, Graphite flakes, H$_2$SO$_4$, KMnO$_4$, H$_2$O$_2$, and HCl were obtained from Merck chemicals.

2.2. Synthesis of rGO–Sm$_2$MoO$_6$–TiO$_2$. Graphene oxide (GO) was prepared from graphite by Hummer’s method. Natural graphite powder (2.0 g) was added to 180 mL of H$_2$SO$_4$ with 1.5 g of NaNO$_3$, and the mixture was stirred at 10 $^\circ$C for 2 h. Then, 6.0 g of KMnO$_4$ was added, and the reaction mixture was stirred continuously for 24 h at 10 $^\circ$C. The solution mixture was transferred into a 200 mL ice reaction container with 10 mL of H$_2$O$_2$. Then, the solid GO mixture is rinsed with deionized water, 30 wt % of HCl, ethanol, and diethyl ether. The final product was dried to 60 $^\circ$C for 12 h to get GO. To 0.05 M of Sm(NO$_3$)$_3$·6H$_2$O in 70 mL of deionized water, 0.05 M of Na$_2$MoO$_4$·2H$_2$O solution was mixed under stirring for 2 h. The pH value was fixed to 10 using NaOH solution for the formation of Sm$_2$MoO$_6$. The Sm$_2$MoO$_6$ suspension was added with 11.84 mL of titanium(IV) butoxide in 100 mL of ethanol and stirred for 3 h. GO and oxalic acid (100 mg) were added to the above suspension, and the whole mixture was kept in an autoclave at 150 $^\circ$C for 10 h. Then, the final product was annealed at 450 $^\circ$C to obtain rGO–Sm$_2$MoO$_6$–TiO$_2$.

2.3. Photocatalytic Measurement. 2 milligrams of Cr(VI), obtained from K$_2$Cr$_2$O$_7$, was mixed in 100 mL of deionized water with 50 mg of prepared photocatalyst. The solution pH values were fixed as 3, 5, 7, and 9 using dilute H$_2$SO$_4$ and NaOH. The solution was stirred for 30 min without a light source to reach adsorption–desorption equilibrium between the catalyst and Cr(VI). During irradiation, 5–6 mL of solution for every 10 min was collected and centrifuged. The concentration of Cr(VI) was recorded by its absorbance at 350 nm using a UV–visible spectrometer.

2.4. Analytical Method. The X-ray diffraction (XRD) pattern was obtained by a XRD 700 model. Transmission electron microscopy (TEM) images were recorded with a JEM-Z300FSC model. Field emission scanning electron microscopy (FE-SEM) recorded by a JEM-ARM300F instrument. Fourier transform infrared (FT-IR) spectra were recorded by a Nicolet (Madison, USA), and UV vis spectra were recorded using a UV 1280 instrument.

3. RESULTS AND DISCUSSION

3.1. Optical Studies. Diffuse reflectance spectra of Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–TiO$_2$, and rGO–Sm$_2$MoO$_6$–TiO$_2$ in the transmittance mode(Figure 1a) reveal the absorption edges with a steep absorption at 320, 376, and 420 nm. The bandgap energies of Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–TiO$_2$, and rGO–Sm$_2$MoO$_6$–TiO$_2$ were calculated from [F(R)hv]$^{1/2}$ using Kubelka–Munk function, and they are 3.91, 3.12, and 2.94 eV, respectively (Figure 1b).

$$F(R)E^{1/2} = \left[1 - R\right]^2 \times \frac{hv}{2R} \times \frac{1}{\sqrt{hv}}$$

The decreased bandgap energy of rGO–Sm$_2$MoO$_6$–TiO$_2$ may enhance the visible light activity of the material. The bandgap energy of Sm$_2$MoO$_6$–TiO$_2$ is reduced by the addition of rGO.

3.2. Crystal Structure Analysis. The XRD analysis was carried out to find the crystal structure and phase purities of...
TiO$_2$, rGO, Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–TiO$_2$, and rGO–Sm$_2$MoO$_6$–TiO$_2$ composites (Figure 2). All diffraction peaks of pure TiO$_2$ are consistent with the anatase TiO$_2$ which well-coincided with JCPDS card no. 89-4203. The XRD peaks at 25.34, 37.70, 47.94, 54.61, and 62.58 correspond to the planes (101), (004), (200), (211), and (204) anatase phase of titania with a monoclinic structure which is in good agreement with JCPDS file no. 70-1729. The rGO peak at 23.92 corresponds to (002) plane; the rGO peaks were not observed in the XRD spectra of rGO–Sm$_2$MoO$_6$–TiO$_2$ as these characteristic peaks of rGO located at 23.92 might have merged with the characteristic peak of TiO$_2$.\textsuperscript{37,38}

### 3.3. Morphology Analysis of rGO–Sm$_2$MoO$_6$–TiO$_2$

The FE-SEM images of the as-prepared rGO–Sm$_2$MoO$_6$–TiO$_2$ composite are depicted in Figure 3. Well-dispersed rGO sheets can be easily distinguished from Figure 3a,b. The morphology of TiO$_2$ particles is spherical in shape, and randomly distributed TiO$_2$, and Sm$_2$MoO$_6$ nanoparticles as depicted in Figure 3c,d. From Figures 3b–d, it can be observed that the TiO$_2$ particle and Sm$_2$MoO$_6$ nanoparticles are grafted nicely onto the rGO, achieved through the bonding among Sm$_2$MoO$_6$, TiO$_2$, and rGO during the hydrothermal process. Energy-dispersive X-ray (EDX) was performed to know the presence of Sm, Mo, Ti, O, and C in this composite material. The elemental mapping results confirmed the presence of samarium (Sm), molybdenum (Mo), titanium (Ti), oxygen (O), and carbon (C) in the catalyst (Figure 4). The morphological structures of the prepared catalyst were analyzed using TEM images, as depicted in Figure 5. Figure 5a,b at different magnifications confirms that the rGO–Sm$_2$MoO$_6$–TiO$_2$ catalyst constitutes of a large amount of TiO$_2$, and Sm$_2$MoO$_6$ particles on the rGO sheet. The high resolution TEM image of the rGO–Sm$_2$MoO$_6$–TiO$_2$ composite at higher magnification depicted in Figure 5c,d shows fringe spacing of 0.35 nm for anatase TiO$_2$ (101) and 0.28 nm for Sm$_2$MoO$_6$ (321), which are consistent with XRD analysis results.

### 3.4. FT-IR Spectral Analysis

FT-IR spectra for TiO$_2$, Sm$_2$MoO$_6$, and rGO are presented in Figure 6. The low-frequency broad absorption 535, 589, and 601 cm$^{-1}$ can be associated with the vibration of Ti–O–C and Ti–O–Ti bonds, assigned to Ti–O–C in the catalyst. The broad peaks at 3436 and 1620 cm$^{-1}$ correspond to the hydroxyl group.\textsuperscript{39} The presence of less absorption peaks around 1630 cm$^{-1}$ are ascribed to the –OH bending mode.\textsuperscript{40} The vibration peak observed between 600 and 500 cm$^{-1}$ is ascribed to Mo–O characteristics stretching vibration, and small intense peaks between 1000 and 900 cm$^{-1}$ are ascribed to Mo=O stretching vibration, respectively.\textsuperscript{41}

### 3.5. FT-Raman

Figure 7 depicts two major characteristic bands at 1345 and 1585 cm$^{-1}$. The D band peak at 1345 cm$^{-1}$ is ascribed to the breathing mode of \textit{k}-point phonons, and the G band position at 1585 cm$^{-1}$ is ascribed to the sp$^2$ hybridization. The D band ratio can be measured as the disorder degree and restoration of the sp$^2$ carbon bonded structure of GO. The intensity ratio values of the D and G bands can reflect the size of sp$^2$ carbon bonded structural disorder of rGO sheets. After the reduction, the $I_D/I_G$ ratio increases compared with the GO. The $I_D/I_G$ ratio values for GO and rGO can be found out, and they are 0.862 and 1.142, respectively. The $I_D/I_G$ of rGO is 1.142, which is higher than that of GO, suggesting an increase in the smaller rGO upon reduction of GO.\textsuperscript{42,43}

### 3.6. X-ray Photoelectron Spectroscopy Spectra of rGO–Sm$_2$MoO$_6$–TiO$_2$

X-ray photoelectron spectroscopy (XPS) was recorded to know the chemical composition of the catalyst, which is shown in Figure 8. The survey spectrum of rGO–Sm$_2$MoO$_6$–TiO$_2$ indicated that elements such as Sm, Mo, Ti, O, and C are present in the catalyst (Figure 8a). The Ti 2p core-level photoelectron spectrum depicted that the binding energy peaks 458.8 and 464.6 eV correspond to Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$, respectively (Figure 8b), which agree with the binding energy value of the pure anatase Ti$^{4+}$ state.\textsuperscript{44} In Sm$_2$MoO$_6$, the typical peaks 1083.6 and 1110 eV correspond to Sm 3d$_{5/2}$ and Sm 3d$_{3/2}$ and are attributed to Sm$^{3+}$ (Figure 8c). The binding energy peaks at 233.1 and 236.2 eV are assigned to Mo 3d$_{5/2}$ and Mo 3d$_{3/2}$, respectively, depicting a six valence oxidation state for Mo$^{6+}$ in the composite material (Figure 8d).\textsuperscript{25,45,46} The Gaussian peaks at 531.6 and 532.8 eV correspond to the lattice oxygen, oxygen vacancy, and O–H bonds, as shown in Figure 8e. The XPS spectral analysis of carbon C 1s was split into three Gaussian peaks 284.8, 286.2, and 288.8 eV and was indexed to C–C, C–O–C, and C–O, respectively (Figure 8f).\textsuperscript{47,48}
3.7. Photocatalytic Reduction of Cr(VI) into Cr(III).

Photocatalytic chromium(VI) reduction was performed with Sm$_2$MoO$_6$, rGO, TiO$_2$, TiO$_2$–rGO, and rGO–Sm$_2$MoO$_6$–TiO$_2$ catalysts, and reduction curves are displayed in Figure 9. The initial test depicted that no reduction was observed without light, resulting that the reduction was mainly due to the photocatalyst. A slight decrease in chromium(VI) concentration around 12% is due to adsorption in the blank condition after 70 min. With prepared catalyst rGO–Sm$_2$MoO$_6$–TiO$_2$, the reduction of Cr(VI) was almost complete in 70 min under visible light illumination. The composite material rGO–Sm$_2$MoO$_6$–TiO$_2$ catalyst was more efficient than other catalysts Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–rGO, TiO$_2$, TiO$_2$–rGO, and rGO–Sm$_2$MoO$_6$–TiO$_2$ catalysts, and reduction curves are displayed in Figure 9. The initial test depicted that no reduction was observed without light, resulting that the reduction was mainly due to the photocatalyst. A slight decrease in chromium(VI) concentration around 12% is due to adsorption in the blank condition after 70 min. With prepared catalyst rGO–Sm$_2$MoO$_6$–TiO$_2$, the reduction of Cr(VI) was almost complete in 70 min under visible light illumination. The composite material rGO–Sm$_2$MoO$_6$–TiO$_2$ catalyst was more efficient than other catalysts Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–rGO, TiO$_2$, and TiO$_2$–rGO. Percentages of chromium Cr(VI) reductions are 41, 57, 72, 81, and 96 under visible light illumination in 70 min for catalysts Sm$_2$MoO$_6$, Sm$_2$MoO$_6$–rGO, TiO$_2$, TiO$_2$–rGO, and rGO–Sm$_2$MoO$_6$–TiO$_2$, respectively, as shown in Figure 9a. To analyze the effect of dosage of rGO–Sm$_2$MoO$_6$–TiO$_2$ in Cr(VI) reduction, various weight ratios such as 30, 40, 50 and 60 mg of catalyst were added and photocatalytic reduction was investigated under identical conditions.
The photoreduction performances of different weight ratios of rGO−Sm$_2$MoO$_6$−TiO$_2$ are 60, 75, 96, and 92%, corresponding to weight ratios 30, 40, 50, and 60 mg, respectively. The increase of the catalyst amount increases the reduction of Cr(IV) due to the increased adsorption by the catalyst particle and increased density in the area of illumination. Under these experimental conditions, 50 mg/100 mL of catalyst is found to be an optimum dosage for effective reduction of Cr(VI) to Cr(III) under visible light illumination in 70 min. Cr(VI) reduction rate increases up to 50 mg/100 mL, and a further increase of the catalyst amount decreases the reduction rate. At 60 mg/100 mL concentration (above 50 mg/100 mL), scattering of light by catalyst particles decreases the reduction rate. Figure 9c,d shows the kinetic curves of photoreduction of Cr(VI) with different catalysts and dosage of rGO−Sm$_2$MoO$_6$−TiO$_2$. The pseudo-first-order rate constant values for Sm$_2$MoO$_6$, TiO$_2$, TiO$_2$−rGO, and rGO−Sm$_2$MoO$_6$−TiO$_2$ are 0.0112, 0.0185, 0.0259, 0.0371, and 0.0716 min$^{-1}$, respectively. The rate constant values of 0.0135, 0.0197, 0.04717, and 0.03406 min$^{-1}$ correspond to 30, 40, 50, and 60 mg weights of the catalyst, respectively. The maximum rate constants are 0.0716 min$^{-1}$ for the composite material and 0.04717 min$^{-1}$ for 50 mg of catalyst, which indicates optimum conditions for maximum chromium reduction under visible light irradiation. From Figure 9e, the decrease in intensity of the absorption band with respect to time of visible light illumination in the presence of the rGO−Sm$_2$MoO$_6$−TiO$_2$ catalyst is observed. The UV absorption peak at 350 nm for K$_2$Cr$_2$O$_7$ decreases over time due to the reduction of Cr(VI). The influence of various Cr(VI) concentrations was performed at 10 to 40 mg/L of Cr(VI) to find the optimum condition with the catalyst used. The concentration change with respect to the illumination time is shown in Figure 10a. The Cr(VI) reduction is decreasing from 95 to 59% by increasing its initial concentration from 10 to 40 mg/L. With the increase of Cr(VI) concentration up to 40 mg/L, the photoreduction is gradually decreased due to the reason that the amount of the catalyst is the same and the difficulty of light entry to the catalyst surface (Figure 10a). The photocatalytic reduction of Cr(VI) by rGO−Sm$_2$MoO$_6$−TiO$_2$ was performed at various pH values from 3, 5, 7, and 9 with the initial Cr(VI) concentration of 10 mg/L, and reduction percentages are shown in Figure 10b. After 70 min visible light illumination, the Cr(VI) reduction percentages are 93.8, 88, 63.3, and 47.8% corresponding to pH values 3, 5, 7, and 9, respectively. The best performance pH level is 3 and 5 for the reduction of Cr(VI). As reported earlier, acidic pH condition is favorable for the electrostatic attraction between the catalyst and chromate ion which increases the reduction of Cr(VI). The rate constant values for different concentrations of Cr(VI) with the rGO−Sm$_2$MoO$_6$−TiO$_2$ catalyst were calculated from.
Figure 9. Photocatalytic reduction of Cr(VI) under different conditions: (a) different catalysts (catalysts: 50 mg, Cr(VI): 10 mg/L), (b) different dosage of rGO–Sm2MoO6–TiO2 (Cr(VI) conc.: 10 mg/L), (c) first-order kinetic plots of ln[C0/C] vs time for different catalysts and (d) different dosage of rGO–Sm2MoO6–TiO2, and (e) absorbance spectrum of Cr(VI) in the presence of 50 mg of catalyst.

Figure 10. Photocatalytic reduction of Cr(VI) under different concentrations: (a) different Cr(VI) concentration, (b) different pH condition of Cr(VI) in the presence of rGO–Sm2MoO6–TiO2, (c) first-order kinetic plots of ln[C0/C] vs time for different concentrations, and (d) different pH of Cr(VI) in the presence of rGO–Sm2MoO6–TiO2.
kinetic curves displayed in Figure 10c,d. The pseudo-first-order rate constants 0.0391, 0.0263, 0.0181, and 0.0129 min⁻¹ correspond 10, 20, 30, and 40 mg/L of Cr(VI), and at pH values 3, 5, 7, and 9, pseudo-first-order rate constants are 0.0373, 0.0288, 0.0134, and 0.0078 min⁻¹, respectively. The highest rate constant values of 0.0391 and 0.0373 min⁻¹ for maximum reduction were observed at 10 mg/L of Cr(VI) and at pH 3.

3.8. Reusability and Recovery Experiment. The reusability efficiency of rGO–Sm₂MoO₆–TiO₂ was investigated by recycling the recovered catalyst, and the results are shown in Figure 11. The reduction percentages for the first two cycles are 88 and 86%, respectively. The efficiency of the catalyst is decreased to 84, 83, 81, and 80% for the third, fourth, fifth, and sixth cycles, respectively. The reduction percentage up to sixth use of the catalyst was not changed much. The slight variation in the photoreduction performance in the recycling experiment may be due to the adsorption of the Cr(VI) solution on the surface of the catalyst. Figure 12 depicts the effect of scavengers used to identify the main reactive species involved in the reduction process. Isopropyl alcohol, AgNO₃, and triethanolamine were used as scavengers for *OH, e⁻, and h⁺, respectively. Cr(VI) reduction with rGO–Sm₂MoO₆–TiO₂ is highly suppressed by AgNO₃ (32.1%), which shows the main role of e⁻ in the reduction process. Band gap energy of TiO₂ is decreased to 2.94, by the presence of Sm₂MoO₆, making the catalyst visible-active. When the rGO–Sm₂MoO₆–TiO₂ composite material is exposed to visible light, the electron in TiO₂ are excited from the valence band to conduction band and the Sm₂MoO₆ as a cocatalyst, effectively separates electron and hole preventing their recombination. Reduced GO sheets was reported to serve as electron collectors and sources of adsorption sites generating the reactive centers of the photoreduction. In addition, rGO resists the recombination of electrons and hole pairs effectively because of its excellent electrical conductivity. Hence, the presence of rGO increases in photocatalytic activity synergistically. Further, the h⁺ reacts with H₂O to form hydroxyl radicals and then H₂O₂ to induce Cr(VI) reduction with the help of h⁺. Based on these observations, a mechanism for photoreduction of Cr(VI) is proposed in Scheme 1.

4. CONCLUSIONS

Ternary semiconductor photocatalyst rGO–Sm₂MoO₆–TiO₂ was prepared by the hydrothermal method and characterized by a suitable analytical method. The FT-Raman spectral analysis confirmed the reduction of GO into rGO sheets. FE-SEM images depicted that TiO₂ and Sm₂MoO₆ particles are randomly distributed onto a well-dispersed rGO sheet. The powder XRD pattern confirmed the formation of anatase TiO₂ with (101) plane. The maximum Cr(VI) reduction of 96% was achieved in 70 min visible light illumination with rGO–Sm₂MoO₆–TiO₂ indicating its higher reduction efficiency than other catalysts. Even at the sixth cycle, the prepared photocatalyst has 80% efficiency for the reduction of Cr(VI) under visible light. The photogenerated electron plays an important role for the reduction of Cr(VI) into nontoxic Cr(III), and holes are captured by water forming hydroxide radicals and then hydrogen peroxide, leading to the separation of h⁺ and e⁻ pairs. Sm₂MoO₆ acts as an effective cocatalyst to enhance the separation of photogenerated electron–holes and rGO as an electron collector increases the photocatalytic activity synergistically.

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The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

The authors thank Kalasalingam Academy of Research and Education for providing research facilities. We are thankful to the Centre for Nanoscience and Technology, Anna University for PT-Raman facility.

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**Notes**

The authors declare no competing financial interest.
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