Novel Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid material as highly efficient CWAO catalyst for dye degradation at ambient conditions

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We report a novel hybrid material Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ as highly efficient catalytic wet air oxidation (CWAO) catalyst, which showed the highest ever activity at room temperature and atmosphere pressure for the degradation of cationic red GTL. SEM and TEM analyses indicated that this hybrid catalyst has bamboo-shaped nanofiber morphology. In view of practical applications, the influence of some key parameters including operation temperature, catalyst calcination temperature, and the volume of dye wastewater have been optimized. The mechanism for the superior catalytic performance was investigated. XRD, XPS, and ESR suggested the Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid catalyst possesses more O$_2$ ions in the oxygen deficient regions than neat α-MoO$_3$, promoting the formation of active ·OH radicals and resulting in a higher activity. Considering the facile preparation and its superior activity, this novel catalyst is promising for practical dye wastewater treatment.

The dye wastewater generated from textile industries contains a wide variety of organic pollutants, which have a severe influence on both environment and human health. Even small amount of dyes in water (about 10–20 mg/L) is highly visible, affecting the water transparency and gas solubility, and consequently the photosynthetic activity in aquatic biota.$^{12}$ Some dyes can be considered as carcinogens or mutagens as well.$^6$ Therefore, it is urgent to search for a suitable method for the treatment of dye wastewater. Previously, many technologies have been developed, which include biological treatment, wet air oxidation (WAO), ozone treatment, and chemical coagulation, etc. However, all the above methods have their own shortages.$^{6-11}$ For instance, although WAO method is very effective in removing color and chemical oxygen demand (COD), high temperature and pressure are always needed (e.g. 175–320°C, 0.5–20 MPa)$^{12-14}$. Recent studies have proven that catalytic wet air oxidation (CWAO) is a very promising advanced oxidation process to efficiently degrade the dyes under relatively mild conditions.$^{15}$ Although CWAO can significantly relax the oxidation condition, it still requires a temperature in the range of 80–180°C and a pressure in the range of 1–5 MPa.$^{15-17}$ From the economical point of view, there is still a need and challenge to further improve the catalytic activity and the long-term stability of catalysts in order to achieve a more efficient degradation of organic compounds under a more mild condition. Particularly it will be ideal for practical applications if the dye wastewater can be efficiently treated at room temperature and atmosphere pressure.

For CWAO, the degradation activities of dyes are highly dependent on the catalysts used. Although there are many catalysts that have been reported for CWAO, only few of them can achieve high performances under room temperature and atmosphere pressure conditions. Such catalysts reported in literatures include Ce/MoO$_3$,$^{17}$ Zn$_2$PW$_{12}$O$_{40}$,$^8$ Mo-Zn-Al-O$^9$, ZnO/MoO$_2$/SiO$_2$,$^{10}$ ZnO/MoO$_3$/SiO$_2$,$^{11}$ CuO-MoO$_2$-P$_2$O$_5$,$^{12}$ Fe$_2$O$_3$-MoO$_3$-TiO$_2$/γ-Al$_2$O$_3$,$^{13}$ Zn$_{13}$PMo$_{12}$O$_{40}$,$^{14}$ etc. All these catalysts, their testing conditions, and catalytic performances were summarized in Table 1. The first CWAO catalyst (Fe$_2$O$_3$-CeO$_2$-TiO$_2$/γ-Al$_2$O$_3$) that showed high activity at room temperature and atmosphere pressure was reported by Liu and Sun in 2007.$^{21}$ With 100 mL and 500 mg/L methyl orange dye solution, 98.1% of color and 96.1% of total organic carbon (TOC) were removed.
within 2.5 h at 25°C and 1 bar. However, a big amount of catalyst (3 g) was required, corresponding to a catalyst/dye ratio of 60. In the same year, Ma et al.² reported CuO-MoO₃-P₂O₅ and Fe₂O₃-MoO₃-P₂O₅ catalysts that can achieve 98.0–99.3% color removal within 10 min (1.33 g catalyst, 100 mL, 300 mg/L, 35°C and 1 bar). The catalyst/dye ratio was slightly decreased, but still as high as 44.3. Later on, several more active catalysts such as ZnO/MoO₃, ZnO/MoO₃/SiO₂, Mo-Zn-Al-O, and Zn₁₅PW₁₂O₄₀ were developed, with the catalyst/dye ratio decreasing to 33.3, 33.3, 32, and 29.3, respectively. Up to the date, the most active catalyst was Ce/MoO₃ with a catalyst/dye ratio of only 3.3. Under the testing condition of 0.1 g catalyst, 100 mL, and 300 mg/L Safranin-T, 98% degradation ratio could be achieved within 20 min at 25°C and 1 bar. In this contribution, we reported a new CWAO catalyst, Na₂Mo₄O₁₃/γ-MoO₃ hybrid material with remarkably higher catalytic activity at room temperature and atmosphere pressure. By adding only 0.05 g catalyst into 300 mL, 200 mg/L dye solution, a 100% decolorization rate could be reached within 30 min at 30°C and 1 bar. The catalyst/dye ratio is only 0.83, the lowest value ever comparing to all the reported catalysts, suggesting that this new catalyst is highly feasible and promising for practical applications in dye wastewater treatments.

### Results

A series of catalysts were first synthesized using hydrothermal method at 120°C with ammonium heptamolybdate tetrahydrate ((NH₄)₁₉Mo₇O₂₄·4H₂O) as precursor. The pH was controlled in the range of 1–7 by adding either HNO₃ or NaOH solution. We found that white products could be obtained when the pH was not higher than 6. However, no solid product was observed with a further increase in pH to 7. Then all the white products were calcined at 400°C in air for 5 h, and evaluated for the degradation of cationic red GTL, as shown in Figure 1. The results indicate that the synthesis pH had a great effect on the performance of obtained catalysts. Generally the activity of the catalysts increased with increasing the synthesis pH. When the synthesis pH was low (1–4), the catalytic activity was very poor, with a degradation efficiency lower than 40% after 90 min. When the synthesis pH was 5, the activity was significantly increased, with a degradation efficiency of ca. 80% after 90 min. But its activity was still not acceptable due to its relatively low kinetics. After 30 min, its degradation efficiency was only ca. 38%. However, surprisingly the catalyst synthesized at pH = 6 was observed to exhibit extremely high activity, i.e., 100% degradation efficiency was achieved within 35 min. This is the highest activity among all the reported CWAO catalysts when evaluated at room temperature and atmosphere pressure, with a catalyst/dye ratio of 1.67. Since for all the catalysts, the only difference was the synthesis pH, we are very much interested in how the synthesis pH influences the chemical composition and activity of the obtained catalysts. Thus, a thorough characterization of all the catalysts was performed in the following sections.

In order to have a better understanding of all the synthesized catalysts and make it clear what is the key parameter determining the activities, XRD analyses were carried out with both fresh and calcined samples. Figure 2(a) shows that when the pH = 1, pure h-MoO₃ was synthesized (JCPDS no. 21-0569). When the pH = 2, it formed the formation of hybrid compound containing (NH₄)₂Mo₇O₂₄ and (NH₄)₂Mo₆O₁₆. However, when the pH was in the range of 3–5, the diffraction peaks of (NH₄)₂Mo₆O₁₆ disappeared, suggesting the formation of pure (NH₄)₂Mo₆O₁₆. Further increasing the pH value to 6, a new hydrate compound of NaNH₄Mo₆O₁₅·H₂O was obtained. Figure 2(b) indicates that after the samples were calcined at 400°C, all the samples synthesized with pH in the range from 1 to 5 were transformed to pure γ-MoO₃ (JCPDS No. 35-0609). The characteristic diffraction peaks of γ-MoO₃ at 2θ = 12.78°, 23.34°, 25.70°, 27.34°, 33.76°, 38.98°, 46.32°, 49.26°, and 58.8° can be indexed to the reflections of 020, 110, 040, 23.34°, 25.70°, 27.34°, 33.76°, 38.98°, 46.32°, 49.26°, and 58.8°, respectively. While the sample synthesized with pH = 6 was transformed into a hybrid material containing Na₂Mo₃O₁₃ and γ-MoO₃. The characteristic peaks of Na₂Mo₃O₁₃ was observed at 2θ = 15.96°, 22.55°, 24.10°, 28.49°, 29.96°, and 32.41° (JCPDS No. 28-1112). Similar phenomenon had been previously observed by Sotani et al.²⁴ By thermal decomposing one type of hydrated potassium brone K₀.₂₃MoO₃(H₂O)₀.₄₅, similar.

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Table 1 | Summary of results from CWAO studies on the degradation of organic dyes

| Catalyst | Catalyst amount (g) | Volume (mL) | Dye concentration (mg/L) | Testing temperature (°C) | Time (min) | g<sub>catalyst</sub>/g<sub>dye</sub>* | Adsorption rate (%) | Ref. |
|----------|---------------------|-------------|--------------------------|--------------------------|------------|-------------------------------|-------------------|------|
| Na₉Mo₄O₁₃/γ-MoO₃ | 0.05 | 300 | 200 | 30 | 30 | 0.83 | 100.0 | This work |
| Ce/MoO₃ | 0.1 | 100 | 300 | 25 | 20 | 3.3 | 98.0 | 17 |
| Zn₁₅PW₁₂O₄₀ | 0.2 | 200 | 34.1 | RT | 360 | 29.3 | 80.0 | 18 |
| Mo-Zn-Al-O | 0.272 | 100 | 85 | RT | 60 | 32 | 80.1 | 19 |
| ZnO/MoO₃/SiO₂ | 1 | 100 | 300 | RT | 25 | 33.3 | 95.3 | 1 |
| ZnO/MoO₃ | 1 | 100 | 300 | RT | 18 | 33.3 | 98.0 | 20 |
| CuO-MoO₃-P₂O₅ | 1.33 | 100 | 300 | 35 | 10 | 44.3 | 99.3 | 21 |
| FeO₂-MoO₃-P₂O₅ | 1.33 | 100 | 300 | 35 | 30 | 44.3 | 99.0 | 22 |
| Fe₂O₃-Co₂TiO₂/γ-Al₂O₃ | 3 | 100 | 500 | 25 | 150 | 60 | 98.1 | 23 |
| Zn₁₅PMo₁₂O₄₀ | 0.1 | 10 | 10 | RT | 40 | 100 | 98.0 | 22 |

*<sub>g<sub>catalyst</sub>/g<sub>dye</sub> represents the catalytic activity of catalysts, the lower value shows the higher catalytic activity of catalyst.
hybrid materials consisting K$_2$Mo$_4$O$_{13}$ and MoO$_3$ were prepared. In couple with the activity tests, these data clearly suggest that the catalytic activity of pure α-MoO$_3$ is moderate, consistent with the literature reports. However, in the presence of Na$_2$Mo$_4$O$_{13}$, the activity was markedly improved, indicating that Na$_2$Mo$_4$O$_{13}$ plays a crucial role in this catalytic degradation of cationic red GTL reaction.

The samples were further characterized by FE-SEM and SEM-EDX. Figure 3 shows the typical SEM images that give a panoramic picture of all the fresh samples synthesized at different pH. Through the hydrothermal decomposition of precursor at pH = 1, well-defined h-MoO$_3$ nanorods were obtained. Figure 3(a) depicts a cluster of unique flower-like morphology of h-MoO$_3$ nanorods. With increasing the pH from 1 to 3, the morphology of the samples changed from nanorods to nanoplates (Figure 3(b,c)). With a further increase of pH from 3 to 5, the nanoplates were gradually cracked down into small pieces, transforming from nanoplates into nanofibers. At pH = 6, the sample was completely transformed into uniform nanofibers, with a chemical composition of NaNH$_4$Mo$_3$O$_{10}$·H$_2$O. The energy dispersive X-ray spectroscopy analysis (EDX) was also analyzed with the fresh sample synthesized at pH = 6. Both Na and N elements were detected with a molar ratio of 1:1. Together with the XRD analysis, it further confirms the formation of NaNH$_4$Mo$_3$O$_{10}$·H$_2$O single crystals at pH = 6. It can be concluded that the synthesis pH value has an important effect on the morphology and size of the samples. Figure 4 illustrates that the morphology of catalysts was changed obviously after being calcined at 400 ºC. Although most of the samples maintained their overall morphologies, the previously well crystallized single crystals were cracked down into small pieces of nanoparticles due to the thermal decomposition. For instance, for the most active hybrid catalyst, i.e., Na$_2$Mo$_4$O$_{13}/$α-MoO$_3$, it was obtained by the thermal decomposition of NaNH$_4$Mo$_3$O$_{10}$·H$_2$O single crystal nanofibers. After being calcined at 400 ºC, it showed bamboo shaped nanofibers, which are composed of many nanoparticles connected together.

Figure 5 shows the TEM images and the SAED patterns of the hybrid catalyst Na$_2$Mo$_4$O$_{13}/$α-MoO$_3$. Figure 5(a) further confirms the bamboo like nanofiber morphology of the synthesized Na$_2$Mo$_4$O$_{13}/$α-MoO$_3$ catalyst, with a diameter of ca. 350–450 nm. HR-TEM analysis suggested that the major component of the nanofibers is α-MoO$_3$. The lattice spacing along two different directions can be observed in Figure 5(b), which correspond to d$_{100}$ (3.6 nm) and d$_{001}$ (3.9 nm) of the orthorhombic α-MoO$_3$ phase, respectively. The SAED pattern (Figure 5(d)) of the sample in Figure 5(c) also confirms the formation of α-MoO$_3$ phase, with the [-1-10] direction as the zone axis. In addition, how the hybrid catalysts were synthesized with different pH. (a) before calcination, (b) after calcination at 400 ºC. (■) h-MoO$_3$, (△) (NH$_4$)$_2$Mo$_4$O$_{13}$, (●) (NH$_4$)$_4$Mo$_8$O$_{26}$, (▼) NaNH$_4$Mo$_3$O$_{10}$·H$_2$O, (□) α-MoO$_3$, and (○) Na$_2$Mo$_4$O$_{13}$.
Na$_2$Mo$_4$O$_{13}$ phase is distributed within the sample is more interesting. During the thermal transformation process from the NaNH$_4$Mo$_3$O$_{10}$·H$_2$O single crystals to the hybrid material Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$, since the calcination temperature (300–400 °C) was not too high, we can expect that the Na$_2$Mo$_4$O$_{13}$ must disperse well with limited agglomerations. Thus, elemental mappings with Mo, O, and Na, Figure 5(e–h), clearly indicate that the Na element was distributed uniformly within the sample. This data suggests that the particle size of Na$_2$Mo$_4$O$_{13}$ should be very small and it was uniformly distributed within the α-MoO$_3$ phase. Both the existence of nanophased Na$_2$Mo$_4$O$_{13}$ and the abundant interfaces created between Na$_2$Mo$_4$O$_{13}$ and α-MoO$_3$ are believed to play an important role in its superior catalytic activity.

By now, novel hybrid materials Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ with bamboo shaped nanofiber morphology have been demonstrated as a highly efficient catalyst for the degradation of cationic red GTL. However, for its practical applications, several important parameters have to be optimized, such as the operation temperature, catalyst calcination temperature, and the volume of dye wastewater, etc. Since this catalyst is aimed to treat dyes at ambient conditions, three temperatures of 25, 30, and 35 °C were chosen. Figure 6(a) depicts the influence of testing temperatures on the degradation efficiency. It is obvious that the catalytic performance of catalyst was changed significantly as varying the testing temperature. Higher temperature resulted in higher degradation efficiency. At 25 °C, it took 60 min to reach 100% degradation efficiency. While only 35 and 17 min were needed at 30 and 35 °C, respectively. This data suggests that the operation temperature is one of the key parameters and has a great influence on the catalytic activity of the hybrid catalyst Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$. Considering that the activity at 25 °C is too low and the temperature of dye wastewaters is rarely as high as 35 °C, all the following tests were performed at 30 °C.

In addition, in order to demonstrate that the removal of cationic red GTL from wastewater is truly due to the catalytic oxidation, not adsorption, an adsorption experiment was designed and carried out as well. To prevent the influence of O$_2$ dissolved in H$_2$O, the dye solution was first purged with N$_2$ for at least 30 min before adding the catalyst. And during the whole test, the system was protected with continuous N$_2$, by which the catalytic oxidation of dyes can be ignored. As shown in Figure 6(a), the adsorption of cationic red GTL was very low, with a removal rate of only 22.8% after 150 min. This experiment clearly indicated that the adsorption of cationic red GTL by catalyst was not obvious and the true activity came from the catalytic oxidation in the presence of O$_2$.

It is well accepted that the calcination temperature might influence the decomposition process, which in turn determine the composition and phase of the obtained catalysts. The influence of calcination temperatures on this novel catalyst Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ was
The calcination temperature also has a great effect on the activity of the novel hybrid catalyst Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$. Thus, it can be concluded that the calcination temperature was found to be 300 °C for 5 h, all samples synthesized with pH in the range from 1 to 3 transformed into pure α-MoO$_3$. However, when the synthesis pH = 4–6, the sample transferred into α-MoO$_3$/Na$_2$Mo$_4$O$_{13}$ hybrid materials.

As the XRD analyses had confirmed the formation of the new hybrid material of Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$, we performed a further study to verify the high catalytic activity of this novel hybrid material. It can be seen from Figure 8 that the catalytic activity of catalysts also increased with the increase in synthesis pH. Under the same test condition, the catalytic activity of samples which were synthesized at lower pH value (pH < 1) was very poor, with the degradation efficiency of 23.55% and 49.71%, respectively. However, when the synthesis pH increased to 3, the activity significantly increased with nearly 100% removal of dye after 90 min. While when the synthesis pH was increased to 4–6, we found that all catalysts showed high catalytic activity, 100% of degradation efficiency can be reached within 30 min. The long-term stability of the catalyst is extremely essential for its practical application. Figure S2(b) shows the degradation efficiency of cationic red GTL in the presence of Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid catalyst during the cycling tests. The catalyst exhibited a very good durability and there was almost no noticeable decrease in the activity even after seven cycles. The degradation percentage of cationic red GTL still reached a value of 99.53% even after 7th cycle.

**Discussions**

In order to know whether the containing of Na is the key parameter determining the catalytic activity, we conducted a control experiment that a series of samples were synthesized at different pH by adding certain amount of NaNO$_3$ (2.04 g) during each synthesis. XRD analyses were carried out with both fresh and calcined samples. As shown in Figure 7(a) that when the pH = 1, pure (NH$_4$)$_4$Mo$_8$O$_{26}$ was synthesized. With the synthesis pH increased from 2 to 3, we found the existence of a kind of hybrid compound which contains (NH$_4$)$_4$Mo$_8$O$_{26}$ and (NH$_4$)$_2$Mo$_4$O$_{13}$. When the pH value was in the range of 4–6, the diffraction peaks of (NH$_4$)$_4$Mo$_8$O$_{26}$ were disappeared, and a new compound of NaNH$_4$Mo$_3$O$_{10}$·H$_2$O was synthesized at the same time. Figure 7(b) indicates that after the calcination at 400 °C for 5 h, all samples synthesized with pH in the range from 1 to 3 transformed into pure α-MoO$_3$. However, when the synthesis pH = 4–6, the sample transferred into α-MoO$_3$/Na$_2$Mo$_4$O$_{13}$ hybrid materials.

With a fixed dosage of catalyst, how much wastewater can be processed is another important parameter for practical application. Apparently the more wastewater the catalyst can treat, the more economical and feasible it will be. Thus, the influence of wastewater volume in the range of 300–500 mL was evaluated with 0.1 and 0.05 g catalyst, respectively. The dye concentration was fixed at 200 mg/L. Figure S1 indicates that the degradation efficiency gradually increased with decreasing the wastewater volume. The higher the volume was, the longer the time was needed for the 100% degradation efficiency. With 0.1 g catalyst, all three volumes reached 100% degradation within 30 min, particularly when the wastewater volume was 300 mL, only 10 min was needed. When the catalyst was reduced to 0.05 g, a relatively longer time was needed for 100% degradation, for instance, 30, 60, and 150 min for 300, 400, and 500 mL, respectively. Since a longer reaction time will increase the energy penalty, 0.05 g catalyst was recommended for usage to treat 300 mL wastewater, in which all dyes could be completely degraded within 30 min.

To further evaluate the catalytic activity of Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid catalyst, mineralization of cationic red GTL was investigated by monitoring the changes of TOC as a function of reaction time. Figure S2(a) indicates that the Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid catalyst is very active, a TOC removal rate of ca. 93% was achieved within 5 min. The long-term stability of the catalyst is extremely essential for its practical application. Figure S2(b) shows the degradation efficiency of cationic red GTL in the presence of Na$_2$Mo$_4$O$_{13}$/α-MoO$_3$ hybrid catalyst during the cycling tests. The catalyst exhibited a very good durability and there was almost no noticeable decrease in the activity even after seven cycles. The degradation percentage of cationic red GTL still reached a value of 99.53% even after 7th cycle.
containing Na₂Mo₄O₁₃ and α-MoO₃ was synthesized. The intensity of Na₂Mo₄O₁₃ in the hybrid catalyst was weakened at 400 °C and disappeared at 500 °C. This trend is consistent with the catalytic activity test, which first increased with the calcination temperature up to 300 °C, and then started to decrease from 400 to 500 °C. This data clearly suggests that the existence of Na₂Mo₄O₁₃ is critical for its good catalytic activity.

The catalytic degradation process of cationic red GTL was monitored using UV-Vis spectroscopy. Figure 10(a) shows the evolution of the UV-Vis spectra of the dye solution as a function of reaction time in the presence of Na₂Mo₄O₁₃/α-MoO₃ catalyst and bubbled air. At the initial stage, two major absorbance peaks at 285 and 488 nm were observed and attributed to the benzene ring and the azo linkage of cationic red GTL 30. However, these two peaks were significantly weakened after 20 min, and completely disappeared after 30 min, indicating that the cationic red GTL molecules were destroyed by catalytic oxidation. The absorbance peak at 203 nm also became weaker in intensity and offset in the direction of long wavelength. After 30 min, a new absorbance peak at 213 nm appeared and its intensity increased with increasing the reaction time, suggesting the production of a new kind of intermediates during the reaction 31. However, if N₂ instead of air was used, a totally different evolution of the UV-Vis spectra was observed, as shown in Figure 10(b). With increasing the treatment time, those three characteristic peaks at 203, 285, and 488 nm still remained, with a slight decrease in intensity. This data further demonstrates that O₂ is critical for the catalytic degradation of dyes. In the absence of O₂, catalytic reaction can not be preceded due to the absence of active ·OH radical, and only a moderate adsorption occurred on the surface of catalyst 32. The specific surface area of the sample synthesized at pH = 6 was also analyzed using N₂ adsorption-desorption isotherm. Before calcination, the product was NaNH₄Mo₃O₁₀·H₂O and its specific surface area was 1.0 m²/g. After being calcined at 400 °C, the product transformed into Na₂Mo₄O₁₃/α-MoO₃ and its specific surface area was 2.9 m²/g. With such low specific surface area, it is reasonable that the adsorption of dye was negligible and the main function was catalytic oxidation.

Figure S3 shows the XPS survey spectra of α-MoO₃ and Na₂Mo₄O₁₃/α-MoO₃, both of which exhibit dominant peaks of Mo and O, along with a C 1s peak due to the surface contamination by sample handling or instrument background. In addition, an extra Na 1s peak was observed for Na₂Mo₄O₁₃/α-MoO₃ at 1070.9 eV. Figure 11(a,b) shows that the O1s peaks are asymmetric and broad, suggesting the coexistence of adsorbed oxygen with high binding energy and lattice oxygen with low binding energy on the surface of catalysts. The peak centered at 530 eV was associated with the
O²⁻ ions in the metal oxide, the peak at 530.6 eV was associated with the O²⁻ ions in the oxygen deficient regions, and the binding energy peak at 530.9 eV was attributed to the surface loosely bound O²⁻. Figure 11(a,b) clearly shows that the relative concentration of O²⁻ ions in the oxygen deficient regions for Na₂Mo₄O₁₃/α-MoO₃ is higher than that for α-MoO₃. This data suggests that more defects were created due to the coexistence of Na₂Mo₄O₁₃ and α-MoO₃ in the hybrid catalyst. According to the literature, the O²⁻ ions in the oxygen deficient regions which have higher mobility than lattice oxygen, can actively take part in the oxidation process and greatly contribute to the catalyst activity.

Particularly, the higher concentration of the O²⁻ ions in the oxygen deficient regions in the Na₂Mo₄O₁₃/α-MoO₃ hybrid catalyst might promote the formation of active -OH radicals. In order to prove this, ESR analysis was performed by placing both α-MoO₃ and Na₂Mo₄O₁₃/α-MoO₃ in water (Figure 12). When the solution was bubbled with air, four characteristic peaks of DMPO-OH were clearly observed for both α-MoO₃ and Na₂Mo₄O₁₃/α-MoO₃ catalysts. And the -OH intensity for Na₂Mo₄O₁₃/α-MoO₃ is higher than that for α-MoO₃, suggesting that more -OH radicals were produced than α-MoO₃ under the same condition. It is also worth to mention that when the solution was bubbled with N₂, no -OH signal was observed. This data provided the intrinsic reason why Na₂Mo₄O₁₃/α-MoO₃ is more active than α-MoO₃ and O₂ is essential for the catalytic oxidation reaction.

In conclusion, a novel hybrid CWAO catalyst of Na₂Mo₄O₁₃/α-MoO₃ was synthesized using a facile hydrothermal method and demonstrated extremely high catalytic activity for the degradation of cationic red GTL even at room temperature and atmosphere pressure, favorable for practical applications. With only 0.05 g catalyst, and 300 mL, 200 mg/L dye wastewater, 100% degradation efficiency could be achieved within 30 min at 30°C and 1 bar. Compared to all the reported catalysts in literature, it showed the highest activity ever, with a catalyst/dye ratio as low as 0.83. This new catalyst was thoroughly characterized and its operation parameters were optimized. Finally, the co-existence of Na₂Mo₄O₁₃ within the α-MoO₃ phase was demonstrated to be crucial, producing more interfaces and more O²⁻ ions in the oxygen deficient regions. It was believed that the O²⁻ ions in the oxygen deficient regions with higher mobility than lattice oxygen, can actively take part in the oxidation process and greatly contribute to the catalyst activity.

In conclusion, a novel hybrid CWAO catalyst of Na₂Mo₄O₁₃/α-MoO₃ was synthesized using a facile hydrothermal method and demonstrated extremely high catalytic activity for the degradation of cationic red GTL even at room temperature and atmosphere pressure, favorable for practical applications. With only 0.05 g catalyst, and 300 mL, 200 mg/L dye wastewater, 100% degradation efficiency could be achieved within 30 min at 30°C and 1 bar. Compared to all the reported catalysts in literature, it showed the highest activity ever, with a catalyst/dye ratio as low as 0.83. This new catalyst was thoroughly characterized and its operation parameters were optimized. Finally, the co-existence of Na₂Mo₄O₁₃ within the α-MoO₃ phase was demonstrated to be crucial, producing more interfaces and more O²⁻ ions in the oxygen deficient regions. It was believed that the O²⁻ ions in the oxygen deficient regions with higher mobility than lattice oxygen, can actively take part in the oxidation process and greatly contribute to the catalyst activity.

Figure 10 | The UV-Vis absorption spectral changes of the cationic red GTL solution as a function of (a) catalytic treatment time, and (b) adsorption time. Testing condition: 0.05 g catalyst (calcined at 400°C), 300 mL, 200 mg/L, 1 bar.

Figure 11| O 1s spectra of (a) α-MoO₃, and (b) Na₂Mo₄O₁₃/α-MoO₃ hybrid catalysts.

Figure 12| ESR spectra of DMPO-OH for α-MoO₃ and Na₂Mo₄O₁₃/α-MoO₃ in aqueous dispersions bubbled with air or N₂.
oxygen can promote the formation of •OH radicals and actively take part in the catalytic oxidation reactions.

Methods

Synthesis of catalysts. The catalysts were synthesized using a hydrothermal route. Briefly, (NH4)2MoO4·4H2O (26.48 g) was dissolved in 50 mL distilled water to form a clear solution at 50 °C. HNO3, or NaOH (4 M) solution was added dropwise into (NH4)2MoO4·4H2O solution under magnetic stirring to control the pH value at 1–7. The resultant solution was transferred onto Teflon-lined stainless-steel autoclave and heated at 120 °C for 18 h. The produced precipitate was filtered and rinsed with deionized water and acetone, followed by drying at 60 °C for 24 h. For the control experiment, the samples were synthesized at different pH using the same condition except that additional 2.04 g Na2MoO4 was added for each synthesis. After careful grinding, the as-prepared samples were calcined in air at certain temperatures (200–500 °C) for 5 h, at a heating rate of 10 °C/min. The calcined samples were directly used as CWAO catalysts for the degradation of cationic red GTL.

Characterization of samples. X-ray diffraction (XRD) measurements of the catalyst powders were recorded using a Shimadzu XRD-7000 instrument in reflection mode with Cu Kα radiation. The accelerating voltage was set at 40 kV with 30 mA current (λ = 1.54 Å) at 0.1° s−1 from 5 to 65°. Field emission scanning electron microscope (FE-SEM) and energy-dispersive X-ray spectroscopy (EDX) analyses were performed on a SU-8020 scanning electron microscope (SEM, HITACHI, Japan) with an accelerating voltage of 5.0 kV. Powder samples were spread on carbon tape adhered to SEM stage. Before observation, the samples were sputter coated with a thin platinum layer to prevent charging and to improve the image quality. High resolution transmission electron microscopy (HR-TEM), selected area electron diffraction patterns (SAED), and elemental mapping analysis were performed on JEM-2100 microscope (JEOL, Japan) with an accelerating voltage of 200 kV. The kinetic energies of photoelectrons were measured using a hemispherical electrostatic analyzer working in a constant pass energy mode. The C 1s peak from the adventitious carbon-based contaminant with a binding energy of 284.8 eV, was used as the reference for calibration. Electron spin resonance (ESR) signal of radicals was obtained on a JEOL FA-200 spectrometer that has been used to detect radical species by their unpaired electrons. The regent for the spin-trapping •OH was T5,5-dimethyl-1-pyrroline-N-oxide (DMPO). For all the samples, the same quartz capillary tube was used to minimize experimental errors.

Catalytic activity tests. The CWAO tests were performed by adding certain amount of catalysts (0.05 or 0.1 g) into a simulated dye wastewater solution containing 200 mg/L cationic red GTL. The volume of the solution was changed in the range of 200–500 mL to evaluate the activity of catalysts under different catalyst/dye ratios. The experiments were conducted in a glass reactor with a capacity of 500 mL equipped with a magnetic stirrer. Air was injected into the bottom of the suspension with a flow rate of 0.4 L/min. About 3 mL samples were taken out by filtration every 30 minutes. In order to maintain the initial concentration (0.5 g) for 5 h, the heating rate of H2O2 was 1 °C/min. The resultant solution was transferred to a Teflon-lined stainless steel autoclave and heated at 120 °C for 18 h. The produced precipitate was filtered and rinsed with deionized water and acetone, followed by drying at 60 °C for 24 h. For the control experiment, the samples were synthesized at different pH using the same condition except that additional 2.04 g Na2MoO4 was added for each synthesis. After careful grinding, the as-prepared samples were calcined in air at certain temperatures (200–500 °C) for 5 h, at a heating rate of 10 °C/min. The calcined samples were directly used as CWAO catalysts for the degradation of cationic red GTL.

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Z.Z. carried out most of the experiments and the analysis of data, and prepared the manuscript. R.Y., Y.G., Y.Z., J.W., L.H., J.G., T.Z., P.L. and Z.G. helped in carrying certain experiments, analysis of certain data, and also provided valuable discussion. Q.W. designed the experiments, analyzed the data, and prepared the manuscript.

Additional information
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