Fabrication of Ultrathin MoS$_2$ Nanosheets and Application on Adsorption of Organic Pollutants and Heavy Metals

Siyi Huang $^1$, Ziyun You $^1$, Yanting Jiang $^1$, Fuxiang Zhang $^1$, Kaiyang Liu $^1$, Yifan Liu $^1$, Xiaochen Chen $^1$ and Yuanci Lv $^{1,2,*}$

$^1$ Fujian Provincial Engineering Research Center of Rural Waste Recycling Technology, College of Environment & Resources, Fuzhou University, Fuzhou 350116, China; N170620033@fzu.edu.cn (S.H.); 061700527@fzu.deu.cn (Z.Y.); 061700506@fzu.deu.cn (Y.J.); 061700529@fzu.deu.cn (F.Z.); liukaiyang123@hotmail.com (K.L.); yfanym@fzu.edu.cn (Y.L.); chenxiaochen@fzu.edu.cn (X.C.)

$^2$ Research Institute of Photocatalysis, Fuzhou University, Fuzhou 350116, China

* Correspondence: yclv@fzu.edu.cn; Tel.: +86-135-6003-1596

Received: 10 April 2020; Accepted: 24 April 2020; Published: 26 April 2020

Abstract: Owing to their peculiar structural characteristics and potential applications in various fields, the ultrathin MoS$_2$ nanosheets, a typical two-dimensional material, have attracted numerous attentions. In this paper, a hybrid strategy with combination of quenching process and liquid-based exfoliation was employed to fabricate the ultrathin MoS$_2$ nanosheets (MoS$_2$ NS). The obtained MoS$_2$ NS still maintained hexagonal phase (2H-MoS$_2$) and exhibited evident thin layer-structure (1–2 layers) with inconspicuous wrinkle. Besides, the MoS$_2$ NS dispersion showed excellent stability (over 60 days) and high concentration ($0.65 \pm 0.04$ mg mL$^{-1}$). The MoS$_2$ NS dispersion also displayed evident optical properties, with two characteristic peaks at 615 and 670 nm, and could be quantitatively analyzed with the absorbance at 615 nm in the range of 0.01–0.5 mg mL$^{-1}$. The adsorption experiments showed that the as-prepared MoS$_2$ NS also exhibited remarkable adsorption performance on the dyes (344.8 and 123.5 mg g$^{-1}$ of $q_m$ for methylene blue and methyl orange, respectively) and heavy metals (185.2, 169.5, and 70.4 mg g$^{-1}$ of $q_m$ for Cd$^{2+}$, Cu$^{2+}$, and Ag$^+$). During the adsorption, the main adsorption mechanisms involved the synergism of physical hole-filling effects and electrostatic interactions. This work provided an effective way for the large-scale fabrication of the two-dimensional nanosheets of transition metal dichalcogenides (TMDs) by liquid exfoliation.

Keywords: transition metal dichalcogenides; liquid exfoliation; adsorption; quenching

1. Introduction

Given the special structure and potential applications, two-dimensional materials have drawn plenty of concerns [1,2], such as graphene, boron nitride, and molybdenum disulfide. Among them, the ultrathin molybdenum disulfide (MoS$_2$) nanosheets, which exhibit an evident layered structure, have attracted ample attentions because of their excellent performance on several fields, such as catalysis, sensors, and pollution remediation [1,3]. Recently, the ultrathin MoS$_2$ nanosheets were reported to show excellent prospects in pollution control [3,4]. Therefore, it was urgent to explore an effective method to produce ultrathin MoS$_2$ nanosheets.

To date, a few methods have been reported for efficient preparation of ultrathin MoS$_2$ nanosheets [5–10], for example, mechanical exfoliation, sputtering, atomic layer deposition, chemical methods, and liquid-based exfoliation. In spite of the excellent performance of the prepared monolayer or few-layer MoS$_2$ nanosheets through mechanical methods, the production efficiency was rather low, which severely limited the large-scale applications. Meanwhile, although most of the chemical
methods like hydrothermal and solvent thermal routes could produce large-scale few-layer MoS\(_2\) nanosheets, they generally needed strict reaction control, such as high temperature and pressure. Instead, due to the controllable operation and high production, liquid-based exfoliation was regarded as the most promising way for the production of ultrathin MoS\(_2\) in large scale. According to previous studies \[7,8\], the solvent showed a significant impact on the exfoliation of MoS\(_2\). Among which, pyrrolidone-based solvents like N-methyl-2-pyrrolidone displayed excellent MoS\(_2\) exfoliation efficiency with 0.3 mg mL\(^{-1}\) of MoS\(_2\) nanosheets concentration, because they showed similar surface energy with MoS\(_2\). Nevertheless, considering their significant environmental risk, high toxicity and high-boiling points of the pyrrolidone-based solvents probably limited the large-scale application. To replace these toxic solvents, a number of polar solvents that own low boiling point and molecular weight were tested, such as water, methanol, ethanol, and isopropanol \[11,12\]. Unfortunately, given the different surface energy between the MoS\(_2\) and polar solvents, most of the polar solvents showed dissatisfactory exfoliation efficiency \[11\]. Interestingly, it was reported that the MoS\(_2\) exfoliation efficiency in the mixed solution with two of the polar micromolecular solvents was much better than those in the single solvent \[13,14\]. Meanwhile, it was worth noting that the MoS\(_2\) exfoliation efficiency could be significantly improved when some organic small molecules, surfactants, or polymers were added in the polar micromolecular solvents, such as sodium cholate, Tween 80, Tween 85, sodium naphthalenide, Brij 30, Brij 700, Triton X-100, and so on \[15–17\]. Nevertheless, the strong van der Waals interaction between the MoS\(_2\) layers still limited the MoS\(_2\) nanosheets production.

Recently, owing to the effective break of the van der Waals force between the MoS\(_2\) layers, quenching was found to be an effective way to exfoliate the graphene analogues \[18–21\]. Previous investigation showed that the high-quality ultrathin graphene sheets were fabricated by rapidly cooling the hot bulk graphite and pre-expanded graphite in aqueous solutions of NH\(_4\)HCO\(_3\) and hydrazine hydrate, respectively \[19,20\]. Meanwhile, the boron nitride and MoS\(_2\) nanosheets were also synthesized via the rapid quenching of hot bulk boron nitride and MoS\(_2\) in the liquid N\(_2\) \[18,21\]. Although the production efficiency of the nanosheets was dissatisfactory, we suspect that if the bulk MoS\(_2\) was pretreated with the quenching process, the exfoliation efficiency of MoS\(_2\) nanosheets in the polar micromolecular solvents could be significantly improved.

Herein, a hybrid strategy with the combination of quenching process and liquid-based exfoliation was employed to fabricate the ultrathin MoS\(_2\) nanosheets. The microstructures, morphology, and optical properties were analyzed. In addition, the adsorption performance of dyes and heavy metals was also discussed.

2. Material and Methods

2.1. Materials

Ammonium tetrathiomolybdate ((NH\(_4\))\(_2\)MoS\(_4\)) was provided by Sam Chemical Technology Co., Ltd. (Shanghai, China). Hydrazine monohydrate (N\(_2\)H\(_4\)-H\(_2\)O) was provided by Aladdin Reagent Co., Ltd. (Shanghai, China). Sodium hydroxide (NaOH), sulfuric acid (H\(_2\)SO\(_4\)), nitric acid (HNO\(_3\)), methylene blue (MB), methyl orange (MO), AgNO\(_3\), CuSO\(_4\), and CdCl\(_2\) were obtained from Sinopharm Chemical Reagent Co. Ltd. (Shanghai, China). The double-distilled water was prepared with a Milli-Q water purification system (Milli-Q®Reference, Millipore, Billerica, Massachusetts, USA).

2.2. Fabrication of the MoS\(_2\) Nanosheets

The MoS\(_2\) nanosheets (MoS\(_2\)-NS) were prepared through a novel combined method including calcination at high temperature, quenching with liquid nitrogen, and ultrasonic-assisted peeling with hydrazine hydrate. Firstly, 4.000 g of (NH\(_4\))\(_2\)MoS\(_4\) was calcinated under nitrogen atmosphere at 800 °C for 5 h with a rate of 5 °C/min and then a black powder (named bulk MoS\(_2\)) was obtained. After that, the high-temperature bulk MoS\(_2\) was quickly transferred into a Dewar bottle containing liquid nitrogen until the liquid nitrogen gasified completely. Subsequently, the pre-expanded bulk
MoS$_2$ was transferred into a serum bottle with 100 mL of hydrazine hydrate and the bottle was sonicated at a frequency of 40 kHz for 24 h. After centrifugation, the residual MoS$_2$ powders were added into another serum bottle with deionized water and sonicated for 12 h (in addition, the recycled hydrazine hydrate can be reused in a new procedure). Finally, the resulting suspensions were centrifuged at 3000 rpm for 2 h and then the dark green MoS$_2$-NS dispersions were obtained. After dialyzed with dialysis tubing with 3000 dalton of molecular weight cut off, the obtained ultimate green dispersions were close to 7 of pH and stored in the fridge at 4 °C.

2.3. Adsorption Batch Experiments

Adsorption isotherm batch experiments were carried out in a 40-mL serum bottle containing 10 mL liquid with 0.1 g L$^{-1}$ of the adsorbent concentration. The adsorption isotherm for MB and MO was conducted under 25 °C in the range of 0.5 to 50 mg L$^{-1}$ of the MB and MO concentration and the pH was adjusted to 6.0 ± 0.1 with 1 M H$_2$SO$_4$ solution, while the experiments for heavy metals were conducted under 25 °C with metal concentration from 0.5 to 30 mg L$^{-1}$ and the pH was adjusted to 5.0 ± 0.1 with 1 M H$_2$SO$_4$ solution. After sealed with polytetrafluoroethylene (PTFE) caps, all the bottles were shaken at 250 rpm for 6 h. At sampling points, one bottle was taken out. After filtered with 0.22 µm glass fiber filters (Tianjin Branch billion Lung Experimental Equipment Co., Ltd., Tianjin, China), the MB/ MO concentrations were determined by UV-vis spectroscopy (UV-1780, SHIMADZU, Japan) at 664/464 nm, while the residual Cu$^{2+}$/Cd$^{2+}$/Ag$^{+}$ concentrations were analyzed with ICP-MS (XSERIES 2, Thermo). The adsorption isotherms data were treated with Langmuir and Freundlich models [22,23].

The experiments for the adsorption kinetics study were operated at 25 °C and 6.0 ± 0.1/5.0 ± 0.1 of pH (adjusted with 1 M H$_2$SO$_4$ solution) in 300 mL dyes/heavy metals solution (20 mg L$^{-1}$ for dyes and 15 mg L$^{-1}$ for heavy metals). All the samples were shaken at 250 rpm for 6 h. At sampling points, 1.5 mL of the solution was taken out and then filtered through the filters. The residual dyes/heavy metals concentrations were determined with ICP-MS. The adsorption kinetics data were treated with the pseudo-first order kinetic and pseudo-second-order non-linear kinetic models.

To study the effects of pH values (2–10)/(3–7) on dyes/heavy metals adsorption, the batch experiments were conducted at 25 °C in a serum bottle with 20 mg L$^{-1}$/15 mg L$^{-1}$ of dyes/heavy metals concentration and 0.10 g L$^{-1}$ of adsorbents.

2.4. Characterization

The X-ray powder diffraction (XRD) data of the bulk MoS$_2$ and MoS$_2$-NS were tested with X-ray powder diffractometer (MiniFlex600, Rigaku, Milwaukee, Wisconsin, USA) coupled with a Cu Ka line at 40 kV and 40 mA.

The microstructural features of prepared bulk MoS$_2$ and MoS$_2$-NS were observed with field emission scanning electron microscope (FESEM, Nova NanoSEM 230, FEI, Hillsboro, Oregon, USA), atomic force microscope (AFM, 5500, Agilent USA), and transmission electron microscope (TEM, TECNAI G2F20, FEI, Hillsboro, Oregon, USA).

The Raman data of bulk MoS$_2$ and MoS$_2$-NS were recorded by a confocal laser Raman microscopy (Invia Reflex, Renishaw, UK) with 532 nm of laser wavelength and 0.6 mW of laser energy.

The X-ray photoelectron spectroscopy (XPS) data were recorded with X-ray photoelectron spectrometer (ESCALAB 250, Thermo Scientific, Waltham, Massachusetts, USA) coupled with the Al Ka radiation at 15 kV and 51 W. The binding energies were confirmed by using the C1s component as the reference and the binding energy of C-C/H bonds were set at 284.5 eV.

The concentrations of MoS$_2$-NS dispersions were analyzed using UV-vis spectrophotometer (UV-2500, Shimadzu, Japan).

The Brunauer–Emmett–Teller (BET) surface areas of the bulk MoS$_2$ and MoS$_2$-NS were obtained from the analysis of N$_2$-adsorption isotherms at 77 K using the N$_2$ physisorption analyzer (ASAP2020, Micromeritics, Norcross, Georgia, USA).
3. Results and Discussion

3.1. Characterization of MoS$_2$ Nanosheets

3.1.1. Microstructures and Morphology

To study the variation of the crystal structure during the MoS$_2$-NS preparation, the precursor ((NH$_4$)$_2$MoS$_4$), bulk MoS$_2$ and MoS$_2$-NS were analyzed by XRD and the results were illustrated in Figure 1. As shown in Figure 1, after calcination under N$_2$, the characteristic peaks of (NH$_4$)$_2$MoS$_4$, located at $\Theta$ = 17.2°, 18.44°, and 29.08°, fully vanished, suggesting the evident change of crystal structure. Instead, the peaks at $2\Theta$ = 14.6°, 33.48°, 39.82°, and 58.94° were assigned to the (100), (103), (105), and (110) plane of hexagonal MoS$_2$ phase (JCPDS card No. 65-0160), indicating that after calcination, the obtained bulk MoS$_2$ was hexagonal phase. The results were similar to Zhang et al.'s findings [24,25]. In addition, after exfoliation by sonication, the resulting MoS$_2$-NS still kept the same peaks with bulk MoS$_2$, manifesting that the 2H-MoS$_2$-NS was successfully obtained. However, compared to the bulk MoS$_2$, the (002) plane peak of MoS$_2$-NS became broadened and lower, suggesting an increase of the $d$ spacing between MoS$_2$ layers [26]. Based on the full width at half maximum (FWHM) of the (002) plane, the layer number of the prepared MoS$_2$-NS could be calculated to be about ~2 layers through Scherrer’s equation. To further confirm the structure of the exfoliated MoS$_2$-NS, Raman spectroscopy (Figure 1b) was employed to characterize the bulk MoS$_2$ and MoS$_2$-NS. Both the bulk MoS$_2$ and MoS$_2$-NS exhibited two dominant peaks ranging from 340 to 450 cm$^{-1}$, corresponding to the E$_{2g}^1$ and A$_{1g}$ mode of the hexagonal MoS$_2$, respectively [26,27], which convincingly proved the successful exfoliation of MoS$_2$-NS. Among which, the E$_{2g}^1$ mode peak at 381.6 cm$^{-1}$ involved the in-layer displacements of Mo and S atoms, whereas the A$_{1g}$ mode peak at 407.9 cm$^{-1}$ represented the out-of-layer symmetric displacements of S atoms along the c-axis [28]. Noticeably, compared to the bulk MoS$_2$, the E$_{2g}^1$ (377.8 cm$^{-1}$) and A$_{1g}$ (402.2 cm$^{-1}$) mode peaks displayed evident blue shift, and the interval ($\Delta$ = 24.4 cm$^{-1}$) between E$_{2g}^1$ and A$_{1g}$ peaks was lower than that of bulk MoS$_2$ ($\Delta$ = 26.3 cm$^{-1}$), which was ascribed to the decrease of the MoS$_2$ thickness. According to the previous literature [4,25,29], it was found that both E$_{2g}^1$ and A$_{1g}$ peaks were the characteristic peaks of MoS$_2$ and their frequencies would vary with the layer number. When the layer number increases, the interlayer van der Waals force in MoS$_2$ suppressed atom vibration, resulting in higher force constants [30]. On the contrast, the force constants between the layers would weaken with the layer number decreases. Thus, both E$_{2g}^1$ and A$_{1g}$ modes were supposed to stiffen (blue-shift) along with the reduction of MoS$_2$ layers.

Figure 2a–d presented the FESEM images of the bulk MoS$_2$ and MoS$_2$-NS. As seen in Figure 2a,b, the bulk MoS$_2$ displayed variated particle-like morphology but clearly thick layer-structure. After exfoliation, the MoS$_2$-NS exhibited evident thin layer-structure with inconspicuous wrinkle (Figure 2c,d), which suggested the successful exfoliation of MoS$_2$-NS. Similar to the bulk MoS$_2$, the size of prepared MoS$_2$-NS still differed widely. In addition, the thickness of the prepared MoS$_2$-NS was analyzed by atomic force microscopy (AFM) (Figure 2). As seen in the AFM images (Figure 2e,f), the height profile of the two selected regions displayed a height of ~1.20 nm ($\pm$0.03 nm) for MoS$_2$-NS, which was about 2 times as thick as the theoretical thickness of monolayer MoS$_2$ (~0.65 nm) [27]. The evident platform of the height curves of the selected MoS$_2$-NS revealed the smooth surface for MoS$_2$-NS. Low-resolution TEM image (Figure 2g) also clearly depicted well-stacked layered structures (~2 layers) of the MoS$_2$-NS, which strongly confirmed the results of XRD and AFM. In the high-resolution TEM (HRTEM) images (Figure 2h), the lattice spacing of 0.27 and 0.16 nm between two adjacent lattice planes could be resolved, which were assigned to the (100) and (110) plane of MoS$_2$. In addition, the HRTEM image (Figure 2i) and associated fast Fourier transforms (FFT) (Figure 2j) from the center of the MoS$_2$-NS evidently exhibited hexagonally symmetric structure, which was consistent with the results of XRD analysis. All the above results manifested that the obtained MoS$_2$-NS still retained hexagonal single crystalline nature during pre-expansion and sonication treatments, which agreed with the previous findings [25,31,32]. However, the BET analysis (Figure 3) showed that the specific
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surface areas of bulk MoS$_2$ and MoS$_2$-NS were 5.6 and 26.6 m$^2$ g$^{-1}$, respectively, indicating that the exfoliation greatly changed the specific surface area of the MoS$_2$ materials. With the decreasing of the layers, more and more MoS$_2$ was exposed, resulting in a promotion of the BET surface.

Figure 1. (a) XRD patterns of (NH$_4$)$_2$MoS$_2$, bulk MoS$_2$, and MoS$_2$-NS and (b) Raman spectra of bulk MoS$_2$ and MoS$_2$ nanosheets.

The chemical composition and element valence on the surface of MoS$_2$ NS were analyzed with XPS (Figure 4). As depicted in Figure 4a, the survey spectra clearly confirmed the presence of C, O, NS, and Mo elements. The weak C1s (~284 eV) peak was attributed into the calibration of binding energy with carbon, while the N1s (~400 eV) peak was ascribed into the adsorbed hydrazine hydrate during the sonication. In Mo3d core-level spectra (Figure 4b), the appearance of Mo3d5/2 (233.5 eV) and Mo3d3/2 (232.6 eV) peaks for Mo3d doublet indicated the characteristic +4 oxidation state [1]. Besides, two weak Mo$^{6+}$ 3d peaks (3d5/2 peak at 233.5 eV and 3d3/2 peak at 235.9 eV) were ascribed to
the slight oxidation of MoS$_2$ NS edge during the MoS$_2$ transfer under high temperature [25]. In the high-resolution scans of S2p (Figure 4c), two feature peaks (S2p1/2 and S2p3/2) were observed at 162.0 and 163.3 eV, respectively, which greatly matched the binding energy of S$^{2-}$ ions in 2H-MoS$_2$ [2]. In addition, the appearance of O1s also confirmed the oxidation of MoS$_2$. In the high-resolution spectra of O1s (Figure 4d), the peak of O$^{2-}$ species located at 532.0 eV and the peak at 533.5 eV was attributed into the absorbed oxygen-containing material like H$_2$O [3].

Figure 2. Field emission scanning electron microscope (FESEM) images (a–d) of the bulk MoS$_2$ and MoS$_2$-NS, atomic force microscope (AFM) images (e,f), height profiles (inset), (transmission electron microscope) TEM and high-resolution transmission electron microscope (HRTEM) images of MoS$_2$ nanosheets (g–i), and the fast Fourier transforms (FFT) pattern of MoS$_2$ NS (j).
3.1.2. Optical Properties of MoS₂ Nanosheets Dispersion

To obtain pure few-layer MoS₂ NS, the suspensions were first centrifuged at 3000 rpm for 2 h to remove the no exfoliated precipitate. Figure 5a displayed the photographs of the as-prepared MoS₂ NS in water. As shown in the Figure 5a, the evident Tyndall phenomenon was observed both of the fresh MoS₂ NS dispersions and the dispersions after 60 days. Meanwhile, the UV-vis absorption spectra (Figure 5b,c) also exhibited no evident change during 60 days. All the results suggested the excellent stability (stable for over 60 days) of as-prepared MoS₂ NS dispersions. In addition, the UV-vis absorption spectra (Figure 5e) of the resulting MoS₂ NS dispersions with different concentrations (Figure 5d) displayed two distinctly characteristic peaks for 2H-MoS₂ [33]. The two peaks located at 615 (B-exciton) and 670 nm (A-exciton) were attributed to the direct excitonic transitions of MoS₂ at the...
K point of the Brillouin zone \cite{34,35}. According to Hai et al.’s study \cite{25}, the relationship between the concentrations of MoS$_2$ NS dispersions and the measured absorbance at a given wavelength (615 or 670 nm) were estimated by using the Beer–Lambert law. The fitting results (Figure 5f) proved that the concentrations of the dispersions showed good linear relationship ($R^2 = 0.9996$) with the absorbance at 615 nm in the range of 0.01–0.5 mg L$^{-1}$, which meant that the quantitative analysis of the MoS$_2$ NS dispersions was available. Based on the above relationship, the concentration of the as-prepared MoS$_2$ NS dispersions was 0.65 ± 0.04 mg mL$^{-1}$, which was much higher than previous findings \cite{7,25}. The initial concentration of the bulk MoS$_2$ (2.510 g of bulk MoS$_2$ were obtained after the calcination of (NH$_4$)$_2$MoS$_4$) was 2.51 mg mL$^{-1}$, and the corresponding few-layer MoS$_2$ NS yield was calculated to be as high as 25.9% in water.

**Figure 5.** Photographs (a), UV-vis absorption spectra (b), absorbance change with standing time (c) of the prepared MoS$_2$ NS dispersions and photographs (d), UV-vis absorption spectra (e) and standard curve (f) of MoS$_2$ NS dispersion in different concentrations.
3.2. Adsorption Behavior of MoS$_2$-NS Towards Dyes and Heavy Metals

3.2.1. Adsorption Isotherms and Kinetics

The adsorption performance of the MoS$_2$ NS was tested by selecting two dyes (methylene blue, MB and methyl orange, MO) and three heavy metal ions (Cu$^{2+}$, Cd$^{2+}$, and Ag$^+)$ as the targets. As seen in Figure 6a, in the bulk MoS$_2$ systems, the equilibrium adsorption capacities of the two dyes only slightly increased with the increasing of the dye concentrations, manifesting that the bulk MoS$_2$ exhibited unsatisfactory adsorption performance of MB and MO. Instead, the equilibrium adsorption capacities of MoS$_2$ NS for MB and MO significantly increased under high concentration of dyes, which were much larger than those of bulk MoS$_2$. Meanwhile, the as-prepared MoS$_2$ NS also displayed more excellent adsorption performance on heavy metals than the bulk MoS$_2$. All the results indicated that the exfoliation was beneficial to improve the adsorption performance of MoS$_2$, which was in accordance with previous studies [3,36,37].

![Figure 6](image-url)

**Figure 6.** Adsorption isotherms (a) and kinetics (c,e) of MB, MO for bulk MoS$_2$ and MoS$_2$ NS at 20 mg L$^{-1}$; adsorption isotherms (b) and kinetics (d,f) of Cu$^{2+}$, Cd$^{2+}$ and Ag$^+$ for bulk MoS$_2$ and MoS$_2$ NS at 15 mg L$^{-1}$.
In addition, to well study the adsorption behavior, the Langmuir and Freundlich models were employed to fit the experimental data (Figure 6a,b, Figure S1). As listed in Table 1, the high $R^2$ values suggested that the Langmuir model better described the adsorption of dyes and heavy metals onto MoS$_2$ NS and bulk MoS$_2$ than the Freundlich model. Based on the Langmuir model fitting, the relative parameters like the maximum adsorption capacity ($q_m$) and affinity constant ($K_L$) for dyes and heavy metals were obtained and listed in Table 1. The $q_m$ values of MB and MO for MoS$_2$ NS were 344.8 and 123.5 mg g$^{-1}$, respectively, which were 12.77 and 6.94 larger than those (27.0 and 17.8 mg g$^{-1}$ for MB and MO, respectively) of bulk MoS$_2$. Meanwhile, the similar results were observed in the heavy metal adsorption, indicating that the MoS$_2$ NS exhibited much more excellent adsorption performance than the bulk MoS$_2$. In addition, for the dyes, the higher $q_m$ and $K_L$ values of MB implied that MoS$_2$ materials exhibited better adsorption capacity and affinity to MB. For heavy metals, the highest $q_m$ value occurred to Cd$^{2+}$ (185.2 mg g$^{-1}$), following Cu$^{2+}$ (169.5 mg g$^{-1}$) and Ag$^+$ (70.4 mg g$^{-1}$), indicating that MoS$_2$ NS were more beneficial to Cd$^{2+}$ and Cu$^{2+}$ adsorption than Ag$^+$. 

Table 1. Fitted parameters for the adsorption of dyes and heavy metals on MoS$_2$ NS and bulk MoS$_2$.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Targets</th>
<th>Langmuir Model</th>
<th>Freundlich Model</th>
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<tr>
<td></td>
<td>$q_m$ (mg g$^{-1}$)</td>
<td>$K_L$ (L mg$^{-1}$)</td>
<td>$R^2$</td>
</tr>
<tr>
<td>MoS$_2$ NS</td>
<td>MB</td>
<td>344.8</td>
<td>0.725</td>
</tr>
<tr>
<td></td>
<td>MO</td>
<td>123.5</td>
<td>0.393</td>
</tr>
<tr>
<td>Bulk MoS$_2$</td>
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<td>0.238</td>
</tr>
<tr>
<td></td>
<td>MO</td>
<td>17.8</td>
<td>0.187</td>
</tr>
<tr>
<td>MoS$_2$ NS</td>
<td>Cd$^{2+}$</td>
<td>185.2</td>
<td>0.606</td>
</tr>
<tr>
<td></td>
<td>Cu$^{2+}$</td>
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<tr>
<td></td>
<td>Ag$^+$</td>
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<tr>
<td>Bulk MoS$_2$</td>
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<td>Cu$^{2+}$</td>
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</tr>
<tr>
<td></td>
<td>Ag$^+$</td>
<td>11.7</td>
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</tr>
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</table>

Figure 6c,d displayed adsorption kinetics data for dyes and heavy metals over MoS$_2$ NS. As revealed in Figure 6c, both MO and MB adsorption increased rapidly at the beginning, then proceeded at a slower rate, and tended to equilibrium at the end. The similar results occurred to the adsorption of heavy metals. Besides, to further analyze the time-dependent variation during the adsorption process, pseudo-first-order and pseudo-second-order kinetic models were employed to fit the dyes and heavy metals adsorption on MoS$_2$ NS (Figure 6e,f). As shown in Table S1, the higher $R^2$ values suggested that the pseudo-second-order model better described both dyes and heavy metals adsorption than the pseudo-first-order model, suggesting that the electron transfer between MoS$_2$ NS and dye molecule or metal ions played a controlling role during the adsorption [38].

3.2.2. Adsorption Mechanism

Based on the results, the MoS$_2$ NS showed much better dye or metal adsorption performance than bulk MoS$_2$. According to the previous studies [3,37,39,40], the main mechanisms reported during the adsorption of dyes or metal by the inorganic materials involved physical hole-filling effects, electrostatic interactions, and ion exchange.

Physical Hole-Filling Effects

The specific surface area often displayed significant effect on the adsorption of the pollutants [41–43]. The adsorbents with large specific surface area usually owned abundant pores, which greatly provided a sufficient adsorption site to capture the pollutants, resulting in the promotion of their adsorption performance. For nano materials, the physical hole-filling effect was considered as one of the important
adsorption mechanisms [41]. According to above-mentioned results, the obtained MoS$_2$ NS owned much larger specific surface area than bulk MoS$_2$, while the MoS$_2$ NS also exhibited more excellent adsorption performance on dyes and heavy metals. Thus, it could be inferred that the physical hole-filling effect probably played a vital role in the promotion of dyes or heavy metal adsorption. Herein, to verify the role of specific surface area during the dyes or heavy metal adsorption over MoS$_2$ NS and bulk MoS$_2$, the obtained $q_e$ data were standardized with the BET surface area and the results were showed in Figure 7. As shown in Figure 7a, for dyes, the equilibrium adsorption capacities of MoS$_2$ NS for MB and MO were 312.0 and 92.6 mg g$^{-1}$, which were 12.89 and 5.61 times larger than those of bulk MoS$_2$, respectively. Meanwhile, the as-prepared MoS$_2$ NS also displayed excellent adsorption performance on heavy metals (Figure 7c), with 141.0, 152.8, and 64.2 mg g$^{-1}$ for Cu$^{2+}$, Cd$^{2+}$, and Ag$^+$, respectively, which were 10.68, 10.12, and 6.42 folds larger than those of bulk MoS$_2$ (13.2, 15.1, and 10.0 mg g$^{-1}$ for Cu$^{2+}$, Cd$^{2+}$, and Ag$^+$, respectively). After standardization (Figure 7b,d), all of the $q_e$ ratios between the MoS$_2$ NS and bulk MoS$_2$ significantly decreased from 12.89 (MB), 5.61 (MO), 10.12 (Cu$^{2+}$), 10.68 (Cd$^{2+}$), and 6.42 (Ag$^+$) to 2.72, 1.12, 2.24, 2.11, and 1.33, respectively, suggesting that the physical hole-filling effect played positive role in the promotion of dyes or heavy metal adsorption over MoS$_2$.

In addition, no evident variation was observed between the standardized $q_e$ values of MoS$_2$ NS and bulk MoS$_2$ (Figure 7b), meaning that the physical hole-filling effect was the sole mechanism during MO adsorption over MoS$_2$ NS. However, the significant enhancement between the standardized $q_e$ values of MoS$_2$ NS and bulk MoS$_2$ (Figure 7b,d) suggested that besides the physical hole-filling effect, some other mechanisms were involved during the adsorption of MB and heavy metals over MoS$_2$ NS.

**Electrostatic Interactions**

Electrostatic interaction was often considered as a possible mechanism to explain the adsorption of dyes and heavy metals [37,40,44]. To confirm the role of electrostatic interaction during dyes and
heavy metals adsorption over MoS$_2$ NS, the adsorption efficiency in various pH values were conducted. As depicted in Figure 8a, the slight fluctuation among the $q_e$ values for MO suggested that the MB adsorption over MoS$_2$ NS was not controlled by the pH values. Instead, the MB adsorption was notably influenced by the pH values. At low pH (<6) conditions, the $q_e$ values increased with the pH value and reached a peak (186.2 mg g$^{-1}$) at pH = 6.0, and then gradually declined when pH > 6. Meanwhile, Zeta potential results (Figure 8c) showed that the isoelectric point of MoS$_2$ NS was about 3.8. This meant that the surface of MoS$_2$ NS displayed a positive charge when the pH value was below 3.8, while a negative charge above 3.8. As a typical cationic dye, MB molecules could strongly adhere to the MoS$_2$ NS through the electrostatic interaction once the surface charge of MoS$_2$ NS turned to negative, leading to an increasing of the $q_e$ values.

Figure 8. Effects of pH on dyes (a) and heavy metals (b) over MoS$_2$ NS, and the Zeta potential (c) of MoS$_2$ NS at different pH values. For dyes: 20 mg L$^{-1}$ of the initial concentration, for heavy metals: 15 mg L$^{-1}$ of the initial concentration.
Similarly, the pH also markedly influenced the adsorption of heavy metals over MoS$_2$ NS (Figure 8b). The $q_e$ values of Cu$^{2+}$, Cd$^{2+}$, and Ag$^+$ evidently increased with an increasing pH, and stabilized at about 112.4, 117.0, and 64.4 mg g$^{-1}$, respectively. When the pH increased, the surface charge of MoS$_2$ NS turned to negative and the values gradually increased, which meant that stronger electrostatic interaction occurred between the heavy metal ions and MoS$_2$ NS at higher pH, resulting in improvement of the adsorption performance. In addition, the charge values of the heavy metal ions also showed visible effects on the adsorption capacity. Due to the lower value of the charge for Ag$^+$, the $q_e$ value of Ag$^+$ was much lower than those of Cu$^{2+}$ and Cd$^{2+}$, which was ascribed into the weaker electrostatic interaction between Ag$^+$ and MoS$_2$ NS. According to the Coulomb law, electrostatic interaction was in direct proportion to the value of the surface charge. The similar results were also found in Yang at al.’s studies [45].

Ion Exchange

According to previous studies [43,46], the ion exchange only occurred with heavy metals adsorption. It was well known that the affinity to the metal ions in the ion exchange process increased with the ion radius and the ion radius of Cd$^{2+}$ and Cu$^{2+}$ were 0.97 Å and 0.73 Å, respectively. If the ion exchange was the main adsorption mechanism, the number of the adsorbed Cd$^{2+}$ should be larger than that of Cu$^{2+}$. Actually, in the system of 15 mg$^{-1}$ L (Figure 8b), the molar adsorption capacity of Cd$^{2+}$ (1.04 mmol g$^{-1}$, 117.0 mg g$^{-1}$) was visibly lower than that of Cu$^{2+}$ (1.75 mmol g$^{-1}$, 112.4 mg g$^{-1}$), which indicated that the ion exchange was not the main mechanism during the heavy metals over MoS$_2$ NS. Similarly, Nguyen et al. also found that the ion exchange played a negligible role during the Cd$^{2+}$ and Cu$^{2+}$ adsorption over the activated carbon [43].

4. Conclusions

In summary, the ultrathin 2H-MoS$_2$ nanosheets with 1–2 layers were successfully obtained via a hybrid stagey with combination of quenching process and liquid-based exfoliation. The as-prepared 2H-MoS$_2$ nanosheets exhibited evident optical properties and could be accurately quantified with the absorbance at 615 nm in the range of 0.01–0.5 mg L$^{-1}$. Besides, the obtained 2H-MoS$_2$ nanosheets also showed a promising application in pollution control. It could be a candidate absorbent for the removal of dyes and heavy metals. This work provided an effective way for the large-scale fabrication of the two-dimensional nanosheets of transition metal dichalcogenides (TMDs) by liquid exfoliation.

Supplementary Materials: The following are available online at http://www.mdpi.com/2227-9717/8/5/504/s1, Figure S1. Linear fittings of dyes adsorption (a) and heavy metals (b and c) over bulk MoS2 and MoS2 NS with the Freundlich model, Table S1 Adsorption kinetics parameters of dyes and heavy metals adsorption over MoS2 NS.

Author Contributions: S.H. and Y.L. (Yifan Liu) conceived the study, designed the experiments and wrote the manuscript. S.H., Z.Y. and Y.J. performed the experiments. F.Z. and K.L. finished the characterization and data analysis. Y.L. (Yuancai Lv) and X.C. edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by by the Open Project Program of National Engineering Research Center for Environmental Photocatalysis (Grant No. 201904), Fuzhou University.

Conflicts of Interest: The authors declare no conflict of interest.

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