ABSTRACT: MoS₂ nanosheets were synthesized by a bottom-up green chemical process where L-cysteine was used as a sulfur precursor. With specific concentrations, molar ratio of reactants, and pre-mixing conditions, MoS₂ nanosheets of 200–300 nm in size and 4.2 nm in average thickness were successfully obtained. Porous membranes were then prepared by depositing the MoS₂ nanosheet suspension on a 0.1 μm pore size poly(vinylidene difluoride) membrane filter in a multiple batch procedure. The membrane deposited with 12 batches of MoS₂ nanosheets achieved 93.78% removal of bovine serum albumin. Acid red removal of 95.65% was also achieved after the second filtration pass. The porous MoS₂ nanosheet membrane also demonstrated a high water flux of 182 ± 2.0 L/(m² h). This result overcame the trade-off between selectivity and permeability faced by polymeric ultrafiltration membranes. The MoS₂ nanosheets as building blocks formed not only intersheet slit pores with a narrow half-width to restrict the passage of organic molecules but also macro-channels allowing easy passage of water. The assembled MoS₂ nanosheet membrane delivered promising separation of protein molecules and a high flux, attributing to its porous nanostructure, and could be a potential membrane for various water applications.

1. INTRODUCTION

The rapid development of the bio-therapeutics industry for both treatment and prevention of disease purposes often involves biomass concentration, protein purification, biomass clarification, and biomolecule concentration. The availability of suitable membranes that can attain excellent separation while maintaining very high permeability is critical.¹ The existing polymeric-based ultrafiltration (UF) membranes have shortcomings of the trade-off between membrane selectivity and membrane permeability.² This means that if the membrane selectivity is increased due to a smaller pore size, then membrane permeability will be reduced and vice versa.³⁻⁵ Other problems to be addressed include pore blockage by suspended solids⁶ or the lack of chemical stability to solvents.⁷ However, the nanomaterial-assisted porous MoS₂ nanosheet membrane reported in this work could offer a solution as a new type of low-pressure membrane addressing the above issues by delivering both high rejection of protein molecules and maintaining a very high flux. A combination of factors like slit pore geometry and intermolecular interactions induced by nanomaterials such as van der Waals forces makes such membranes a promising candidate for bioprocessing applications (Figure 1).

Two-dimensional (2D) materials and their derivatives have been viewed as ideal candidate materials for next-generation separation membranes because of their extraordinary proper-
ties of being thin, mechanically robust, and chemically resistant. Although a large amount of research has been conducted in developing either monolayer nanoporous graphene membranes or rGO laminate membranes, there are still many challenges that need to be tackled to achieve ideal ion and water separation and for scaling up to large-scale applications. These challenges present excellent opportunities for innovative research to explore large families of 2D materials, such as transition-metal dichalcogenides (TMDs) and MXenes. A breakthrough in designing and developing high-performance membranes is anticipated.

Among the 2D materials families, molybdenum disulfide (MoS₂) is a TMD layer compound; its 2D nanosheets or nanoplatelets can be obtained by either a top-down approach of exfoliation or a bottom-up approach of chemical synthesis. The 2D crystal of MoS₂ has a sulfur–molybdenum–sulfur trilayered structure and an inorganic analogue of graphene-like nanosheets. MoS₂ with its extremely smooth and low-friction surface has been recently reported as a successful fouling-resistant membrane coating. For water and environmental applications, MoS₂ nanosheets have been used in aqueous suspensions for photocatalytic decolorization. Hybrid aerogel filters have been synthesized using immobilized MoS₂ nanosheets on cellulose scaffolds to remove contaminants from water. The MoS₂ shell was coated on the CdS core by the solvothermal technique for photocatalytic hydrogen generation. In addition, MoS₂ has some distinct properties such as zero swelling in water, attributed to the balance between attractive van der Waals forces among neighboring nanosheets and repulsive hydration forces. However, in most research works MoS₂ nanomaterials were obtained by the exfoliation method, that is, the top-down strategy for preparing the MoS₂ nanosheets. In one research study, MoS₂ laminate membranes were prepared to separate different molecules, such as organic dye molecules and cytochromes. In another research project, nanoporous MoS₂ nanosheets were fabricated by the cavitation process, and the prepared membrane was used in the forward osmosis process, achieving high salt and water separation due to the highly porous yet charged interface that offered high permeability while achieving selectivity simultaneously. Dye-functionalized MoS₂ membranes were also prepared and reported for ionic species rejections. In contrast, Lu et al. discussed their findings on the stacking of MoS₂ nanosheets resulting in the formation of larger microporous defects with significant reduction of the membrane selectivity. The authors concluded that due to the limitations of using the top-down approach to fabricate 2D materials, developing more refined MoS₂ nanosheets is needed. This fabrication process allows carefully tuning the 2D nanosheets as building blocks with a sufficiently defined lamellar structure as it is critical for preparing excellent 2D water purification membranes. This has motivated us to carefully investigate the usage of a non-exfoliation technique. Distinct from other research works, we have chemically synthesized MoS₂ nanosheets. By controlling the conditions affecting molecular crystallization, we can have better control on the resultant MoS₂ nanomaterials’ structures including the geometric shape, dimensional size, and nanosheet thickness. It is interesting to study the properties and performance of separation membranes prepared by using chemically synthesized MoS₂ nanosheets.

In this work, bottom-up chemical synthesis with green precursors and modified reaction conditions was employed to prepare MoS₂ nanosheets. Our study demonstrated that the different dimensional structures of MoS₂ materials such as nanospheres, nanoplatelets, and nanosheets can be obtained under different chemical and physical conditions during synthesis (Figure 2). Although thiourea was reported as an essential sulfur source in the chemical synthesis of MoS₂ nanosheets, non-toxic green chemical l-cysteine was used as a precursor in this study to synthesize MoS₂ nanosheets. These small nanosheets were detached and flexible, making them a suitable candidate material for preparing porous MoS₂ laminate membranes. The MoS₂ dispersion was filtered on the substrate batch by batch, and this method not only increased the control in membrane fabrication but also probed the effect of amount of nanomaterials used on the membrane separation capability. Finally, the potential of porous MoS₂ nanosheet membranes to facilitate both a high water flux and separation of contaminants such as the BSA protein and dye molecule acid red was evaluated by filtration experiments.

Figure 2. Synthesis of MoS₂ nanospheres, MoS₂ nanoplatelets, and MoS₂ nanosheets.
2. METHODOLOGY

2.1. Materials. All chemicals and reagents used for nanoparticle synthesis, characterization, and analytical studies were of scientific grade and used as received with no modification. The support filter used for membrane fabrications was a 0.1 μm Durapore filter from Merck. Sodium molybdate dihydrate (Na2MoO4) (purity ≥ 99%), L-cysteine (purity = 97%), and 1 M hydrochloric acid (HCl) from Sigma Aldrich were used in synthesizing the MoS2 nanoparticles. The chemicals used for the analytical studies were bovine serum albumin (BSA) (lyophilized powder with purity ≥ 96% with a molecular weight of 66 000 g/mol) from Sigma Life Science and Acid Red 1 (with 60% dye content and a molecular weight of 509.42 g/mol) from Sigma Aldrich.

2.2. Synthesis of MoS2 Nanoparticles. In order to obtain the thin MoS2 nanosheets suitable for membrane preparation, multiple trials have been conducted in this study. In each trial, the experiment conditions and reactant quantity were varied, which affected the morphology of the synthesized product. Figure 2 illustrates the difference in reaction conditions and the MoS2 obtained for each condition. Trial 1 led to the formation of MoS2 nanospheres, and trial 2 resulted in flat and thick nanoplatelets. Trial 3 successfully produced MoS2 nanosheet with the desired morphology for membrane. To synthesize MoS2 nanosheets; 0.1005 g of L-cysteine and 0.0485 g of sodium molybdate dihydrate (molar ratio 1.5:1) were each dissolved in 30 mL of water. The solutions were combined and mixed vigorously at 90 °C, and the pH was adjusted to 2 using 1 M HCl before being transferred to a hydrothermal reactor. The reactor was kept at 210 °C for 24 h. The final product obtained after 24 h was a gray-colored solution with uniformly suspended particles throughout the solution. The solutions were well sonicated before the membrane fabrication procedure. Figure 2 illustrates the procedure involved in MoS2 synthesis.

2.3. Characterization. Scanning electron microscopy (SEM, Quanta 250, FEI Company) coupled with energy-dispersive X-ray (EDX) spectrometry and transmission electron microscopy (TEM, Tecnai from FEI Company operating at 200 KV) were employed to examine the sample’s morphology, nanostructure, and elemental compositions. To obtain surface topographical information such as thickness of the MoS2 nanosheets, an atomic force microscope from Concept Scientific Instrument (France) was used. X-ray diffraction (XRD) measurements of the MoS2 nanosheets were carried out using a Panalytical Rayons-X XRD spectrometer with Cu Kα radiation and scanned from 20 to 80°.

2.4. Membrane Fabrication. The porous MoS2 nanosheet membrane was prepared by the deposition of the as-synthesized MoS2 nanosheets onto a commercial 0.1 μm Durapore membrane filter from Merck. The diluted MoS2 solution was poured onto the filter kept in a vacuum filter apparatus, and it was let to sit for 2 h under gravity so that a stable layer of MoS2 is formed on the support. After 2 h, the vacuum pump was switched on, and the permeate was allowed to flow through the membrane. The obtained wet membrane was dried in an oven at 35 °C for 18 h to evaporate loosely adsorbed water. The procedure was repeated batch by batch until 12 layers of MoS2 were deposited on the membrane.

2.5. Separation and Filtration Experiments. The as-prepared porous MoS2 nanosheet membranes were subjected to separation experiments using 1 g/L BSA and 10 mg/L acid red dye. To test the BSA rejection of the membrane, the BSA feed solution was passed through the membrane, and the permeate samples were analyzed using an ultraviolet−visible (UV−vis) spectrophotometer (PerkinElmer Lambda 35) to quantitatively determine the concentration of BSA remaining in the permeate after passing through the membrane. The experiment was repeated thrice, and the average value was taken for removal measurements. The acid red dye removal by the membrane was done in a similar manner, and the percentage removal was calculated using eq 1:

\[
\text{% removal} = \frac{C_{\text{feed}} - C_{\text{permeate}}}{C_{\text{feed}}} \times 100
\]

Here, \( C \) is the concentration in g/L.

The filtration experiments of the MoS2 nanosheet membranes were carried out in a lab-scale setup using a Convergence Inspector (Convergence, Netherlands). A feed pressure of 1 bar and a flow rate of 5 L/h were maintained. After the initial water flux was measured, the filtration of 0.1 g/L BSA solution was carried out for 30 min. The fouled membrane was then washed thoroughly using DI water for 1 h. After washing, the water flux was measured again, and the flux was recorded. The flux recovery rate (FRR) was calculated using eq 2:

\[
\text{FRR} = \frac{J_f}{J_0} \times 100
\]

where \( J_0 \) is the initial flux and \( J_f \) is the recovered flux after washing the fouled membrane.

3. RESULTS AND DISCUSSION

3.1. Bottom-Up Synthesis of MoS2 Nanosheets. In this green chemical synthesis route, a safe and non-toxic amino acid, L-cysteine, was employed as a sulfur precursor to substitute toxic thiourea. As depicted in Figure 2, a series of trials have been conducted to finally obtain thin MoS2 nanosheets that were suitable for membrane preparation. It was found that different reaction conditions, including the concentration of the reactants, hydrothermal reaction temperature and time, and pre-mixing conditions, led to the resultant MoS2 products with different dimensional structures. MoS2 nanospheres synthesized from trial 1 had a round morphology and MoS2 nanoplatelets obtained from trial 2 were too thick, so both materials were rejected. Finally, thin MoS2 nanosheets were successfully obtained in trial 3 and used in the membrane assembly. The chemical reactions involved in the synthesis of MoS2 nanoparticles are given below:

\[
\text{HSCH}_2\text{CHNH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{COOCOH} + \text{NH}_3 + \text{H}_2\text{S}
\]

\[
4\text{MoO}_4^{2-} + 9\text{H}_2\text{S} + 6\text{CH}_3\text{COOCOH} \rightarrow 4\text{MoS}_2 + 3\text{SO}_4^{2-} + 6\text{CH}_3\text{COOCO}^- + 12\text{H}_2\text{O}
\]

In trial 3, after the 24 h hydrothermal reaction at 210 °C, a gray-colored translucent dispersion with uniformly suspended black particles was obtained. The black particles remained suspended in the solution without precipitation overnight. SEM and TEM analysis had confirmed them as detached thin MoS2 nanosheets. The amount of MoS2 produced per batch...
was estimated to be 0.03217 g. In contrast, when nanospheres and nanoplatelets were obtained under different conditions as described above (Figure 2), their final solutions displayed a very dense black color and precipitation occurred quickly.

SEM imaging (Figure 3) of the vacuum-dried sample was conducted to examine and confirm the microscopic structure of MoS₂ as nanosheets. At a lower magnification (Figure 3a), the SEM image depicted platelet-like structures and were stacked together. The individual sizes of sheets were observed in the range of 200−300 nm, and these more flat sheet-like morphologies were different from previously reported densely arranged randomly oriented “flower-like” sheets in the literature. On increasing the magnification, flat sheets of MoS₂ were observed. At a 500 nm scale, the thin sheet structure of the MoS₂ nanoparticles became evident (Figure 3c−e). Folded edges with wrinkles found in high-magnification images revealed that they were flexible thin sheets. The morphology of the synthesized MoS₂ can be thus elaborated as thin wrinkled nanosheets. In Figure 3f, the characteristic peaks of MoS₂ nanosheets were observed at 33.69° (100) and 59.51° (110), and the broad and weak peaks indicated that the resultant MoS₂ materials were few-layer nanosheets.

TEM analysis was carried out to further verify the sheet-like structures of the synthesized MoS₂. Figure 4a−c illustrates that the MoS₂ samples were aggregated thin sheets. In addition, higher-magnification TEM images in Figure 4d−f show the
well-stacked layers of MoS$_2$ nanosheets with a visible interlayer distance.

In order to determine the thickness of MoS$_2$ nanosheets, atomic force microscopy (AFM) profiling was conducted by scanning the surface of the MoS$_2$ nanosheets. Figure 5 shows the height profiles of four individual sheets. The thickness of the sheets was in the range 3.6 to 5.0 nm with an average thickness of 4.2 nm. They further confirmed that the synthesized MoS$_2$ nanosheets were of 200–300 nm dimensions and a few nanometer thickness. This thickness information was not available in previously reported works.27

**3.2. Deposited Porous MoS$_2$ Nanosheet Membrane.** After confirming their thin sheet-like structure, the synthesized MoS$_2$ nanosheets were then used in membrane fabrication. The light-gray solution containing uniformly suspended MoS$_2$ nanosheets was poured carefully onto a 0.1 μm Durapore filter support that was placed on a vacuum filtration assembly. The detailed procedure is explained in the “Methodology” section. Figure 6a shows the membrane layers formed after pouring one batch of the MoS$_2$ solution, named M1. A light-gray-colored film was seen on the membrane, and the prepared membrane was then placed in an oven at 35 °C for 18 h to remove the excess water. The coated MoS$_2$ membrane was stable and showed no color change or particle detachment when immersed in water. Multiple batches of MoS$_2$ nanosheet solutions prepared by the same hydrothermal process were

![Figure 5. AFM height profiles probing the MoS$_2$ nanosheet thickness.](image)

![Figure 6. (a–c) Membrane surfaces deposited with different batches of MoS$_2$ nanosheets and (d–f) cross-sectional SEM images of MoS$_2$ nanosheet membrane layers deposited on the polymer support at different magnifications.](image)
poured onto the same substrate in a batch-by-batch manner. The membrane surface appearance after the second batch (M2) is shown in Figure 6b. It can be seen that the membrane surface displayed a darker shade of gray after the second batch of MoS2. The above process was repeated for multiple batches, and more MoS2 nanosheets were deposited on the built membrane surface. Each batch resulted in a darker membrane than the previous batch until 12 batches (M12) of MoS2 nanosheets were deposited. The quantity of permeate passing through the membrane layers also became noticeably slower than the previous batch. This was due to the increase in the thickness of the MoS2 sheet layers. Figure 6c shows the image of the membrane after the eighth batch. As is seen, the membrane surface was uniform and smooth with a dark color, associated with the amount of the deposited MoS2 nanosheets. The MoS2 nanosheet membrane was stable without any physical change both in water and under dry conditions. Thus, a stable porous membrane consisting of multilayers of MoS2 nanosheets was fabricated.

Figure 6d–f shows the cross-sectional images of the MoS2 nanosheet membrane at different magnifications. Distinct sections of the polymer substrate and MoS2 layers are clearly seen. The arrows in Figure 6d indicate about a 25–30 μm thickness of deposited MoS2 membrane layers. In addition, these images displayed the porous nature of the membrane layers built by deposited MoS2 nanosheets. As explained above, these porous characteristics of membrane layers consisting of numerous slit pores form intersheets, contributed to enhanced selectivity while retaining the high flux, in comparison to the classic cylindrical pores in the polymeric matrix. These images further illustrated that the synthesized MoS2 nanosheets were curled up to form a porous structure as macro-channels for water molecule passage (Figure 6f). At the same time, some arrows in Figure 6d indicated about a 25 μm thickness of deposited MoS2 membrane layers. These images further illustrated that the synthesized MoS2 nanosheets were curled up to form a porous structure as macro-channels for water molecule passage. At the same time, the unique slit pores formed by the assembly of detached few nanometer thin MoS2 nanosheets enabled the narrow and uniform half-width h to exhibit an excellent sieving effect and high selectivity. The advantages of nanosheets as building blocks of the membrane offering both macro-channels and intersheets slit pores are confirmed in a later section. Elemental mapping using EDX analysis was performed on the MoS2 nanosheets (Figure 7). The identified sulfur layer clearly confirmed the presence and thickness of MoS2 nanosheet membrane layers. Mo mapping is not visible here due to detection interference. The filter support made from the poly(vinylidene difluoride) (PVDF) polymer used for MoS2 nanosheet membrane fabrication explained the presence of fluorine and carbon in the elemental mapping.

3.3. Separation of BSA Protein Molecules by Porous MoS2 Nanosheet Membrane Layers. Figure 8a illustrates the batch-by-batch procedure used in the membrane fabrication. After each batch deposition of MoS2 nanosheets, the separation characteristics of membrane layers were evaluated by measuring the BSA protein molecule rejection. The 1 g/L BSA feed solution was filtered through the membrane, and the permeate was collected and quantitatively analyzed using a UV–vis spectrophotometer. The difference in BSA concentrations in the feed and the permeate gave the percentage of BSA rejected by the membrane layers. Rejection was measured using eq 1. The experiment was repeated thrice, and the average value was taken for rejection measurements. Figure 8b describes the change in BSA rejections with the increase amount of MoS2 nanosheets, with each bar chart representing that the rejection percentage of BSA corresponds to the different batches in preparing the membrane. M1 depicts the percentage rejection of BSA by the first batch of MoS2 nanosheet deposition, which shows a rejection of 60% BSA. Similarly, M2, M3...M12 bars show the rejection percentage of BSA by 2nd batches to 12th batches of MoS2 nanosheets deposited on the membrane. It can be seen from Figure 8b that there was a linear increase in the rejection percentage of BSA with an increase in the nanosheet thickness on the membrane. After the seventh batch, a rejection higher than 90% was accomplished. With a total of 12 batches of thin MoS2 nanosheets deposited on the membrane layers, as high as 93.78% rejection of BSA was achieved. Figure 8c shows the UV absorbance curve obtained. More the MoS2 nanosheets deposited on the membrane, lesser the absorbance intensity of the permeate sample, that is, less BSA molecules in the permeate. In a total of 12 batches, the absorbance curve was almost flat, indicating the efficient removal of BSA molecules. As the UF membrane was normally characterized by the membrane’s nominal molecular weight cutoff, which is typically defined as the molecular weight of a solute that has a rejection of 90%, our MoS2 nanosheet membrane layers have met this requirement and can be used for the successful separation of BSA from water.

3.4. Highly Permeable Porous MoS2 Nanosheet Membrane. It is interesting to investigate if this porous MoS2 nanosheet membrane can achieve high selectivity and high flux and overcome the trade-off problem faced by the classic UF membranes. Filtration experiments were carried out using a low-pressure filtration setup as shown in Figure 9a. The initial water flux was obtained as 182 ± 2.0 L/(m² h) (Figure 9b), which was higher than most of the reported UF membranes. Then, the filtration of BSA solution was carried out, followed by thorough washing by water. The recovered water flux of 156 ± 1.5 L/(m² h) was obtained, and a flux recovery rate of 85.7% by water washing was obtained using eq 2. The unique nanomaterial-assisted porous membrane structure had a significant impact on the separation.
mechanism. The macro-channels formed by curled-up thin MoS₂ nanosheets allowed easy passage of water molecules, while the microscopic slit pores formed by intersheets restricted the passage of protein molecules like BSA and dyes (Figure 1).³¹⁻³³

3.5. Removal of Acid Red Dyes by Porous MoS₂ Nanosheet Membrane Layers. The use of polymeric membranes for the separation of both dyes and proteins is of significant benefit.³² Different nanoparticles have been incorporated in the casting of polymeric nanofiltration membranes with the purpose of enhancing resistance to foulants and the increase in dye removal.³³,³⁴ Such nanomaterial-assisted nanofiltration membranes achieved dye removal but at a low flux at the applied pressure. The dye molecule

Figure 8. (a) Illustration of the batch-by-batch approach to build MoS₂ nanosheet membrane layers; (b) increase in BSA removal with the increase of MoS₂ nanosheet quantity; and (c) UV–vis absorbance of BSA for membrane layers M1 to M12.

Figure 9. (a) Filtration experiment setup for the flux study and (b) bar chart showing initial and final water fluxes with percentage recovery.

Figure 10. (a) Photo showing the color of initial, first pass, and second pass acid red dye solution and (b) bar chart showing the initial concentration and removal percentages at first and second pass.
separation capability of MoS₂ nanosheet membranes was evaluated next. Figure 10a shows the difference in color intensity achieved by passing 10 mg/L acid red dye solution through the MoS₂ nanosheet membrane. UV−vis spectrophotometer analysis was conducted to quantify the dye concentration in both feed and permeate solutions. It can be seen in Figure 10b that after the first pass, the acid red concentration was reduced to 2.6 mg/L (73.97% removal) and the second pass further reduced the color concentration to 0.43 mg/L, and a total of 95.65% color removal has been achieved. These good results were due to the highly porous nature of the membrane that adsorbed the dye molecules inside of the membrane pores. The challenging tasks of more than 90% BSA protein rejection as well as significant dye rejection have been demonstrated by the MoS₂ nanosheet membrane.

### 3.6. Mechanism of Porous 2D MoS₂ Membrane Separation and Permeability

The performance characteristics of different low-pressure porous membranes such as UF are the trade-off between the membrane selectivity and membrane permeability. This means that if the membrane selectivity is increased due to a smaller pore size, then membrane permeability will be reduced and vice versa. The intrinsic membrane transport properties, that is, the permeability and sieving coefficient, are affected by the specific pore size characteristics of the membrane. For classic polymeric membranes, by narrowing down the pore size distribution during the casting step, one can achieve limited improvement of the membrane performance characteristics, and other factors such as pore geometry also affect the membrane trade-off issue.

According to the Hagen−Poiseuille equation, membrane hydraulic permeability (L_p) is related differently to the radius R of cylindrical shape pores (Figure 11a), which are typical in the classic polymer matrix, and to the slit half-width h of a slit pore (Figure 11b) which forms between thin nanosheets, that is, intersheet slit pores. For the same value of R and h, that is, to reject the same-size molecules, according to eqs 5 and 6, the permeability is in much more in favor of the slit pores with 2.67 times (8/3) higher flux than the cylindrical pores, or equivalently, under the same permeability, the slit pore membrane displays higher selectivity. This difference is due to combined intermolecular interactions between the membrane and solute in the unique slit pore geometry, such as van der Waals (LW), acid–base (AB), and electrostatic (EL) forces. This suggests that optimizing a slit pore geometry can enhance the selectivity while retaining high permeability

\[
L_p = \frac{\varepsilon R^2}{8\mu \delta_m}
\]  

(5)

When the porous MoS₂ nanosheet membrane was assembled by deposition of numerous detached thin MoS₂ nanosheets into layers, a large number of slit pores were formed by intersheets by the MoS₂ nanosheets with a 200−300 nm size and a 4.2 nm thickness. On one hand, the slit half-width h was controlled by the uniform thickness of the MoS₂ nanosheets and dictated the sieving effect of separation. The 93.78% rejection of BSA achieved in the experiment in Section 3.4 demonstrated that the slit pores can effectively stop the passage of BSA molecules of an estimated size of 7.5 × 6.5 × 4 nm due to combined intermolecular interactions between the membrane and solute. On the other hand, such porous separation barriers built from numerous individual nanosheets projected less hydraulic resistance and a much higher flux of 182 ± 2.0 L/(m²·h), which were higher than all reported MoS₂-based membranes as well as all UF membranes. Although slit pores could be formed by other types of nanosheets, the size and flexibility of the nanosheets are critical for the success. For example, graphene oxide has a thin layer structure; however, its size is often in microns, and the layers are soft and wrinkle easily. Both the factors lead to more resistance and less water passage of the pores.

### 4. CONCLUSIONS

In this work, MoS₂ nanosheets were synthesized by a bottom-up green chemical process where a safe and non-toxic amino acid, L-cysteine, was employed as a sulfur precursor. With the specific concentration of reactants and pre-mixing conditions, MoS₂ nanosheets were obtained after the 24 h hydrothermal reaction at 210 °C. SEM and TEM analyses confirmed the wrinkled flexible structure of the nanosheets with a 200−300 nm size. In addition, AFM profiling provided its average thickness as 4.2 nm. The porous MoS₂ nanosheet membranes were prepared by depositing MoS₂ nanosheets in solution using a multiple batch procedure. BSA protein filtration was carried out and the removal percentage was measured to evaluate the separation characteristics of each membrane. The membrane deposited with a total of 12 batches of MoS₂ nanosheets achieved 93.78% removal of BSA protein. The total acid red dye removal of 95.65% has been achieved after the second pass of filtration. Simultaneously, a high water flux of 182 ± 2.0 L/(m²·h) was obtained, which outperformed almost all reported UF membranes. The trade-off between selectivity and permeability faced by classic polymeric UF membranes was overcome by this porous MoS₂ nanosheet membrane. The nanosheets with a uniform thickness affected the half-width h of the slit pores formed by intersheets, which governed the excellent membrane selectivity to restrict the passage of BSA and dye molecules; numerous wrinkled nanosheets curled up to form macro-channels that allowed easy passage of water molecules. Overall, the chemically synthesized porous MoS₂ nanosheet porous membrane can deliver both high rejection of protein molecules and maintaining a high flux, attributing to combined factors of slit pore geometry and less hydraulic-resistant micro-channels formed by numerous individual nanosheets, making such membranes a promising candidate for bioprocessing and water treatment.

![](image-url)
AUTHOR INFORMATION

Corresponding Author
Linda Zou — Department of Civil Infrastructure and Environment Engineering, Khalifa University of Science and Technology, Abu Dhabi 127788, United Arab Emirates; orcid.org/0000-0001-5222-6173; Email: Linda.zou@ku.ac.ae

Authors
Fatima Arshad — Department of Civil Infrastructure and Environment Engineering, Khalifa University of Science and Technology, Abu Dhabi 127788, United Arab Emirates
Cyril Aubry — Department of Research Laboratories Operations, Khalifa University of Science and Technology, Abu Dhabi 127788, United Arab Emirates

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c06480

Author Contributions
F.A.: experimental work, result and data collection and analysis, and manuscript drafting; L.Z.: conceptual design, experimental method development, result and data interpretation, and manuscript writing; C.A.: TEM and AFM method development, analysis, and result interpretation.

Notes
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