Novel Method for Producing Oleophilic Polyurethane Foam to Remove Oil from Open Water

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Abstract
In this study, a novel recyclable, hydrophobicity foam with excellent oil/water separation based on polyurethane (PU) and polypropylene glycol (PPG) grafted stearic acid (PGGA) has been developed. PGGA was simply synthesized by the esterification of stearic acid and PPG, while the PU/PGGA foam was fabricated by the reaction of PPG and methyl diphenyl diisocyanate (MDI) with the addition of PGGA. The PU/PGGA foam exhibits improved oil adsorption capacity, water rejection as well as oil/water selectivity with the increase of PGGA weight loadings. The presence of PGGA at high loading (≥ 5 wt%) reduces the pore size and porosity of PU/PGGA foam due to the high viscosity of PGGA preventing the foam formation reaction. As a result, the oil adsorption capacity of PU/PGGA foam is slightly neglected, nevertheless, the oil/water selectivity is significantly enhanced compared to the original PU foam. The result in this work suggests a simple and cost-effective method with potential in oil removal at large scale application.

Graphical Abstract
In this study, novel hydrophobicity agent (PGGA) is developed for enhancing the oil/water separation of polyurethane (PU) foam. At lower weight loading of PGGA (≤ 3 wt%), the PU/PGGA foam exhibits improvement in oil adsorption capacity, water rejection and oil/water separation. Above 5 wt% loading of PGGA, the oil adsorption of PU/PGGA foam is decreased, however, the oil/water selectivity were drastically improved. With this result, the PU/PGGA foam is highly potential for oil removal at large scale application.

Keywords Oil adsorption · Oleophilic polyurethane foam · Oil removal · Polypropylene glycol grafted stearic acid · Oil/water separation

Introduction
Many activities such as industrial effluent release, offshore and onshore petroleum industry as well as accidental spills cause petroleum hydrocarbon contaminated water. Petroleum hydrocarbon (crude oil, diesel oil, engine oil…) cause
many toxic compounds which are potent immunotoxicants and carcinogenic to human being [1]. Therefore, these activities have a catastrophic impact on the aquatic ecological environment and our living environment and also cause huge economic loss [2]. Accordingly, it is very important to seek effective method to separate oil from water. Various approaches including combustion, gravity separation, flotation and adsorption as well as filtration have been studied for oil/water separation [3–8]. However, these methods usually exhibit the disadvantages, such as low efficiency, unrecyclable, high-cost and causing secondary pollution. In recent years, porous materials have been widely used in the fields of tissue scaffolds, stain sensor, oil/water separation, and self-cleaning [9–15]. In this respect, (super) hydrophobic porous materials, such as mesh, foam, membrane and monolith, foam, textile, have been extensively utilized in the field of oil/water separation due to their ability to selectively filter or adsorb oil from water [9, 16–26].

Among all the oil pollution treatment methods, adsorption or filtration is considered to be one of the most effective techniques to clean up the oil contaminated water [27, 28]. Tremendous efforts have been made to construct a material with high adsorption capacity or high oil–water separation efficiency. Besides, facile regeneration and excellent recyclability are also significant factors for an ideal oil–water separation material, to save cost and avoid additional pollution to the environment [29, 30]. The conventional absorbents such as vegetable fibers, wool fibers, cotton fibers, zeolites, and activated carbons display some drawbacks including low adsorption capacity and poor recyclability and selectivity [31–35]. Alternatively, a great variety of synthetic polymer fibers and sponge-like carbonaceous materials such as carbon nanotubes (CNTs) or graphene aerogel have been used [36–39]. Despite the high performance of polymer fibers, their production was not cost effective. In general, an appropriate sorbent should possess superior sorption capacity, good selectivity, and cost effective. Recently, a great attention is attracted to commercially modified polymer foams due to their good ability in separating oils/organic solvents from water [1].

Polyurethane (PU) foam with unique 3-dimensional (3D) structure has been used as a promising adsorbent owing to its outstanding features like high porosity, good oil sorption rate, high oil sorption capacity, inter-connected void volumes, and large surface area [40]. PU foam (PUF) has the benefits of good reusability and flexibility, easy availability, high mechanical durability, facile design, eco-friendly, and cost-effective compared with other porous materials such as aerogel foams and chitosan sponge [41, 42]. Unfortunately, PU foam is naturally hydrophilic substance owing to its carboxyl and amino groups [43]. Superhydrophilic surface with high wet ability results in small water contact angle (WCA) (10°) while large water contact angle (150°) corresponds to low wet ability and superhydrophobic surface. As such its structure then requires to be modified and its hydrophilic properties have to be converted into superhydrophobic features.

Li et al. applied attapulgite to a PU foam’s surface and obtained a hydrophobic sponge with good oil–water separation performance for various organic solvents [40]. Superhydrophobic nanodiamond particles were decorated on the PU sponge for improved hydrophobicity with a WCA of 145° [44]. Graphene was also introduced into the foam substrate to construct micro-roughness or an enhanced specific surface area [45, 46]. A new type of inorganic material, metal–organic framework (MOF) nanoparticles, has also applied in the PU foam structure to enhance the rough surface [47]. Furthermore, the combination of graphene and MOF composite materials preserved the intrinsic properties both of the constituents and prevented the restacking and aggregation of the graphene nanosheets, which imparted the foam skeleton with excellent mechanical strength, adjustable porous structure, and facilely tailored superwettability [48, 49]. Finally, a PU foam with high sorption selectivity and a quite fast adsorption rate was obtained. In fact, the foam material modified with solid particles tends to show a decrease in oil adsorption capacity due to the increase of the foam density to some extent. Santos et al. found that the oil adsorption capacity increased after the PU foam was impregnated with lignin, because the density of the PU foam changed a little and the lignin itself was able to absorb oil [50]. However, the WCA decreased with the increase of lignin content, derived from the hydrophilicity of lignin. To enhance hydrophobicity of the PU foam, sometimes both the solid particles and a low-surface-energy polymer were adopted to modify the foam substrate simultaneously. Zhou et al. constructed a recyclable superhydrophobic micronano-hierarchical PU@Fe3O4@PS sponge [51]. Fe3O4 nanoparticles and polystyrene (PS) brushes were attached on the PU foam skeleton surface by means of ultrasonic dip-coating and self-initiated photo-grafting and photo-polymerization. In addition, hydrophobic nanomaterials, such as graphene, nano-zinc oxide, titanium dioxide, nano-diamond, and hydrophobic silicon dioxide have been used for foam modification [44, 46, 52–59].

This research aims to prepare low cost, simple fabrication method but also effective foam material for oil extraction from water. In this work, poly propylene glycol (PPG) was firstly grafted with stearic acid by esterification reaction to form a hydrophilizing agent (PGGA) before introducing into PU foam for enhancing the hydrophobicity. As far as we know, for the first time PGGA was introduced to improved the oil–water separation of PU foam. The presence of PGGA effectively improved the oil adsorption capacity, water rejection as well as oil extraction efficiency of PU/PGGA foam compared to the neat PU foam. Such simple
and cost-effective method is very promising for large scale oil removal application.

**Experiment**

**Materials**

Methyl diphenyl diisocyanate (MDI) and polypropylene glycol (PPG) were supplied by Chemours (USA). Stearic acid was purchased from Xilong Scientific (China). Acetone, ethanol, and dichloromethane were supplied by Sigma-Aldrich (USA).

Three types of oil including commercial diesel oil (DO), engine oil residue (EOR) and commercial crude oil (CO) were used for the oil adsorption and oil/water adsorption tests. The commercial diesel oil and commercial crude oil was purchased from Binh Son oil refinery factory, Dung Quat industrial zone, Vietnam. The EOR was supplied by Honda motor factory (Hanoi, Vietnam).

**Preparation of Porous PU and PU/PGGA Particles**

**Preparation of PGGA**

Stearic acid (10 g) and PPG (20 g) were added into a beaker with a condensation tube and heated rpm. The solution was left to cool down in the fume hood until forming solid mixture to obtain the PGGA. The to 140 °C in 4 h with stirring speed of 200 reaction of stearic acid and PPG was described in Scheme 1.

In order to remove the excess stearic acid, the obtained mixture was dispersed into distilled water and heated up to 80 °C for 30 min. The excess stearic acid formed single layer above the water bulk and was subsequently removed by extraction. The remaining PGGA in water was filtered and dried at 100 °C in vacuum for 24 h before characterizations.

**PU and PU/PGGA Particles Preparation**

The PU/PGGA foam was prepared by free swelling method. The loading of PGGA was calculated based on the total weight of initial PPG and MDI used. The predetermined PPG, PGGA and finally MDI were added into a mold and vigorously stirred (1200 rpm, 2 min). The mold was subsequently closed to allow the formation and free swelling of the PU/PGGA foam in the duration of 235–260 s. The obtained PU/PGGA foam was dried at 100 °C under vacuum for 24 h before use. The weight contents of PPG, MDI and PGGA used were showed in Table 1. The reaction of PPG and MDI was illustrated in Scheme 2.

**Characterizations**

The Fourier transform infrared spectroscopy (FTIR) was performed on the Fourier NEXUS 670 spectrometer (USA).

The cross-surface morphologies of the samples were obtained with a JEOL JMS63660LV field emission scanning electron microscope (FESEM) at 8 kV.

The porosity of the samples was calculated by helium psychometry method as followed:

$$\varepsilon = \left(1 - \frac{d_a}{d_m}\right) \times 100\%$$

where $\varepsilon$ is the porosity, $d_a$ is the apparent density and $d_m$ is the true density of the foam.

The water contact angle was measured with a Phoenix 300 (Republic of Korea) portable contact angle measuring instrument using a test droplet size of 5 µL.

| Samples   | Weight content [%] |
|-----------|--------------------|
| PU        | 0                  |
| PU/PGGA-1 | 1                  |
| PU/PGGA-3 | 3                  |
| PU/PGGA-5 | 5                  |
| PU/PGGA-10| 10                 |
The Oil Adsorption Test

The oil adsorption were carried out following previous work using three types of oil (DO, EOR, CO) as mentioned earlier [60]. In short, to test oil adsorption capacity of PU foam (PUF), the prepared foams were floated in glass beakers containing 200 ml oil for 1 h. The foams were removed from the beakers and weighed. The oil sorption of sorbent was calculated using the following equation:

\[
\text{Oil sorption (g/g)} = \frac{W_t - W_0}{W_0},
\]

where \( W_0 \) is the initial dry weight of a sorbent and \( W_t \) is the weight of sorbent with oil absorbed.

The Oil/Water Mixture Adsorption Tests

The oil/water (distilled water and salt water) mixture adsorption test was conducted using oil/water mixture at 1:1 volume ratio. To test oil/water mixture absorbency of PUF, the prepared foams were floated in glass beakers containing 200 ml oil/water (1:1 v/v) for 1 h. The foams were removed from the beakers and weighed. The oil absorbed in the foams was extracted repeatedly with several additions of dichloromethane (a total of 200 ml), and oil was weighed after the evaporation of dichloromethane. The weight of absorbed water was calculated by subtracting the weight of absorbed oil and foam from total weight.

All experiments were performed at least 3 times. The oil sorption, water sorption and oil/water selective adsorption ratio was calculated as follow:

\[
A_{\text{oil}} = \frac{W_{\text{oil}}}{W_0} (g/g)
\]

\[
A_{\text{water}} = \frac{W_{\text{water}}}{W_0} (g/g)
\]

\[
S = \frac{A_{\text{oil}}}{A_{\text{water}}}
\]

in which \( W_{\text{oil}}, W_{\text{water}} \) and \( W_0 \) are the weight of absorbed oil, absorbed water and initial dry weight of sorbent, respectively. \( A_{\text{oil}}, A_{\text{water}} \) and \( S \) are the oil adsorption capacity, water adsorption capacity and the oil/water selectivity of the sorbent.

The reusability of PU and PU/PGGA foam were determined by repeating the oil/water adsorption/desorption of the foam for 10 cycles and the adsorption capacity of the foam were calculated after each cycle.

Results and Discussion

Characterization of PGGA

Figure 1 showed the FT-IR of original PPG, PGGA and stearic acid. The peaks at 2979 cm\(^{-1}\), 2867 cm\(^{-1}\) are corresponding to the C–H stretching bands, while the peaks at 1455 cm\(^{-1}\) and 1372 cm\(^{-1}\) are corresponding to the C-H bending vibrations in the main chains of PPG. Besides, a strong peak observed at 1092 cm\(^{-1}\) is attributed to the vibration of C–O bonding in PPG. Compared to the PPG, PGGA showed characteristic peaks of both PPG and stearic acid. The peaks appeared at 2915 và 2848 cm\(^{-1}\) with stronger signals are ascribed to the (-CH\(_2\)-) chain of stearic acid, while the peak at 1698 cm\(^{-1}\) is associated with the (C = O) stretching vibration in carbonyl group of stearic acid. Interestingly, the peak at 1697 cm\(^{-1}\) in the spectra of stearic acid attributed to the (C–O) bonding shifted to 1698 cm\(^{-1}\) in case of PGGA, which can be related to the esterification reaction between the (-COOH) group in stearic acid with (-OH) group in PPG. These results indicated that stearic acid was successfully reacted with PPG molecules to form PGGA.

PU/PGGA Foam Characterization

The Morphology of PU and PU/PGGA Foam

The surface morphology of original PU and PU/PGGA foam were characterized by FESEM images. Figure 2a showed that PU foam possessed a porous 3D web-like microstructure with smooth surface and average pore size from 50 to 200 µm. Similar structures were observed with PU/PGGA foam samples (Fig. 2b–d). However, the average pore size of PU/PGGA foams reduced with the increasing content of PGGA, which were 40–150 µm, 30–125 µm and 10–115 µm with 3 wt%, 5 wt%, and 10 wt% loading of PGGA, respectively. The introduction of PGGA probably increased the viscosity of the reaction mixture and therefore disrupted the foam formation PU, leading to the smaller pore sizes of PU/PGGA foam compared to neat PU.

To further investigate the effect of PGGA on the morphology of PU/PGGA foam, the density and porosity of PU/PGGA foam were calculated and showed in Table 2. The density of PU/PGGA foam increased along with the addition of PGGA contents which is due to the higher density of PGGA compared to the original PU foam. In the other hand, the porosity of PU/PGGA foam decreased with the increase of PGGA contents. It can be explained that the combination of higher density and viscosity of
Fig. 1 FT-IR spectra of: a original PPG, b PGGA and c stearic acid

Fig. 2 FESEM images of: a PU; b PU/PGGA-3; c PU/PGGA-5 and d PU/PGGA-10
PGGA in comparison with PU reduced the pore formation efficiency of PGG-MDI reaction. Moreover, high loading of PGGA could deteriorate the dispersion of PGGA in the PU matrix, which reduced the uniform of the PU/PGGA pore structure and therefore decreased the porosity of PU/PGGA foam. These results are in alignment with the SEM observation mentioned earlier, in which the presence of PGGA reduced the average pore size of PU/PGGA foam due to the increase in viscosity of the reaction mixture.

**Water Contact Angle**

Wettability is one of the most important properties of absorption materials for oil/water separation. Herein, the hydrophobicity of the PU and PU/PGGA foam was evaluated by water contact angle (WCA) measurement. As shown in Fig. 3, the WCA on PU particle was $81 \pm 1^\circ$, indicating that the original PU is not effective for oil–water separation. The introduction of PGGA is capable of increasing the hydrophobicity of the porous PU foam, corresponding by the WCA on PU/PGGA 1 wt%, 3 wt%, 5 wt% and 10 wt% are $95 \pm 0.5^\circ$, $111 \pm 1^\circ$, $116 \pm 0.7^\circ$ and $124 \pm 1.3^\circ$, respectively. The improvement of hydrophobicity of PU/PGGA foam may be due to the presence of long alkyl chains in the PGGA molecules, which lower the surface energy and reduced the attachment of water droplets on the surface of PU/PGGA foam.

For an ideal smooth surface, the WCA can be obtained by Young’s equation:

\[
\text{WCA} = \theta = \cos^{-1} \left( \frac{2\gamma_{lv}}{\gamma_{lv} + \gamma_{sv}} \right)
\]

**Table 2** The porosity of original PU and PU/PGGA foam

| Samples     | Density (g/cm³) | Porosity (%) |
|-------------|-----------------|--------------|
| PU          | 0.037           | 83.52        |
| PU/PGGA-1   | 0.056           | 81.17        |
| PU/PGGA-3   | 0.048           | 76.33        |
| PU/PGGA-5   | 0.044           | 74.92        |
| PU/PGGA-10  | 0.043           | 73.52        |

**Fig. 3** Water contact angle of original PU and PU/PGGA foam: a original PU, b PU/PGGA-1, c PU/PGGA-3, d PU/PGGA-5 and e PU/PGGA-10
where $\theta$ represents the intrinsic contact angle, and $\gamma_{gs}$, $\gamma_{sl}$, $\gamma_{gl}$ are the surface tension of gas–solid, solid–liquid, and gas liquid interfaces, respectively (Fig. 4). For porous surface, the WCA can be calculated using the Cassie equation, $\cos \theta^{*} = \phi_s (\cos \theta + 1) - 1$. Herein, $\theta^{*}$ represents the water contact angle on the PU/PGGA surface, $\phi_s$ represents the fraction of superhydrophobic surface areas wet by the water droplet and $(1 - \phi_s)$ represents the interfacial areas of the entrapped air on the hydrophobic surface. The presence of hydrophobic PGGA may prevent the contact of water droplet with the hydrophilic groups in PU main chains, thus reducing the attractive force between water surface and PU/PGGA foam surface and higher solid/liquid surface tension ($\gamma_{sl}$) compared to the original PU foam without PGGA. As a result, the $\cos \theta$ value was decreased along with the $\cos \theta^{*}$ value, which indicated higher WCA of PU/PGGA foam. Additionally, according to previous work in the literature [61–63], the trapped air inside the pore near the surface of the foam material can act as the superhydrophobic medium, which repels water wetting and penetration and simultaneously increase the WCA of PU/PGGA foam. This result indicates that the introduction of PGGA can effectively improve the water rejection of the PU/PGGA foam.

To further investigate the effect of PGGA on the hydrophobicity of the PU/PGGA foam, the morphologic changes of water droplets over time on the surface of foam were studied. As shown in Fig. 5, after being dripped onto the neat PU surface, the water droplet was gradually absorbed into the foam and the WCA reduced to around $27^\circ$ in 30 s. In contrast, water droplets on the surface of PU/PGGA foam were absorbed into the foam domain at significant lower rate and the WCA gradually reduced. Additionally, the higher the weight loading of PGGA was, the more stable the water droplet remained on the surface of PU/PGGA foam. At 5 wt% and 10 wt% of PGGA, the water droplet remained stable with negligible change in WCA after 100 s. This result is in agreement with the WCA test mentioned above as the presence of hydrophobic long alkyl chains in PGGA molecules provided drastical enhancement in hydrophobicity of the PU/PGGA foam. Moreover, the high viscosity of PGGA may also reduce the pore formation of foam leading to lower adsorption of $\text{H}_2\text{O}$ as well as more stable water droplet on the surface of the foam. These results confirmed the improvement in hydrophobicity of PU/PGGA foam with the presence of PGGA.

### Oil—Water Separation Performance

The effect of PGGA on the oil adsorption property of PU was investigated by using the porous PU/PGGA to absorb different types of oil, including diesel oil (DO), engine oil, and car oil (CO)...

| Samples     | Oil adsorption [g (oil)/g (foam)] |
|-------------|-----------------------------------|
|             | DO                  | EOR                 | CO                  |
| PU          | 12.50 ± 0.42        | 8.51 ± 0.44         | 7.34 ± 0.47         |
| PU/PGGA-1   | 14.06 ± 0.24        | 12.88 ± 0.26        | 11.09 ± 0.41        |
| PU/PGGA-3   | 15.08 ± 0.23        | 13.74 ± 0.12        | 12.78 ± 0.26        |
| PU/PGGA-5   | 13.32 ± 0.36        | 10.97 ± 0.11        | 9.46 ± 0.09         |
| PU/PGGA-10  | 12.47 ± 0.16        | 7.86 ± 0.23         | 6.96 ± 0.14         |
residue and crude oil (Table 3). The adsorption of DO, EOR and CO of original PU foam were 12.50 ± 0.42 g/g, 8.51 ± 0.44 g/g and 7.34 ± 0.47 g/g, respectively. The presence of PGGA effectively increased the oil adsorption of PU/PGGA, with the highest enhancement at 3 wt% loading of PGGA. However, at higher loadings of PGGA (> 3 wt%), lower oil adsorption performances compared to PU/PGGA-1 were observed. As explained above, the high loading of PGGA may increase the viscosity of the reaction mixture and reduce the efficiency of the foam forming reaction during the sample preparation, leading to the decrease of porosity of PU/PGGA particles and the deterioration in oil adsorption.

The oil–water separation performance was evaluated by using the original PU and PU/PGGA particles to recover oil (DO, EOR and CO) in the mixtures of oil/water (50/50 wt.%). As showed on Fig. 6, the water absorption of PU/PGGA samples significantly decreased along with drastic improvement in oil adsorption compared to the neat PU with the increase of the PGGA loading. PGGA structure possesses long alkyl chains combined of PPG and stearic acid molecules which improved the hydrophobicity of the PU/PGGA foam as mentioned above, leading to the reduction in water adsorption and enhancement of crude oil adsorption. The PU/PGGA foam showed highest oil adsorption (11.91 g/g) at 3 wt% loading of PGGA. Interestingly, at the PGGA loading higher than 3 wt%, the oil adsorption capacity of PU/PGGA foam reduces to 10.42 and 6.47 g/g with PU/PGGA-5 and PU/PGGA-10, respectively. This result is in agreement with the data showed above as the presence of PGGA at high loading (≥ 5 wt%) reduced the pore formation efficiency of PU/PGGA foam fabrication due to the high viscosity of PGGA. However, the PU/PGGA-5 and PU/PGGA-10 foam still exhibited excellent oil/water selectivity, at 25.22 and 27.25, respectively. Apparently, the presence of PGGA significantly increased the hydrophobicity of PU/PGGA foam, leading to the drastical decrease in water adsorption, even overwhelming the reduction in oil adsorption of the foam. As a result, the PU/PGGA-5 and PU/PGGA-10 exhibited significant improvement in oil/water selectivity though showing lower oil adsorption capacity compared to the other samples. Similar trends were observed in cases of DO/water and EOR/water separation (Figs. 7, 8). This result demonstrated that the introduction of PGGA is an effective method for enhancing the oil removal capability of PU foam for different types of oil, which is highly potential for large scale applications.

In order to further evaluate the potential of the PU/PGGA foam for large scale oil removal application, the oil/salt water separation factor was evaluated by using the original PU and PU/PGGA foam to recover crude oil in the mixture of crude oil/salt water (50/50 wt.%). Similar trends to the oil/water separation performance are observed on Fig. 9, as the presence of PGGA significantly decreased the water absorption of PU/PGGA samples along with drastic improvement in oil adsorption compared to the neat PU with the increase of the PGGA loading. Slight reduction in
adsorption capacity of the PU/PGGA foam for both crude oil and salt water were observed, probably due to adsorption of the metal ions in salt water into the pore of PU/PGGA foam, which occupied and reduced the effective sites for oil and water adsorption. However, PU/PGGA foam showed higher oil/salt water separation factor, indicated that clear improvement in oil removal capability of the PU/PGGA foam was still expressed. This result evidenced the potential of the PU/PGGA foam for large scale oil removal application in salt water environmental.

A comparison of the maximum sorption capacity of modified PU foam used in this study with other previously reported sorbents is presented in Table 4. The oil/water selectivity as well as the improvement rate of the oil sorption capacity achieved compared to the original PU foam are superior than those reported in the literature. Additionally, the method proposed in this work exhibited the advantage of simple and cost-effective which are necessary for large scale applications.

The recycling capability of PU/PGGA for oil adsorption were investigated by exposing the samples to repeated adsorption/desorption of crude oil for 10 times. As shown in Table 5, the oil adsorption capacity of PU/PGGA foam were retained with negligible decrease. Therefore, this result demonstrated that the oil adsorption capacity of PU/PGGA foam were maintained after repeated adsorption/desorption cycles.

**Conclusion**

In this work, PGGA was introduced in order to enhanced the oil/water separation performance of the PU foam. The addition of PGGA is able to significantly improve the hydrophobicity of PU/PGGA foam and thus increase the oil adsorption as well as water rejection of the foam. At high loading of PGGA (above 5 wt%), the high viscosity of PGGA may affect the pore formation of PU/PGGA foam fabrication, leading to the decrease in porosity of the foam as well as lower oil adsorption capacity while still improve the oil/water selectivity factor. Additionally, the oil adsorption and oil/water separation performance of the PU/PGGA foam were retained with negligible deterioration after ten cycles, indicating adequate reusability. Owing to the cost effective, simple fabrication, excellent improvement in adsorption performance and reusability, the foam modification method...
proposed in this work is highly promising for the removal of oil from water in large scale application.

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Declarations

Conflict of interest There is no conflict of interest and all authors have agreed with this submission and they are aware of the content.

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Table 5 The oil adsorption capacity of PU and PU/PGGA foam from oil/water mixture after 10 cycles

| Cycles | Crude oil adsorption capacity (g/g) |
|--------|-----------------------------------|
|        | PU      | PU/PGGA-1 | PU/PGGA-3 | PU/PGGA-5 | PU/PGGA-10 |
| 1      | 7.08±0.13 | 10.69±0.14 | 11.91±0.21 | 10.42±0.12 | 6.47±0.18 |
| 2      | 7.05±0.16 | 10.69±0.19 | 11.89±0.17 | 10.39±0.14 | 6.46±0.22 |
| 3      | 6.97±0.19 | 10.67±0.19 | 11.85±0.16 | 10.36±0.11 | 6.45±0.16 |
| 4      | 6.92±0.14 | 10.65±0.23 | 11.82±0.19 | 10.35±0.21 | 6.45±0.12 |
| 5      | 6.82±0.21 | 10.64±0.13 | 11.81±0.10 | 10.32±0.22 | 6.43±0.18 |
| 6      | 6.76±0.22 | 10.63±0.27 | 11.80±0.14 | 10.31±0.15 | 6.41±0.20 |
| 7      | 6.73±0.11 | 10.62±0.15 | 11.78±0.13 | 10.31±0.24 | 6.39±0.19 |
| 8      | 6.71±0.18 | 10.62±0.10 | 11.75±0.16 | 10.30±0.18 | 6.35±0.16 |
| 9      | 6.68±0.20 | 10.60±0.14 | 11.73±0.11 | 10.29±0.22 | 6.33±0.18 |
| 10     | 6.68±0.10 | 10.59±0.13 | 11.73±0.10 | 10.27±0.21 | 6.33±0.18 |
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