



Polyurethane Sorbents with Optimized Open-Pore Structure for Efficient Oil Spill Cleanup Produced in a Mobile Manufacturing Complex

^{1*}Iskalieva A.Z., ²Kenzhaliyev O.B., ¹Ibray D., ¹Sakhnov S.

¹ School of Chemical Engineering, Kazakh-British Technical University, Almaty, Kazakhstan

² Karaganda Industrial University, Temirtau, Kazakhstan

* Corresponding author email: asylzat@bk.ru

<p>Received: January 28, 2026 Peer-reviewed: March 12, 2026 Accepted: March 30, 2026</p>	<p>ABSTRACT Oil spill cleanup is one of the major environmental issues facing the world today; this problem is often compounded by the delayed response of emergency teams in the supply of sorbents for cleanup operations. Although sorption is considered the preferred method of cleanup, its success is often hindered by the centralized production of synthetic sorbents. In this paper, we report on the development of a mobile manufacturing container to produce polyurethane-based oil sorbents. The system has been optimized for the entire production process of polyurethane-based sorbents through the precise measurement of polyether polyol, isocyanate, and water ratios in the mixture to produce an open-cell foam with a density of 16 kg/m³ and a special pore structure in which 80% of the pores are less than 50 μm in diameter. From the experimental results obtained using this sorbent, it was evident that it was capable of fully absorbing 100 mL of crude oil on the surface of water within 10 minutes; in addition, this sorbent was able to maintain its high performance after 5-10 cycles of mechanical regeneration. The transition from a centralized production system to one of decentralized production of sorbents for cleanup operations is a major step towards solving the problems of delayed response in cleanup operations.</p>
	<p>Keywords: polyurethane sorbent; oil spill response; mobile manufacturing complex; open-cell foam; sorption capacity; reusable sorbents.</p>
<p>Iskalieva Asylzat</p>	<p>Information about authors: Ph.D, School of Chemical Engineering, Kazakh-British Technical University, Str. Tole bi, 59, 050000, Almaty, Kazakhstan. Email: asylzat@bk.ru; ORCID ID: https://orcid.org/0000-0003-4806-4137</p>
<p>Kenzhaliyev Olzhas</p>	<p>Ph.D., Karaganda Industrial University, Republic Ave. 30, 101400, Karaganda region, Temirtau, Kazakhstan. Email: o.kenzhaliyev@ttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724</p>
<p>Ibray Danat</p>	<p>School of Chemical Engineering, Kazakh-British Technical University, Str. Tole bi, 59, 050000, Almaty, Kazakhstan. Email: danat.ibray@gmail.com; ORCID ID: https://orcid.org/0009-0007-4549-5229</p>
<p>Sakhnov Sergey</p>	<p>School of Chemical Engineering, Kazakh-British Technical University, Str. Tole bi, 59, 050000, Almaty, Kazakhstan. Email: sakhnov67@gmail.com; ORCID ID: https://orcid.org/0000-0002-8435-9349</p>

Introduction

Oil spills are among the most alarming types of anthropogenic impact on the environment. The expansion of oil exploration and manufacturing activities at sea increases the risk of oil spills. After oil spills in a body of water, oil spreads rapidly on the surface of the water in a thin film and then undergoes processes of evaporation, emulsification, dissolution, and finally sedimentation. These processes make oil spill cleanups more complicated and have negative consequences for the environment [[1], [2]].

Recent major oil spill occurrences include the tanker accident "Prestige" (2002), the Deepwater Horizon disaster (2010), and the Agia Zoni II spill

(2017), which caused significant environmental damage worldwide [[3], [4],[5]]. These have demonstrated that the marine ecosystem is vulnerable to oil spills and that immediate action is necessary for oil spill cleanups [6]. Oil spills pollute water and affect the balance of oxygen in water, penetrate less light into the water, and affect aquatic organisms. These processes cause a reduction in biodiversity and negatively impact the economy through fisheries and tourism industries [7].

Oil spill cleanups use various methods such as mechanical cleanups, in situ burning, dispersants, and oil sorption [8]. Oil sorption was accepted for its efficiency and ease of use in oil spill cleanups without the creation of secondary pollutants [9].

Recovery and recycling are easier due to the changed form of oil sorbents from a liquid to a solid.

Materials used as oil sorbents are typically divided into mineral, natural organic, and synthetic types [10]. Mineral-based sorbents, such as clay and fly ash, are cost-effective, but after saturation, they form a strong sediment, thereby polluting bottom sediments [11]. Natural organic sorbents, such as cotton, straw, sawdust, and rice husks, are biodegradable and inexpensive, yet they typically exhibit limited hydrophobicity and moderate oil absorption capacity [12]. Chemical or thermal modification is often used to improve their sorption properties [13].

Synthetic polymer sorbents, particularly those based on polypropylene and polyurethane, exhibit excellent oleophilicity, buoyancy, and mechanical strength [14]. However, industrial production of these materials is typically centralized, creating logistical challenges during emergency response. Transporting sorbents to remote spill sites can be time-consuming, reducing the overall effectiveness of recovery efforts.

An effective solution to this problem is on-site sorbent production using mobile production systems. Mobile, container-based units allow for the production of sorbent materials directly at the site of an emergency, significantly reducing response time and transportation costs. Polyurethane foams are particularly promising among synthetic materials due to their variable pore structure, low density, high oil absorption capacity, and the ability to be reused repeatedly through mechanical pressing [[15], [16]].

Statistical assessments of past oil spills indicate that tankers, cargo ships, and offshore drilling platforms account for the largest share of marine pollution incidents. Crude oil and diesel fuel are considered the most common hydrocarbon spills. The distribution of spill sources and oil types, according to literature data, is shown in Figure 1.

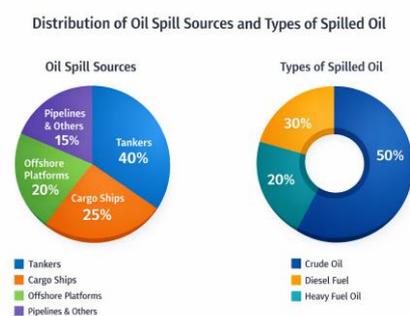


Figure 1 - Distribution of oil spill sources and types of spilled oil

Therefore, the objective of this study is to develop and evaluate a container-based mobile production system for the on-site production of polyurethane oil sorbents with an optimized open-cell structure and improved reusability.

Literature review

Scientific interest in oil spill response technologies has been steadily growing over the past two decades. A bibliometric analysis was carried out for the period from 2000 to 2025 based on data from the Scopus database. The results of the analysis showed a significant increase in the number of publications devoted to the development and application of sorption methods for cleaning oil pollution. This indicates the high relevance of this topic and the steady development of research in the field of materials for oil spill response. The growth of publication activity also reflects the scientific community's desire to find more effective, environmentally sound, and economically sound solutions. The dynamics of publications for the period from 2000 to 2025 are shown in Figure 2.

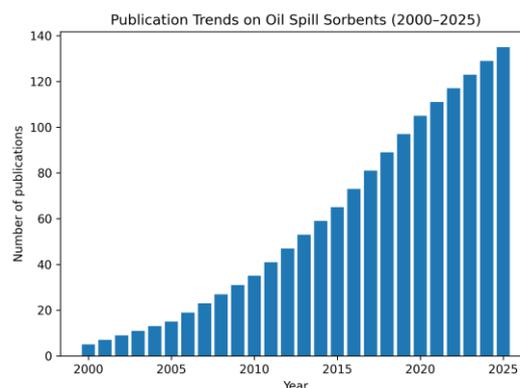


Figure 2 - Publication trends on oil spill sorbents (2000–2025)

Mineral Sorbents

Fly ash, montmorillonite clay, and silica-based materials have been studied as oil sorbents. Karakasi et al. [17] revealed that the sorption capacity of fly ash with a high calcium content reaches 0.9 g/g. Kanygina et al. [18] demonstrated that when using clay rich in iron oxide, the absorption of oil is 4 g/g. However, mineral sorbents tend to settle after saturation and are poorly suited for reuse.

Natural Sorbents

Agricultural waste such as wheat straw, rice husks, corn stalks, and banana fibers has been investigated as biodegradable sorbents. According to studies, untreated lignocellulose materials have a

sorption capacity, usually in the range of 5-10 g/g [19]. To improve hydrophobicity, surface modification methods such as mercerization, acetylation, and polymer grafting are used [[20], [21], [22]]. Acetylated cotton fibers demonstrated oil sorption of up to 22 g/g [23]. However, natural sorbents, as a rule, have lower buoyancy and low mechanical strength.

Synthetic Sorbents

Synthetic polymers provide excellent sorption characteristics. When electro-spinning PVC/PS fibers, an oil absorption capacity of up to 146 g/g [24]. The polyolefin absorbents reported by

Durairajan and co-authors [25] absorbed oil 45 times their own weight. Polyurethane and rice husk composites showed a sorption capacity of 14-15 g/g [26].

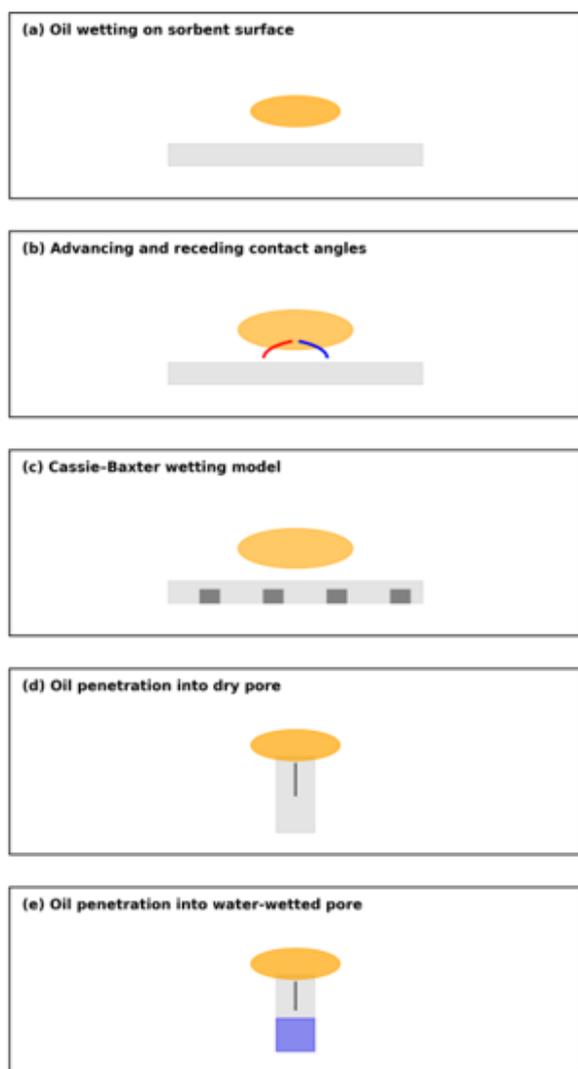
Commercial polypropylene and polyurethane sorbents are widely used due to their hydrophobicity, oleophilicity, and buoyancy [27]. However, delays in centralized production and transportation remain critical constraints in emergency response.

The efficiency of oil sorption is determined by the wettability of the interface and the capillary penetration of hydrocarbons into porous materials. Characteristics such as contact angle, surface roughness, and pore connectivity determine the penetration of oil into the sorbent structure. The main mechanisms of interaction between oil and sorbent are described in the literature and are shown in Figure 3.

Need for Mobile Production

Existing mobile wastewater treatment plants are mainly focused on oil collection rather than sorbent production. Modular container-based production plants have been proposed as a new generation of response systems that allow the production of customized sorbents on site. This technological innovation represents a significant step forward compared to traditional methods of supply in stationary factories.

The proposed container-based mobile production facility includes all the key steps to produce polyurethane sorbents in a 40-foot-long transportable module. The functional diagram of the process unit, which includes sections for dosing, mixing, foaming, cutting and molding, is shown in Figure 4.



(a) Wettability of oil on a sorbent surface, (b) advance and retreat angles on a rough surface, (c) Cassie and Baxter's theory of initial and progressive wetting of a porous surface, (d) penetration of oil into an idealized pore of a dry sorbent, (e) penetration of oil into an idealized pore of a wetted aqueous sorbent

Figure 3 - Oil-sorbent interfacial wetting and capillary penetration mechanisms

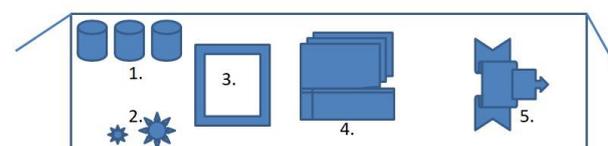


Figure 4 - Functional layout of the mobile container-based sorbent production unit

Emerging Related Technologies and Advanced Adsorbent Development

The latest research trends are mainly focused on advanced adsorption materials and integrated environmental technologies, which are closely related to the development of new-generation sorbents to prevent oil spills. Studies on spent brine treatment and modified Solvay processes have

shown effective ion removal and CO₂ capture from industrial streams with high salinity. This gives an idea of scalable modular technologies of ecological recycling [28]. Although these works focus on water desalination and carbon capture, their technological principles support the concept of mobile water purification plants in containers proposed in this study.

Fundamental studies of wettability and interfacial phenomena are important for understanding the interaction of oil and sorbent. Classical models of surface wetting proposed by Wenzel and Cassie–Baxter are widely used to interpret liquid penetration into porous sorbents and predict sorption efficiency [[29], [30]].

In addition, recent studies of thermally modified and pyrolyzed adsorbents obtained from biomass confirm that the chemical composition of the surface and the pore structure strongly affect the efficiency of oil absorption [[31], [32], [33], [34], [35]]. The development of carbon-based aerogels and biochar-based sorbents from renewable raw materials additionally demonstrates the growing interest in lightweight porous materials with high adsorption capacity used to remove oil and organic solvents [36]. These results justify the choice of open-pore polyurethane foam as a promising material combining controlled pore morphology, hydrophobicity, and mechanical stability.

Experimental part

Raw Materials

The polyurethane foams were prepared using a polyol component of Laprol 5003-2B-10. The polyol has a molecular weight of approximately 5000 and contains three hydroxyl groups. It was used for its flexibility, which allows for the regeneration of the material through a squeezing mechanism. The isocyanate component had an average of 2.5 functional groups per molecule, and distilled water acted as the blowing agent.

Foaming Procedure

The synthesis technique began with the precise weighing of the polyol, isocyanate, and distilled water in accordance with the predetermined formulas. These components were subjected to high-speed mechanical agitation at 1500 rpm for 10-15 seconds to ensure complete chemical homogeneity. The reactive mixture was promptly discharged into 100 × 100 × 100 mm cubic molds lined with release paper for easy removal after it had stabilized. The foaming process was carried out

under ambient settings, with the mixture expanding and curing firm polyurethane blocks within a few minutes.

Formulation Optimization

To determine the most effective formulation for oil sorption, four separate polyurethane foam samples were created by systematically altering the mass ratios of polyol, isocyanate, and water. Figure 5 shows the generated foam specimens and the crude oil utilized for performance evaluation.



Figure 5 - Polyurethane foam samples and crude oil used.

Four mass ratios were analyzed:

Sample I: 1 : 1.0 : 0.10

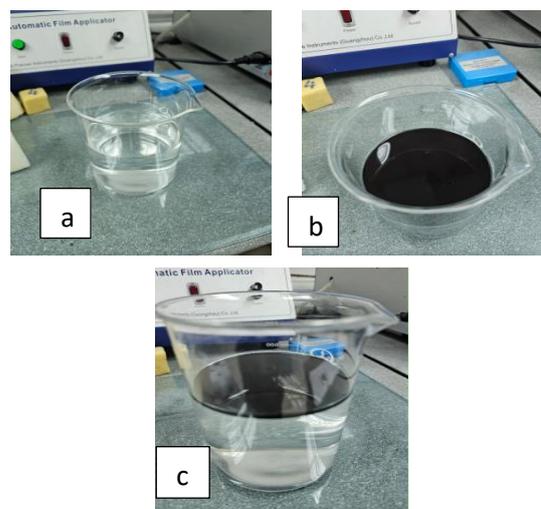
Sample II: 1 : 0.7 : 0.10

Sample III: 1 : 0.5 : 0.10

Sample IV: 1 : 0.5 : 0.085

The samples were tested for pore shape, mechanical stability, and sorption effectiveness.

Sorption performance was assessed using a model oil-water system designed to imitate realistic oil spill conditions in a controlled laboratory setting. Figure 6 shows the experimental configuration, which includes the aqueous phase, crude oil, and a customized testing tank.



(a) – Water, (b) – Oil, (c) – Water-Oil
(b)

Figure 6 - Oil and water system for sorption.

Sorption Testing

A model system was created by applying 100 milliliters of crude oil to the water's surface inside a glass container to assess sorption capability.

The sorption capacity of the polyurethane sorbent was calculated using the following equation:

$$Q = (m_s - m_o)/m_o,$$

where Q is the sorption capacity (g oil/g sorbent), m_s is the mass of the sorbent after oil absorption, and m_o is the initial mass of the dry sorbent.

The polyurethane foam specimens were then added to the oil layer and kept for a duration of 10 minutes. Sorption efficiency was quantitatively assessed through both visual observation and exact measurement of the recovered oil volume. All sorption experiments were performed in triplicate to ensure reproducibility of the results, and the average values and standard deviations were calculated.

After saturation, the material's capacity for regeneration was assessed using mechanical compression to remove the hydrocarbons that had been absorbed, and then sorption-desorption cycles were used to confirm performance stability.

Structural Characterization

The physical and morphological properties of the synthesized foams were investigated through density tests and optical microscopic studies. The optimized formulation, Sample IV, presented a lightweight material with a density of 16 kg/m³. Microscopic studies indicated that the pores were open-cell structured, with 80% of them having diameters less than 50 μm, thus improving capillary action in oil sorption.

Mobile Manufacturing Complex

The mobile complex discussed in this text refers to a self-contained 40-foot containerized mini-plant for the entire process of sorbent production. This includes a raw material dosing system for precise component delivery, a high-speed reactor for homogenous mixing, as well as specific equipment for foaming, curing, and cutting. Additionally, a unique screw filling system allows the production of various shapes of functional sorbents, such as booms, pads, and pillows. This allows for the quick deployment of the complex via truck or by sea, thus enabling autonomous operation as soon as it arrives at the spill site. This complex reduces the time lag associated with the response to a spill and the consequent environmental impact by enabling on-

site production according to the precise extent of the spill, as well as pressing equipment for quick regeneration of the sorbent and the spilled oil.

Results and Discussion

Foam Morphology

The oil flow in this material was affected by the presence of irregularly spaced voids and the densely packed cell structure in samples I-III. For sample IV, there was a uniform structure and evidence of interconnections between the voids. The interconnected void structure allowed faster oil flow by virtue of an enhanced capillary effect. Figure 7 shows that minor changes in content affect the openness and uniformity of the foam structure under both routine and microscopic inspections. An accurate formulation ratio is required in polyurethane foam to attain an optimal pore structure.

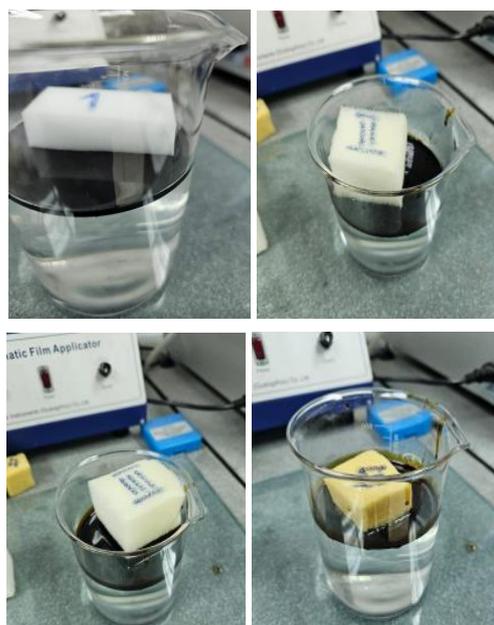


Figure 7 - Samples of polyurethane foam created using several mass ratios.

Sorption Performance

The modified formulation, Sample IV, with a mass ratio of 1:0.5:0.085, showed the highest sorption capacity, completely removing 100 mL of crude oil from the water surface in 10 minutes.

Based on the experimental results, the optimized polyurethane foam demonstrated an average sorption capacity of 5.2 ± 0.3 g oil/g sorbent. This value was calculated based on the mass of absorbed crude oil and the initial mass of the dry sorbent.

Experiment Sorption capacity

1. 5.0 g/g
 2. 5.4 g/g
 3. 5.2 g/g
- Среднее: 5.2 g/g

Std deviation: $\approx 0.2-0.3$

The efficiency of the sorbent is significantly higher compared to that of natural sorbents, ranging from 5 g/g to 15 g/g, and is still very competitive compared to the results of other synthetic sorbents as reported in the literature [[37], [38]]. The obtained sorption capacity is consistent with the reported performance of polyurethane-based sorbents and confirms the effectiveness of the optimized open-cell foam structure.

The sorption kinetics and capacity of the synthesized material can be attributed to its very low density, surface hydrophobicity, and pore structure. The various steps of the crude oil removal process by the optimized polyurethane sorbent are shown in Figure 8.

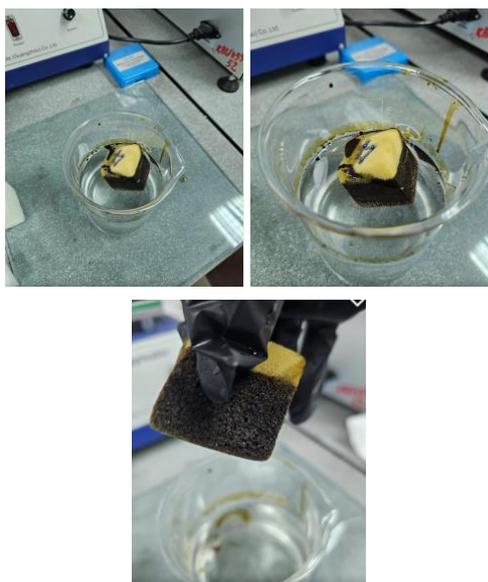


Figure 8 - Complete oil removal using an improved polyurethane sorbent (Sample IV).

Reusability

The practical applicability of the developed sorbent material can also be further demonstrated by the considerable regeneration potential of the material. As shown in the mechanical compression tests, it has been demonstrated that the material can endure between 5 and 10 regeneration cycles without significant deterioration in performance, greatly reducing secondary waste material and overall costs compared with the single-use natural material. Once the material has been saturated with

the crude oil, it can then be recovered by mechanical compression, as shown in Figure 9.



Figure 9 - Oil recovered by mechanical compression.

The regenerated polyurethane sorbent maintained high sorption efficiency across repeated use cycles, confirming its robust reusability. The continuous effectiveness of the recycled foam is demonstrated in Figure 10. The experimental results demonstrated good repeatability with only minor deviations between repeated measurements.



Figure 10 - Regenerated polyurethane sorbent usage.

Comparison with Literature

Summarized table comparison:

Fly ash: 0.7–0.9 g/g [11]

Cotton fiber: 18–22 g/g [9]

Polyurethane-rice husk composite: 15 g/g [15]

PVC/PS electrospun fibers: 146 g/g [23]

The engineered polyurethane foam removes all oil while remaining durable for multiple cycles of reuse.

Unlike mineral sorbents, which commonly lose buoyancy, this substance remains afloat even when saturated. Furthermore, unlike electrospun fibers, it can be readily manufactured on-site using simple, scalable equipment.

Technological Significance

The proposed movable complex successfully bridges the gap between material performance and emergency response logistics. By allowing for instantaneous sorbent manufacture at spill sites, the method provides rapid remediation, minimizes

environmental damage, and decreases vital reliance on centralized supply systems.

Conclusions

The current research aims to develop and experimentally validate the design of a mobile container-based production system for the in-situ production of polyurethane-based sorbents for cleaning up oil spills. The suggested technology platform encompasses all the major steps of sorbent production, including raw material dosing, high-speed mixing, foaming, curing, and product shaping. The integrated approach facilitates immediate deployment of the sorbents for cleaning up oil spills at the site of the spill, thus reducing response time significantly.

The optimization of the polyurethane composition resulted in the production of a low-density foam with a density of 16 kg/m³ and an interconnected pore structure in which 80% of the pores are less than 50 µm in diameter. The sorbent has shown good results in laboratory experiments for the cleanup of 100 mL of crude oil from the water surface in 10 minutes. The results show the potential of the sorbent for immediate response to oil spill emergencies.

The main advantage of the suggested polyurethane-based sorbent for cleaning up oil spills is its reusability after pressing the sorbent for the extraction of the absorbed oil. The sorbent can be reused up to 5-10 times without a significant reduction in its sorption capacity.

The comparison of the properties of the sorbent with other sorbents reported in the literature has shown good results in terms of sorption capacity, buoyancy in water, mechanical strength, and fast production of the sorbent using the suggested technology platform. In contrast to mineral-based sorbents, the sorbent floats on the surface of the water after saturation; in contrast to nanofiber-based sorbents reported in the literature, the sorbent can be produced using simple equipment.

The integrated approach of using optimized polyurethane-based sorbents in combination with a mobile production system has shown good potential for a cost-effective, flexible, and environmentally friendly approach for cleaning up oil spills in the environment. The suggested approach has significant potential for real-world application in emergency response situations for cleaning up oil spills in marine environments or on land. The suggested technology platform is a major step towards the development of next-generation technologies for immediate response to emergencies related to oil spills in the environment.

Conflicts of interest.

On behalf of all authors, the corresponding author states that there is no conflict of interest.

CRedit author statement: **A. Iskalieva:** Conceptualization, Methodology, Writing original draft, Investigation. **O. Kenzhaliyev:** Investigation, Project administration, Supervision. **S. Sakhnov:** Data curation, Validation, Resources. **D. Ibray:** Visualization, Reviewing, and Editing.

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Жылжымалы өндіріс кешенінде өндірілетін мұнайдың төгілуін тиімді тазарту үшін оңтайландырылған ашық кеуекті құрылымы бар полиуретанды сорбенттер

^{1*}Искалиева А.Ж., ²Кенжалиев О.Б., ¹Ибрай Д., ¹Сахнов С.

¹ Химиялық инженерия мектебі, Қазақстан-Британ техникалық университеті, Алматы, Қазақстан

² Қарағанды индустриялық университеті, Теміртау, Қазақстан

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Қабылданды: 30 наурыз 2026

ТҮЙІНДЕМЕ

Мұнай төгілуіне қарсы әрекет ету бүгінгі таңда әлем алдында тұрған негізгі экологиялық мәселелердің бірі болып табылады, бұл мәселе көбінесе тазалау жұмыстарына сорбенттерді жеткізудегі төтенше жағдайларға жауап беру топтарының кідірістерімен ұшығып барады. Сорбция тазартудың ең қолайлы әдісі болып саналғанымен, оның жетістігіне синтетикалық сорбенттердің орталықтандырылған өндірісі жиі кедергі келтіреді. Бұл мақалада біз полиуретан негізіндегі май сорбенттерін өндіруге арналған жылжымалы өндірістік

	контейнердің әзірлеу туралы хабарлаймыз. Бұл жүйе полиуретан негізіндегі сорбенттерді өндірудің бүкіл процесі үшін оңтайландырылған, тығыздығы 16 кг/м ³ және кеуектердің 80%-ы диаметрі 50 мкм-ден аз болатын арнайы кеуекті құрылымы бар ашық ұяшықты көбік алу үшін қоспадағы полиэфир полиолының, изоцианаттың және судың қатынасын дәл өлшеу арқылы жүзеге асырылады. Осы сорбентті қолдану арқылы алынған тәжірибелік нәтижелерден оның су бетіндегі 100 мл шикі мұнайды 10 минут ішінде толығымен сіңіре алатындығы анық болды; сонымен қатар, бұл сорбент механикалық регенерацияның 5-10 циклынен кейін өзінің жоғары өнімділік сипаттамаларын сақтай алды. Тазарту операциялары үшін орталықтандырылған өндіріс жүйесінен орталықтандырылмаған Сорбент өндірісіне көшу тазарту жұмыстары кезінде кешіктірілген жауап беру мәселелерін шешудегі маңызды қадам болып табылады.
	Түйін сөздер: полиуретанды сорбент; мұнайдың төгілуіне қарсы әрекет ету; жылжымалы өндіріс кешені; ашық жасушалы көбік; сорбциялық сыйымдылық; қайта пайдалануға болатын сорбенттер.
Искалиева Асылзат Жамбуловна	Авторлар туралы ақпарат: PhD, Химиялық инженерия мектебі, Қазақстан-Британ техникалық университеті, Төле би көшесі, 59, 050000, Алматы, Қазақстан. Email: asylzat@bk.ru; ORCID ID: https://orcid.org/0000-0003-4806-4137
Кенжалиев Олжас Бақдаулетұлы	PhD, Қарағанды индустриялық университеті, Республика даңғ. 30, 101400, Қарағанды облысы, Теміртау. Қазақстан. Email: o.kenzhaliyev@ttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724
Ибрай Данат Дулатұлы	Химиялық инженерия мектебі, Қазақстан-Британ техникалық университеті, Төле би көшесі, 59, 050000, Алматы, Қазақстан. Email: danat.ibray@gmail.com; ORCID ID: https://orcid.org/0009-0007-4549-5229
Сахнов Сергей Владимирович	Химиялық инженерия мектебі, Қазақстан-Британ техникалық университеті, Төле би көшесі, 59, 050000, Алматы, Қазақстан. Email: sakhnov67@gmail.com; ORCID ID: https://orcid.org/0000-0002-8435-9349

Полиуретановые сорбенты с оптимизированной структурой открытых пор для эффективной ликвидации разливов нефти, произведенные на мобильном производственном комплексе

^{1*} Искалиева А.Ж., ² Кенжалиев О.Б., ¹Ибрай Д., ¹Сахнов С.

¹ Школа химической инженерии, Казахстано-Британский технический университет, Алматы, Казахстан

² Карагандинский индустриальный университет, Теміртау, Казахстан

	АННОТАЦИЯ Ликвидация разливов нефти - одна из основных экологических проблем, стоящих сегодня перед миром; эта проблема часто усугубляется несвоевременным реагированием аварийных бригад на поставки сорбентов для проведения работ по ликвидации последствий. Хотя сорбция считается предпочтительным методом очистки, ее успеху часто препятствует централизованное производство синтетических сорбентов. В этой статье мы сообщаем о разработке мобильного производственного контейнера для производства масляных сорбентов на основе полиуретана. Система была оптимизирована для всего процесса производства сорбентов на основе полиуретана благодаря точному измерению соотношения полиэфирполиола, изоцианата и воды в смеси для получения пены с открытыми порами плотностью 16 кг/м ³ и специальной пористой структурой, в которой 80% пор меньше 50 мкм в диаметре. Из экспериментальных результатов, полученных с использованием этого сорбента, было очевидно, что он способен полностью поглотить 100 мл сырой нефти на поверхности воды в течение 10 минут; кроме того, этот сорбент смог сохранить свои высокие эксплуатационные характеристики после 5-10 циклов механической регенерации. Переход от централизованной системы производства к децентрализованному производству сорбентов для операций по очистке является важным шагом на пути решения проблем запоздалого реагирования при операциях по очистке.
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Искалиева Асылзат Жамбуловна	Информация об авторах: PhD, Школа Химической инженерии, Казахстано-Британский технический университет, ул. Төле би, 59, 050000, Алматы, Казахстан. Email: asylzat@bk.ru; ORCID ID: https://orcid.org/0000-0003-4806-4137
Кенжалиев Олжас Багдаулетович	PhD, Карагандинский индустриальный университет, проспект Республики, 30, 101400, Карагандинская область, Теміртау, Казахстан. Email: o.kenzhaliyev@ttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724

Ибрай Данат Дулатұлы	<i>Школы химической инженерии, Казахстанско-Британский технический университет, ул. Толе би, 59, 050000, Алматы, Казахстан. Email: danat.ibray@gmail.com; ORCID ID: https://orcid.org/0009-0007-4549-5229</i>
Сахнов Сергей Владимирович	<i>Школа Химической инженерии, Казахстанско-Британский технический университет, ул. Толе би, 59, 050000, Алматы, Казахстан. Email: sakhnov67@gmail.com; ORCID ID: https://orcid.org/0000-0002-8435-9349</i>

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