ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№3
2026

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

3 (477)

JUNE – JULY 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan Nº KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 3.
Number 477 (2026), 200–214

https://doi.org/10.32014/2026.2518-170X.649

UDC: 66.067.8
IRSTI: 61.53.19

©Kovaleva A.A.[1], Issayeva A.N.[2*], Levdansky A.E.[1], Kulevets P.S.[1], Zhumadullayev D.K.[3], 2026.
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FLOTATION AS A METHOD FOR SELECTIVE SEPARATION OF PLASTIC MIXTURES

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Abstract. *Relevance.* Separation of mixed plastic waste with similar density values remains one of the major challenges in modern recycling technologies. Conventional sorting methods often demonstrate insufficient efficiency for engineering plastics with close physical properties. In this regard, flotation is considered a promising method for selective polymer separation based on differences in surface wettability. *Methods.* The study investigated flotation separation of two model plastic mixtures: acrylonitrile-butadiene-styrene (ABS) with polybutylene terephthalate (PBT), and polyethylene terephthalate (PET) with polyphenylene sulfide (PPS). Experimental studies were carried out using a laboratory flotation column with pneumatic aeration operating in batch mode. The influence of surfactant type, concentration, air flow rate, and working solution temperature on flotation efficiency was studied. Alkyl polyglucoside, sodium laureth-3 sulfosuccinate, and polysorbate 80 were used as flotation reagents. *Results.* It was established that flotation efficiency strongly depends on reagent composition and operating parameters. For the ABS–PBT mixture, alkyl polyglucoside at a concentration of 3.88 mg/dm³ provided recovery of up to 95% and concentrate purity above 98% at an air flow rate of 2.2 m³/(m²·h) and a temperature of (20 ± 1) °C. For the PET-PPS mixture, the combined use of sodium laureth-3 sulfosuccinate and polysorbate 80 produced a synergistic effect, increasing flotation selectivity and process stability. Under optimal conditions, recovery reached 93-95%, while concentrate purity was 97-98% at a temperature of (13 ± 1)°C. *Conclusions.* The obtained results confirmed the high potential of flotation for selective separation of polymer mixtures with similar physical properties. Optimization of surfactant systems and hydrodynamic conditions allows effective control of polymer wettability and flotation selectivity. The proposed approaches may serve as a basis for further studies involving multicomponent and contaminated post-consumer plastic waste streams.

Keywords: flotation, plastic mixtures, selective separation, surfactants, hydrophobicity, hydrophilicity, recovery rate, concentrate purity, recycling

For citations: *Kovaleva A.A., Issayeva A.N., Levdansky A.E., Kulevets P.S., Zhumadullayev D.K. Flotation as a Method for the Selective Separation of Plastic Mixtures. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. 2026. No.3. Pp. 200–214. DOI: https://doi.org/10.32014/2026.2518-170X.649*

©Ковалева А.А.[1], Исаева А.Н.[2*], Левданский А.Э.[1], Кулевец П.С.[1], Жумадуллаев Д.К.[3], 2026.

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ФЛОТАЦИЯ – ПЛАСТМАССА ҚОСПАЛАРЫН СЕЛЕКТИВТІ БӨЛУДІҢ ӘДІСІ РЕТІНДЕ

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Аннотация. ***Өзектілігі.*** Тығыздық мәндері жақын пластмасса қалдықтарының қоспаларын бөлу полимерлерді қайта өңдеудің заманауи технологияларындағы негізгі мәселелердің бірі болып табылады. Дәстүрлі сұрыптау әдістері физикалық қасиеттері ұқсас инженерлік пластмассаларды бөлу кезінде жеткілікті тиімділік көрсете бермейді. Осыған байланысты флотация полимерлерді олардың бетінің суланғыштық айырмашылығына негізделген селективті бөлу әдісі ретінде перспективалы бағыт болып саналады. ***Әдістері.*** Жұмыста екі модельдік пластмасса қоспасының флотациялық бөлінуі зерттелді: акрилонитрилбутадиенстирол (АБС) мен полибутилентерефталат (ПБТ), сондай-ақ полиэтилентерефталат (ПЭТ) пен полифениленсульфид (ПФС). Эксперименттік зерттеулер периодтық режимде жұмыс істейтін пневматикалық аэрациясы бар зертханалық флотациялық колоннада жүргізілді. Флотациялық бөлудің тиімділігіне беттік-белсенді заттардың түрі мен концентрациясының, ауа шығынының және жұмыс ерітіндісі температурасының әсері зерттелді. Флотациялық реагенттер ретінде алкилполиглюкозид, натрий лаурет-3-сульфосукцинаты және полисорбат 80 қолданылды. ***Нәтижелері.*** Флотациялық бөлудің тиімділігі реагенттік жүйе құрамына және процестің технологиялық параметрлеріне айтарлықтай тәуелді екені анықталды. АБС-ПБТ қоспасы үшін 3,88 мг/дм³ концентрациядағы алкилполиглюкозидті қолдану ауа шығыны 2,2 м³/(м²·сағ) және температурасы (20 ± 1) °С болғанда 95%-ға дейінгі алу дәрежесін және 98%-дан жоғары концентрат тазалығын қамтамасыз етті. ПЭТ-ПФС қоспасы үшін натрий лаурет-3-сульфосукцинаты мен полисорбат 80 қоспасын бірге қолдану синергетикалық әсер беріп, флотация селективтілігі мен процесс тұрақтылығын арттырды. Оңтайлы жағдайларда алу дәрежесі 93–95%, ал концентрат тазалығы 97–98% құрады, температурасы (13 ± 1) °С болды. ***Қорытынды.*** Алынған нәтижелер физикалық қасиеттері жақын полимер қоспаларын селективті бөлу үшін флотация әдісінің жоғары әлеуетін растады. Реагенттік жүйелер мен гидродинамикалық параметрлерді оңтайландыру полимер бетінің суланғыштығын және флотация селективтілігін тиімді басқаруға мүмкіндік береді. Ұсынылған тәсілдер көпкомпонентті және ластанған посттұтынушылық пластик қалдықтарын зерттеуге негіз бола алады.

Түйін сөздер: флотация, пластмасса қоспалары, селективті бөлу, беттік-белсенді заттар, гидрофобтылық, гидрофильділік, алу дәрежесі, концентрат тазалығы, қайта өңдеу

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ФЛОТАЦИЯ КАК МЕТОД СЕЛЕКТИВНОГО РАЗДЕЛЕНИЯ СМЕСЕЙ ПЛАСТМАСС

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Аннотация. *Актуальность.* Смеси пластиковых отходов с близкими значениями плотности представляют собой одну из основных проблем современных технологий переработки полимеров. Традиционные методы сортировки часто оказываются недостаточно эффективными для инженерных пластмасс с близкими физическими свойствами. В связи с этим флотация рассматривается как перспективный метод селективного разделения полимеров, основанный на различии смачиваемости их поверхности. *Цель.* Оценить эффективность флотации как метода селективного разделения смесей пластмасс с близкими физическими свойствами и определить оптимальные реагентные и технологические параметры процесса. *Методы.* В работе исследовано флотационное разделение двух модельных смесей пластмасс: акрилонитрилбутадиенстирола (АБС) и полибутилентерефталата (ПБТ), а также полиэтилентерефталата (ПЭТ) и полифениленсульфида (ПФС). Экспериментальные исследования проводились на лабораторной флотационной колонне с пневматической аэрацией, работающей в периодическом режиме. Изучалось влияние типа и концентрации поверхностно-активных веществ, расхода воздуха и температуры рабочего раствора на эффективность флотационного разделения. В качестве флотационных реагентов использовались алкилполиглюкозид, лаурет-

3-сульфосукцинат натрия и полисорбат 80. *Результаты и выводы*. Установлено, что эффективность флотационного разделения существенно зависит от состава реагентной системы и технологических параметров процесса. Для смеси АБС - ПБТ использование алкилполиглюкозида в концентрации 3,88 мг/дм³ обеспечило степень извлечения до 95% и чистоту концентрата более 98% при расходе воздуха 2,2 м³/(м²·ч) и температуре (20 ± 1) °С. Для смеси ПЭТ - ПФС совместное применение лаурет-3-сульфосукцината натрия и полисорбата 80 обеспечило синергетический эффект, повысив селективность флотации и устойчивость процесса. В оптимальных условиях степень извлечения составила 93–95%, а чистота концентрата - 97–98% при температуре (13 ± 1) °С. Полученные результаты подтверждают высокий потенциал флотации для селективного разделения полимерных смесей с близкими физическими свойствами. Оптимизация реагентных систем и гидродинамических параметров позволяет эффективно управлять смачиваемостью поверхности полимеров и селективностью флотации. Предложенные подходы могут служить основой для дальнейших исследований многокомпонентных и загрязненных пластиковых отходов постпотребительского происхождения.

Ключевые слова: флотация, пластмассы, селективное разделение, ПАВ, гидрофобность, гидрофильность, степень извлечения, чистота концентрата, переработка

Introduction. The rapid growth in the production and consumption of plastic materials over recent decades has led to a significant increase in plastic waste generation. Due to their durability, low cost, and versatile properties, plastics are widely used in packaging, construction, automotive, and consumer goods industries. However, the accumulation of plastic waste in landfills and natural environments has become a global environmental challenge, necessitating the development of efficient recycling and waste management technologies (Kökkılıç et al., 2022; Lange, 2021).

A critical stage in plastic recycling is the effective separation of mixed polymer waste streams. Conventional sorting methods, such as density-based separation, electrostatic separation, and infrared spectroscopy, are widely used in industrial practice. Nevertheless, these techniques often exhibit limited efficiency when dealing with multicomponent plastic mixtures, especially when polymers have similar densities, surface properties, or optical characteristics (Kökkılıç et al., 2022). This limitation significantly reduces the quality of recycled materials and increases processing costs. In addition, contamination of recycled fractions significantly limits their reuse in high-value engineering applications (Hopewell et al., 2009).

It should be noted that real post-consumer plastic waste streams are usually multicomponent and may contain various contaminants such as adhesives, printing inks, labels, and organic residues. These impurities can significantly affect interfacial interactions and flotation selectivity due to their surface-active behavior. Therefore, investigation of model polymer mixtures under controlled laboratory conditions represents an important preliminary stage for understanding the fundamental mechanisms of selective flotation separation.

Flotation has emerged as a promising alternative method for the selective separation of plastic mixtures (Fraunholcz, 2004; Kökkılıç et al., 2022). Unlike traditional approaches, flotation is based on differences in surface wettability of materials, allowing for the separation of particles with similar physical characteristics. In this process, hydrophobic particles attach to air bubbles and rise to the surface, forming a froth product, while hydrophilic particles remain in the liquid phase (Abramov, 2016).

The efficiency of flotation largely depends on the control of interfacial interactions, which can be achieved through the use of surfactants. Surfactants are capable of modifying the surface properties of polymers by altering their hydrophobicity or hydrophilicity, thus influencing their behavior in a flotation system. Previous studies have demonstrated that the appropriate selection and combination of surfactants can significantly enhance the selectivity and efficiency of plastic separation processes (Levdansky et al., 2019; Kovaleva et al., 2023; Leudanski et al., 2020).

Despite the growing interest in flotation-based recycling methods, there remains a need for systematic investigation of the influence of surfactant type and concentration on the separation efficiency of specific polymer mixtures. In particular, mixtures consisting of polymers with close density values present a significant challenge and require optimized process conditions (Fraunholcz, 2004; Shen, 2000).

Therefore, the aim of this study is to develop effective flotation methods for the selective separation of plastic mixtures by optimizing process parameters and surfactant systems to achieve high recovery and concentrate purity. Particular attention was paid to polymer systems with similar density values, which are difficult to separate by conventional methods.

Literature Review. One of the key technological challenges in polymer recycling is the separation of mixed plastic waste. In industrial practice, several conventional sorting methods are applied, including density separation, electrostatic sorting, sensor-based classification, and infrared spectroscopy. Although these techniques are effective for certain waste streams, their performance decreases significantly when polymers possess similar density values, overlapping optical signatures, or comparable surface characteristics (Kökkılıç et al., 2022). As a result, mixed engineering plastics such as ABS/PBT or PET/PPS are particularly difficult to separate using standard technologies (Fraunholcz, 2004).

Flotation has attracted considerable attention as an alternative selective separation method for plastic mixtures. In contrast to density-based processes, flotation utilizes differences in surface wettability between polymer particles. Hydrophobic particles tend to attach to air bubbles and rise into the froth phase, whereas hydrophilic particles remain suspended or settle in the pulp. The probability of particle–bubble attachment is governed by collision, adhesion, and stability mechanisms. This principle has long been applied in mineral processing and has increasingly been adapted for plastic recycling applications (Abramov, 2016; Shen, 2000).

The effectiveness of flotation separation depends strongly on the surface chemistry of the polymers. Since many plastics naturally exhibit hydrophobic behavior, selective modification of their surfaces is required to generate sufficient differences in flotation response (Fagkaew et al., 2022). For this reason, surfactants and wetting agents are widely used as conditioning reagents. Depending on their molecular structure, surfactants can adsorb onto polymer surfaces, alter interfacial tension, and increase either hydrophobicity or hydrophilicity. Appropriate reagent selection therefore plays a decisive role in flotation selectivity (Fraunholcz, 2004; Pita et al., 2023).

Previous studies have demonstrated the feasibility of separating common post-consumer plastics such as PVC, PET, PE, PP, and PS by flotation using various chemical reagents. Kökkılıç et al. (2022) concluded in a comprehensive review that froth flotation is one of the most promising technologies for complex plastic waste treatment, particularly when particle density differences are insufficient for gravity-based methods.

Recent investigations have also emphasized the importance of operational parameters such as particle size distribution, air flow rate, bubble size, pulp temperature, and reagent dosage. Variations in these factors can substantially influence collision probability between particles and bubbles, froth stability, and entrainment behavior, ultimately affecting recovery and concentrate purity (Shen, 2000; Fraunholcz, 2004). Therefore, optimization of both chemical and hydrodynamic conditions is necessary for industrial implementation.

Despite the progress achieved in flotation recycling technologies, limited information is available regarding the separation of engineering thermoplastics with closely related densities and high commercial value, particularly mixtures containing ABS/PBT and PET/PPS. These materials are increasingly used in automotive, electrical, and electronic industries, where recycling demands are continuously growing. Their effective separation would enable recovery of higher-value secondary raw materials and reduce disposal volumes.

Thus, the available literature confirms the high potential of flotation for polymer recycling while highlighting the need for further studies on selective reagent systems and optimized process parameters for difficult-to-separate engineering plastic mixtures. This need forms the basis of the present investigation.

Materials and methods. Two plastic mixtures were used in this study. The first mixture consisted of polybutylene terephthalate (PBT), manufactured in accordance with technical specification TU 2253-025-11517367-2002 (with amendments 1 and 2), and acrylonitrile–butadiene–styrene (ABS), conforming to TU 2212-019-00203521-96. The second mixture included polyethylene terephthalate (PET), meeting the requirements of GOST R 51695-2000, and polyphenylene sulfide (PPS), produced in accordance with TU 2224-001-86535236-2016. The plastic particles had an approximately cylindrical shape, with a height ranging from 3 to 4 mm and a diameter of 2 to 3 mm. The density of PBT particles was 1210 ± 10 kg/m³, while ABS exhibited a density of 1119 ± 10 kg/m³. In the second mixture, the densities of PET and PPS were 1390 ± 10 kg/m³ and 1370 ± 10 kg/m³, respectively. All materials were dried under ambient laboratory conditions before experimentation. The similarity in geometric and physical properties of the materials ensured standardized and reproducible conditions for flotation experiments.

Three types of surfactants were used to modify the surface properties of the polymers:

– sodium laureth-3 sulfosuccinate (Setacin 103, Zschimmer & Schwarz, Italy), an anionic surfactant presented as a transparent, colorless liquid;

– polysorbate 80 (Tween 80, "AiS" Company, Russia), a nonionic surfactant presented as a viscous, oily, light-yellow liquid;

– alkyl polyglucoside C8–C14 (50%) (Green APG 0814 2000 UP, Nanjing Tichem Industry Co., Ltd., China), a nonionic surfactant presented as a light-yellow, turbid, viscous aqueous solution with an active substance content of 50–53 wt.%.

The experiments were carried out using a laboratory-scale flotation unit with pneumatic aeration of the working solution (Kovaleva et al., 2023). A schematic diagram of the setup is shown in Figure 1. The design concept is consistent with laboratory flotation columns reported in previous studies (Fuerstenau et al., 2007).

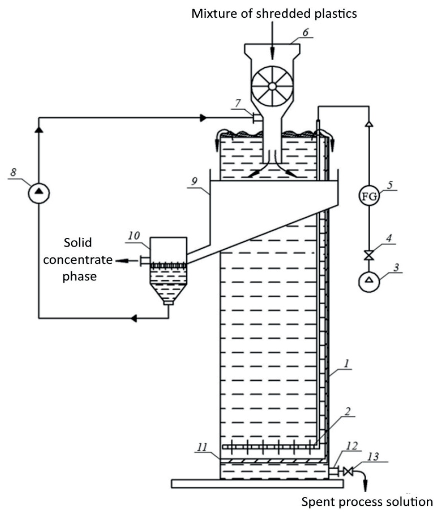

Figure 1. Schematic representation of the flotation column with pneumatic aeration.
1 – column; 2 – spiral aerator; 3 – compressor; 4 – air supply valve; 5 – rotameter; 6 – cell feeder; 7 – working solution inlet pipe; 8 – pump; 9 – discharge launder; 10 – concentrate separator; 11 – removable grid; 12 – outlet nozzle for spent working solution; 13 – valve for draining the spent working solution.

The flotation apparatus consisted of a column (1) made of transparent polymer material, which allowed visual observation of the process. To ensure uniform distribution of air bubbles across the column cross-section, a spiral aerator (2) was installed in the lower part of the column. The aerator contained openings with a diameter of 0.33 mm, spaced at intervals of 2.5–3.0 cm. The column design allowed adjustment of the working liquid height, enabling control of the liquid level. Air was supplied from a compressor (3) through a valve (4) and regulated using a rotameter (5), after which it entered the aerator. The plastic mixture was fed into the upper part of the column through a cell feeder (6). The immersion depth of the feed inlet into the solution was maintained at 2.5–3.5 cm. A circulation system of the working solution was implemented to ensure continuous removal of the froth concentrate. To prevent the accumulation of plastic particles in the feeding zone, the solution was recirculated back into the column through a pipe (7) using a pump (8). The froth product was discharged via a launder (9) into a separator (10), where solid particles were separated from the liquid phase. The separator also served as a reservoir for the circulating working solution. The liquid was drained from the column through an outlet nozzle (12) and a valve (13). During flotation, hydrophilic plastic particles settled on a removable grid (11), which was removed after completion of the experiment and emptying of the column.

The flotation process was considered complete when no plastic particles were visually observed in the working solution. The concentrate, together with the froth, was collected from the top of the apparatus, while the settled particles were removed from the bottom as tailings. The efficiency of flotation separation was evaluated by determining the amount of each type of plastic in the concentrate and tailings.

The laboratory flotation unit operated in a batch mode and was intended primarily for investigation of flotation separation mechanisms and evaluation of the influence of operating parameters on separation efficiency. Depending on the experimental conditions and availability of plastic materials, the mass of the processed plastic mixture in a single experiment varied from 30 to 200 g. The flotation column had a height of 1.0 m and an internal diameter of 0.18 m, corresponding to an effective working volume of approximately 0.025 m^3. The duration of the flotation process typically ranged up to 2 min and depended on the air flow rate and polymer feeding conditions.

Based on the experimental data, the recovery of the floated component and the concentrate purity were calculated using the following equations (Abramov, 2016; Fuerstenau et al., 2007)

$$\varepsilon = \frac{m_{conc}}{m_{\text{feed}}} \cdot 100\%,$$

$$\beta = \frac{m_{conc}}{m_{\text{c}}} \cdot 100\%.$$

where m_{conc} is the mass of the PET component in the concentrate (kg), m_{feed} is the initial mass of PET fed into the flotation process (kg), and m_{c} is the total mass of the concentrate (kg).

To improve the reliability of the results, each experiment was performed in triplicate. The obtained data were averaged, and corresponding dependencies were constructed.

Results and discussions. A series of experiments was conducted to investigate the effect of the nature and concentration of surfactants on the flotation separation of various plastic mixtures. Based on the obtained results, two methods for flotation separation of plastic mixtures were developed (Kovaleva et al., 2023; Kovaleva et al., 2024). For each method, optimal process parameters were identified, ensuring a recovery of the target polymer and a concentrate purity of at least 95%.

Additional experimental observations demonstrated that moderate variations in air flow rate and surfactant concentration did not result in critical deterioration of flotation performance. Variations of process parameters within approximately ±10% caused gradual changes in recovery and concentrate purity; however, the flotation system generally maintained stable separation behavior near the optimal operating region.

The most suitable operating parameters, including the temperature of the working solution and the air flow rate, required to achieve high flotation efficiency, were determined experimentally.

Figure 2 illustrates the effect of alkyl polyglucoside concentration on the efficiency of flotation separation of a plastic mixture consisting of PBT and ABS. The flotation experiments were carried out at an air flow rate of 2.2 $m^3/(m^2 \cdot h)$ and a working solution temperature of (20 ± 1) °C.

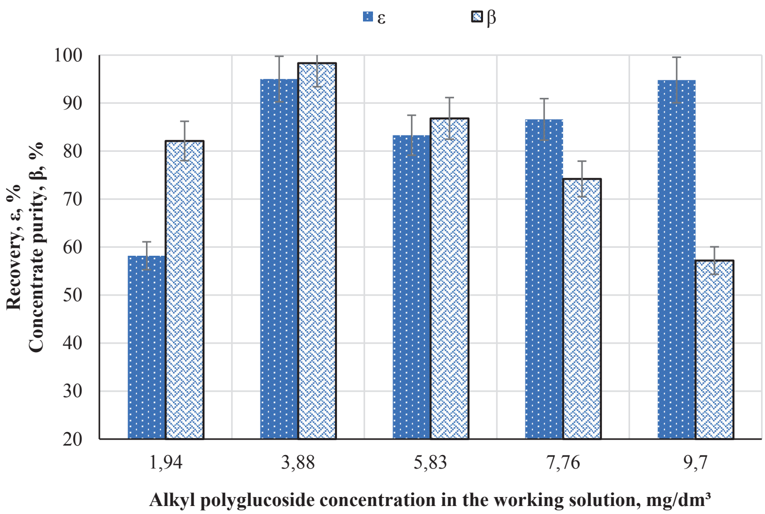

Figure 2. Effect of alkyl polyglucoside concentration in the working solution on PBT recovery and concentrate purity.

The analysis of the data presented in Figure 2 indicates a pronounced hydrophobicity of PBT particle surfaces with respect to the working solution. At an alkyl polyglucoside concentration of 3.88 mg/dm^3, the recovery of PBT reached 95%, while the concentrate purity exceeded 98%, which suggests a high hydrophilicity of the ABS surface under these conditions. Comparable high recoveries were reported for selectively conditioned polymer systems in previous flotation studies (Fraunholcz, 2004). This confirms that selective surface conditioning of PBT was successfully achieved under the chosen reagent dosage.

An increase in surfactant concentration to 5.83 mg/dm^3 resulted in a decrease in PBT recovery to 83.5%. Further increases in surfactant concentration led to a decline in flotation efficiency, which is likely associated with disruption of the interfacial interaction balance in the system. Excess surfactant may reduce the selectivity of particle–bubble attachment due to changes in surface wettability and possible formation of excessive adsorption layers.

Thus, the flotation separation efficiency of the PBT–ABS mixture exceeded 95% at an alkyl polyglucoside concentration of 3.88 mg/dm^3, an air flow rate of 2.2 $m^3/(m^2 \cdot h)$, and a working solution temperature of (20 ± 1) °C.

In the study of surfactant effects on the flotation separation of PET–PPS mixtures, it was found that the best results were achieved using polysorbate 80 as a surfactant. At a concentration of 8.0 mg/dm^3, the PET recovery reached 94%. However, under these conditions, PPS particles exhibited insufficient hydrophilicity, which led to their partial attachment to air bubbles and subsequent entrainment into the concentrate. As a result, the concentrate purity decreased to 70%. This result indicates insufficient selectivity when a single surfactant system was used.

Therefore, despite the high recovery of PET, the obtained results indicate the need for an additional purification stage to improve the quality of the target product. It was hypothesized that combining surfactants of different nature could produce a synergistic effect, enabling more precise control of the hydrophobic–hydrophilic balance of particles and stabilization of the froth phase, thereby enhancing both selectivity and overall flotation efficiency (Pita et al., 2023).

Figures 3–5 present the effect of different ratios of polysorbate 80 and sodium laureth-3 sulfosuccinate on the flotation separation efficiency of the PET–PPS mixture. The experiments were carried out at an air flow rate of 3.3 $m^3/(m^2 \cdot h)$ and a working solution temperature of (13 ± 1) °C.

The selected temperature range was determined experimentally as the most favorable for achieving selective flotation separation of PET and PPS. Lower temperatures improved the selectivity of surfactant adsorption and enhanced the difference in wettability between polymer surfaces, which contributed to higher concentrate purity and recovery.

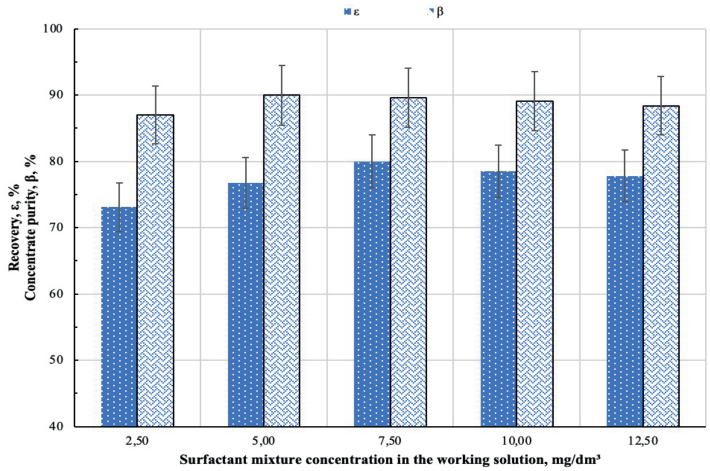

Figure 3. Effect of surfactant mixture concentration in the working solution on PET recovery and concentrate purity at a sodium laureth-3 sulfosuccinate: polysorbate 80 ratio of 1:1.

Figure 3 shows the dependence of PET recovery and concentrate purity on the concentration of a surfactant mixture consisting of sodium laureth-3 sulfosuccinate and polysorbate 80 applied at a ratio of 1:1. According to the obtained data, the concentrate purity reached 90%, indicating high wettability of PPS particle surfaces and their pronounced hydrophilic properties. At the same time, PET recovery remained within the range of 73–80%, which suggests limited hydrophobicity of PET particle surfaces under the given flotation conditions.

Figure 4 illustrates the effect of the concentration of a sodium laureth-3 sulfosuccinate : polysorbate 80 mixture at a ratio of 1:2 on the flotation separation efficiency of the PET–PPS mixture.

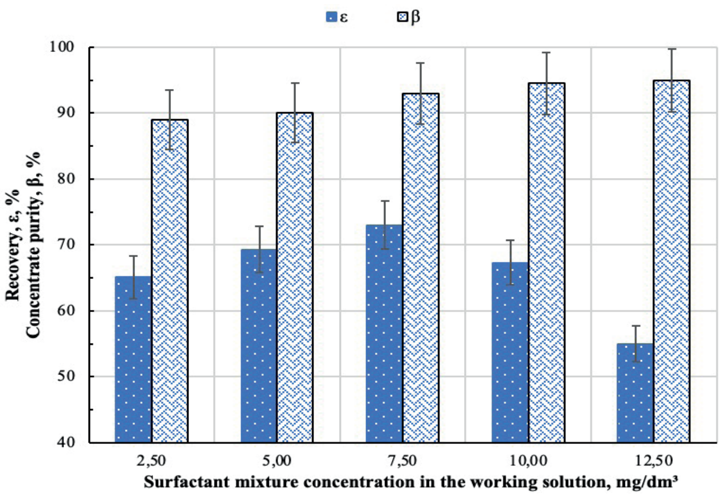

Figure 4. Effect of surfactant mixture concentration in the working solution on PET recovery and concentrate purity at a sodium laureth-3 sulfosuccinate : polysorbate 80 ratio of 1:2.

According to the data presented in Figure 4, PET recovery did not exceed 73%, indicating insufficient hydrophobicity of PET particle surfaces with respect to the applied working solution. As a result, part of the material settled under gravitational forces, reducing the efficiency of flotation recovery. At the same time, the high concentrate purity, ranging from 88% to 95%, indicates the pronounced hydrophilicity of PPS particles, which ensured their stable wetting by the working solution and effective separation from PET.

The effect of the concentration of a sodium laureth-3 sulfosuccinate and polysorbate 80 mixture at a ratio of 2:1 in the working solution on PET recovery and concentrate purity during flotation separation of the PET–PPS mixture is presented in Figure 5.

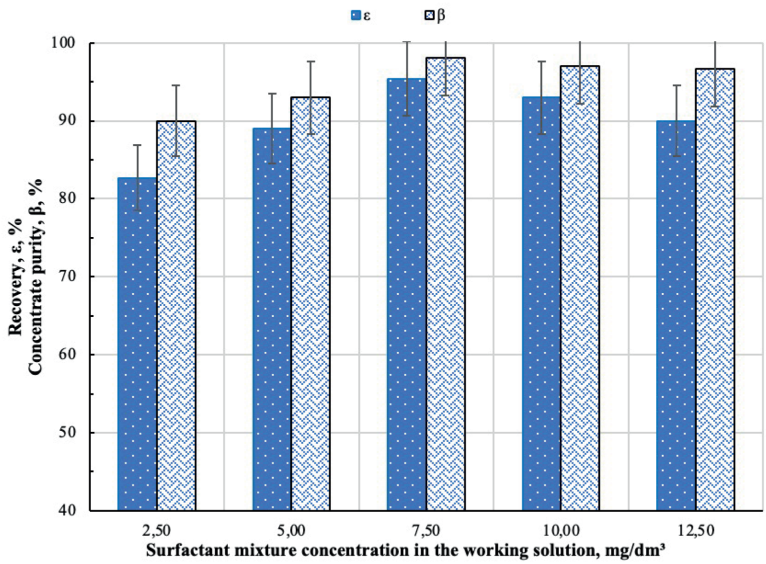

Figure 5. Effect of surfactant mixture concentration in the working solution on PET recovery and concentrate purity at a sodium laureth-3 sulfosuccinate : polysorbate 80 ratio of 2:1.

The results presented in Figure 5 demonstrate the high efficiency of flotation separation of the polyethylene terephthalate (PET) and polyphenylene sulfide (PPS) mixture when combined surfactants were used. At a total surfactant concentration in the range of 7.5–10 mg/dm^3, including 2.5–3.3 mg/dm^3 of sodium laureth-3 sulfosuccinate and 5.0–6.7 mg/dm^3 of polysorbate 80, PET recovery reached 93–95%, while the concentrate purity was 97–98%. The improved performance may be associated with synergistic adsorption effects of anionic and nonionic surfactants on polymer surfaces.

These indicators confirm that the selected parameters provided an optimal balance between the hydrophobic and hydrophilic surface properties of the separated particles, thereby ensuring high flotation efficiency (Fujita et al., 2014).

Conclusion. Based on the results of the study, two flotation methods for the separation of plastic mixtures were developed, and the corresponding technological parameters ensuring high process efficiency were determined.

It was established that effective flotation separation of the acrylonitrile–butadiene–styrene (ABS) and polybutylene terephthalate (PBT) mixture, with a recovery of 95% and a concentrate purity of 98%, was achieved at an alkyl polyglucoside concentration of 3.88 mg/dm³, an air flow rate of 2.2 m³/(m²·h), and a working solution temperature of (20 ± 1) °C.

For efficient separation of the polyethylene terephthalate (PET) and polyphenylene sulfide (PPS) mixture, high separation performance (95% recovery and 98% concentrate purity) was achieved using a surfactant mixture with a total concentration of 7.5 mg/dm³, including 2.5 mg/dm³ of sodium laureth-3 sulfosuccinate and 5.0 mg/dm³ of polysorbate 80. Suitable operating parameters were an air flow rate of 3.3 m³/(m²·h) and a working solution temperature of (13 ± 1) °C.

The conducted studies demonstrated the possibility of achieving efficient flotation separation of polymer mixtures with similar density values through optimization of reagent systems and operating parameters under controlled laboratory conditions.

One of the important directions for future research is the investigation of flotation separation under conditions closer to industrial recycling systems, including multicomponent plastic mixtures and contaminated post-consumer waste streams. Particular attention should be paid to the influence of organic impurities and residual surface-active substances on flotation selectivity and process stability.

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www:nauka-nanrk.kz
http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Managing Editor: *T. Apendiev*
Editors: *D.S. Alenov, A.Shormakova*
Computer layout: *G.D. Zhadyranova*

Signed for print: July 10, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 3.

«Central Asian Academic Research Center» LLP
Almaty, Shevchenko Street, 28