

Article

Application of Flotation for Removing Barium(II) Ions Using Ionized Acyclic Polyethers in the Context of Sustainable Waste Management

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Abstract: Energy transition is one of the basic actions taken to counteract and prevent climate change. The basic assumption of energy-related changes is its sustainable use according to the closed-loop model, as well as moving away from fossil fuels, in particular from coal, the combustion of which contributes to excessive harmful carbon dioxide emissions. One of the most popular solutions towards green energy is nuclear energy. Its use allows for a significant reduction in greenhouse gas emissions harmful to the environment and climate, but it also involves the generation of radioactive waste that requires appropriate processing. This paper presents the results of the flotation removal of barium(II) ions from a dilute aqueous solution using ionized acyclic polyethers. The basic factors determining the efficiency and kinetics of the process were defined. It has been shown that as the acidity of the attached polyether molecules increases: the flotation rate constant $\underline{1}$ (0.1667 min^{-1}) $< \underline{3}$ (0.2468 min^{-1}) $< \underline{2}$ (0.3616 min^{-1}) and the separation degree Ba^{2+} : $\underline{1}$ (86.8%) $< \underline{3}$ (99.3%) $< \underline{2}$ (99.4%). The presented results of ion flotation tests may facilitate the collective or selective separation of radioactive isotopes, i.e., Cs-137, Sr-90, Ba-133 and Co-60, from radioactive wastewater in the future. The results of the experimental work described in the article can also be used to develop individual processes for separating mixtures of radioactive isotopes (radioactive wastewater) into individual components (isotopes) and subjecting them to subsequent transformation processes. The obtained results allow us to claim that the tested organic compounds can be used in the future in the selective treatment of hazardous wastewater, which will translate into a reduction in unit costs of industrial processes. The selective recovery of individual pollutants is the basis for the next step in waste management, i.e., designing a cheap method of waste disposal, which also directly affects the economics of the process and its use in industrial conditions.

Keywords: flotation; barium ions; selective removal; radioactive waste; energy transition



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1. Introduction

The dynamic development of technology and the civilization progress in the world determine the contemporary approach to the quality of life and natural environment protection. One of the biggest challenges in the context of the constantly increasing demand for innovations in various economic sectors and everyday life is their impact on climate change. According to the Sustainable Development Goals (SDG), promoting prosperity is equivalent to protecting the planet [1]. Climate action is part of SDG 13, which indicates

that one of the main factors contributing to negative climate change is greenhouse gases, the emissions of which can be reduced, among others, by changing the global industrial, transport, and energy model [2]. As indicated in SDG 7, “Affordable and Clean Energy”, energy consumption is the largest contributor to climate change, accounting for approximately 60% of global greenhouse gas emissions [3]. In particular, carbon dioxide (CO₂) emissions are generated during combustion to these fossil fuels: coal, oil, and gas [4–6]. contribute to this. To slow down the process of climate change, various actions are taken in the context of energy transformation and modification of energy and economic systems, striving to change the use of fossil fuels in favor of renewable sources, rational use of resources, and achieving the highest possible energy efficiency [7–10]. Moreover, attention is drawn to the fact that the energy transformation applies not only to manufacturing enterprises and other industrial companies but also to individual household users, responsible for approximately 27% of energy consumption in the European Union member states. It is intended for space heating, domestic water heating, lighting, power supplies, and cooking [11].

Due to the introduction of the principles of sustainable development, as well as the pursuit of a circular economy model with a closed loop of energy use and broadly understood activities towards energy transformation, the approach to energy raw materials has changed over recent years (Figure 1). In the 1990s in the European Union, oil, petroleum, and solid fossil fuels—coal—were mainly used for energy generation (over 60% in total). In turn, only 5% of the energy produced came from renewable sources. The situation was similar in 2001. Changes in the approach to burning fossil fuels can be seen nowadays: in 2021, less than half of the total energy was produced from oil, and coal, in favor of the use of natural gas (23.3%) and renewable energy sources (17.2%). It is worth noting that over the years 1991–2021, the use of nuclear energy remained at a similar level, constituting on average 13–14% of the share of total energy produced in the EU (Figure 1).

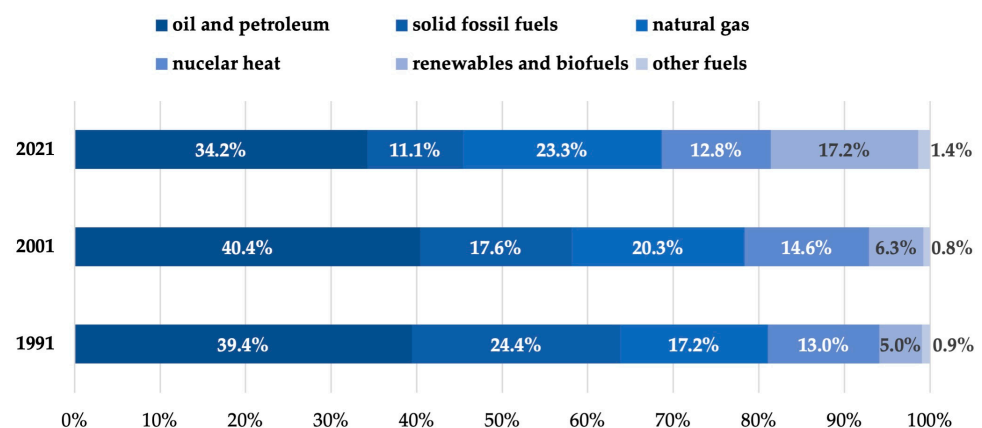


Figure 1. Energy sources used in the European Union in 1991–2021 [12].

Operating nuclear reactors in 2022 were located in 13 European Union countries, including France, Spain, Sweden, Belgium, and Germany [13]. Most often, nuclear energy is used to produce electricity: in France and Slovakia, over 60% of electricity comes from nuclear resources [14]. Nuclear energy is considered a low-carbon energy source that emits much fewer greenhouse emissions than fossil fuels and is therefore considered an effective and safe technology in the context of climate change [15–19]. Moreover, despite the tendency to increase the use of renewable energy sources, nuclear sources are still very popular in the world, and new nuclear power plants are planned all over the world, including Poland, Lithuania, Jordan, Saudi Arabia, Turkey, and Egypt [19,20].

In addition to reducing the impact of ongoing climate change in line with sustainable development and energy transformation, the use of nuclear energy is also associated with a significant increase in the production of radioactive waste, i.e., solid, liquid, and gaseous waste containing radioactive elements [21,22]. In Poland, despite the lack of nuclear power plants, they are produced in significant quantities, for example, in scientific

research, including the operation of the Maria research reactor (MARIA Reactor | NCBJ, <https://www.ncbj.gov.pl/en/maria-reactor> (accessed on 24 March 2024)). Radioactive waste is generated in industrial, research, agricultural, military, and medical activities. The largest source is the nuclear energy industry: radioactive waste is produced at all stages of the nuclear fuel cycle—from the extraction of uranium ore, through the production of fuel, its use, and then final management [23]. However, it is worth seeing that the general amount of waste produced by the nuclear power industry is relatively small when compared to electricity generation from fossil fuels.

According to the World Nuclear Association, radioactive waste includes any material that is either intrinsically radioactive or has been contaminated by radioactivity, and that is deemed to have no further use. Radioactive waste could be divided into short-lived, medium-lived, and long-lived waste or very low-level, low-level, intermediate-level, and high-level waste [24]. The division of waste into the above-mentioned categories depends on the half-life of radioactive elements and the criterion of radioactive activity expressed in becquerels (1Bq). High-level waste includes mainly partially used fuel from reactors and liquid waste generated during its storage and processing. This waste group, because of the heat of decay and therefore temperature rise, requires cooling and shielding. The spent fuel management policy is a long-term strategy defined at the national level. In most countries, spent fuel is usually stored for some time. The storage length depends on the spent fuel management strategy adopted, and could vary from a few years up to several decades. When spent fuel is recycled, the storage period is relatively short. Storage systems include wet (storage pools) or dry methods (storage casks, canisters, or vaults). Currently, over 70% of spent fuel is stored using wet methods. Intermediate-level waste amounts to about 5% of total radioactive waste and is characterized by relatively high radioactivity but a lower amount of decay heat produced compared to high-level waste. Therefore, wastes of this group, such as contaminated materials from reactor decommissioning and sludges, require only shielding. Low- and very low-level waste does not require shielding and is suitable for disposal in near-surface facilities. In this group, waste from industry and the medical sector, such as tools, clothing, and towels, could be distinguished. Low-level radioactive waste constitutes above 90% of the radioactive waste stream volume. Before final disposal, they are often mechanically compacted [24–26].

Radionuclides are isotopes with unstable nuclei, that spontaneously undergo radioactive transformation with radiation emission [27]. The multistage process of nuclear decay ultimately leads to nonradioactive product formation. Isotopes with long half-lives are mainly less harmful alpha and beta emitters. Isotopes with short half-lives tend to emit also more penetrating gamma radiation. The radionuclides group includes, among others, barium isotope Ba-133, with a half-life of 10.54 years [28]. The Ba-133 isotope is produced during the fission of nuclear fuel and is one of the most toxic radionuclides found in radioactive liquid waste [29]. As a result of high-level radioactive waste storage, large amounts of post-process wastewater contaminated with barium and other radionuclides are generated. Barium can accumulate in the natural environment: in soil, bottom sediments, and tissues of living organisms [30]. The most common technologies for barium removal from aqueous solutions involve chemical and physical treatment, mainly chemical precipitation, ion exchange, membrane processes, and, above all, adsorption [31]. The main advantages of adsorption are low costs, the simplicity of the process, and a wide range of adsorbents that can be used. Literature sources indicate the possibility of using activated carbon based on nut shells, dolomite powder, and bentonite for the adsorption of barium and other radioactive elements [32–34].

Due to differences in the stability of individual radionuclides, it seems reasonable to initially separate individual radioactive waste streams by using selective methods. In [35], a selective barium adsorption method using an ion trap with an organometallic structure and strong chelating compounds was used. Kim and Lee [36] used chemically modified alginate beads with enhanced Ba²⁺ affinity to selective barium adsorption. Then, the Cs-131 isotope, formed as a result of adsorbed Ba-130 and Ba-131 isotope decay, was selectively eluted from

the adsorption column. Another method of radionuclide selective separation is the flotation process [37–39]. The flotation process allows for the removal of ions from dilute aqueous solutions by ionogenic organic compounds. Key determinants influencing this process are collector type and concentration, the removed ions' type and concentration, aqueous phase composition, temperature, and gas flow rate. The flotation mechanism is based on the occurrence of adsorption and electrostatic phenomena at the interface (Figure 2).

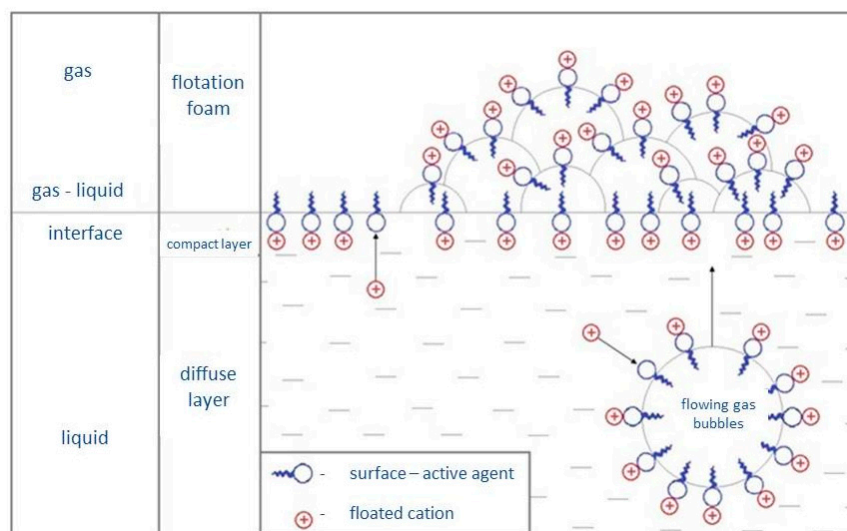


Figure 2. Mechanism of ion flotation.

Monatomic ions present in aqueous solutions do not accumulate at the gas–liquid interface. As a result, collectors play a crucial role in ion flotation. They exhibit high activity within the solution, reducing interfacial tension. This change in tension leads to the adsorption of the collector onto the solution surface. At the gas–liquid interface, characteristic hydrophobic segments of the surface-active agent are directed toward the gas phase while the hydrophilic parts face the aqueous solution. This creates an adsorption layer (known as the compact layer), the thickness of which depends on the size of the ion creating it. Collectors adsorbed at the gas–liquid interface generate a uniform electrostatic field. Consequently, they draw counter-ions from the diffuse layer (fuzzy layer) and transport them to the surface of gas bubbles above the solution. Additionally, adsorption of the surfactant and the establishment of ion–collector connections also occur on the surface of flowing gas bubbles. Therefore, the formation and maintenance of a stable foam are substantial aspects of the ion flotation process [40].

The goal of this publication is to assess the effectiveness of the flotation separation process for removing Ba(II) ions from model solutions using ionized acyclic polyethers. This method serves as an alternative to commonly used, nonselective methods for removing barium and other radionuclides from radioactive waste.

2. Materials and Methods

2.1. Reagents

The initial aqueous solutions were prepared with double distilled water and $\text{Ba}(\text{NO}_3)_2$. The gamma-radioactive isotope Ba-133 was purchased from the Atomic Energy Chemistry and Technology (Otwock-Świerk, Poland). As the surfactants were used acyclic ionizable polyethers **1**, **2**, and **3** from Prof. R. A. Bartsch, Department of Chemistry and Biochemistry, Texas Tech University, Lubbock, TX, USA (Table 1). The initial solution was prepared with THF from Merck (Rahway, NJ, USA). The nonionic foaming agent was octylphenyloxydecyl (ethylene glycol) ether (Triton X-100).

Table 1. Tested compounds ionizable acyclic polyethers.

Number of the Chemical	Structural Formula	-R	-Y	-X
<u>1</u>		$-C_8H_{17}$	$-(CH_2CH_2)_2O$	$-CH_3$
<u>2</u>				$-CF_3$
<u>3</u>				$-C_6H_4-pNO_2$

2.2. Ion Flotation Procedure

The ion flotation experiments were conducted in a glass flotation column measuring 45.7 cm in height and 2.4 cm in diameter—Figure 3. Argon gas was utilized for the flotations, maintaining a flow rate of $12 \text{ m}^3/\text{min}$ [41]. Each initial feed solution had a volume of 100 cm^3 and contained $Ba(NO_3)_2$ and Ba-133. The solution's pH was adjusted to 4.0, 5.0, 6.0, 7.0, or 9.0 using either nitric or ammonium hydroxide solutions to maintain the desired pH levels. Both single and multichannel gamma radiation spectrometers VARIAN, Palo Alto, CA, USA SpectrAA 20 Plus spectrometer[®] served as detectors to measure radiation intensity at specific energy levels.

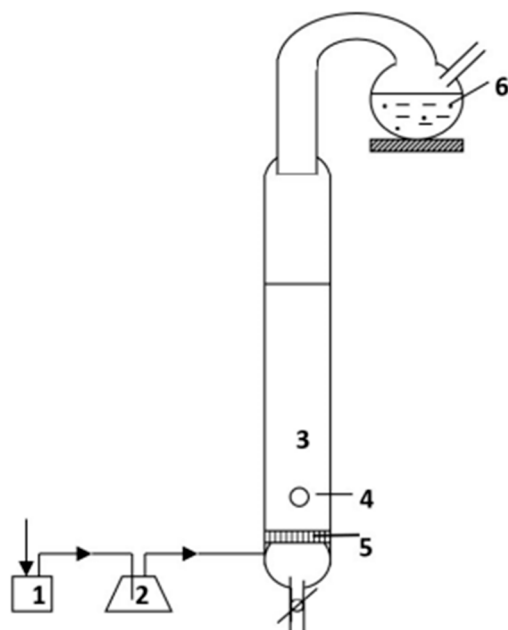


Figure 3. Scheme of ion flotation apparatus. 1—gas flow regulator, 2—aqueous scrubber, 3—flotation column, 4—injection capable valve (for collector), 5—sintered glass sparger, 6—foam receiver.

3. Results and Discussion

The flotation removal of Ba^{2+} from dilute aqueous solutions was conducted using ionizable acyclic polyethers: 1, 2, and 3. The collectors have the same size pseudo-crown and lipophilic chain ($-C_8H_{17}$), but differed in end-group: 1— CH_3 , 2— CF_3 , 3— $C_6H_4-pNO_2$. Their efficiency and kinetics in ionic flotation were investigated at different solution pH levels, as well as with a reduced concentration of the collector.

3.1. Effect of pH

The pH of the aqueous solution was varied in the range of 4.0 to 9.0 and measured before each experiment. Also, the initial concentration of the collector was 5.0×10^{-5} M. The results are shown in the following table (Table 2).

Table 2. Influence of pH on the barium(II) ions' flotation process by ionizable acyclic polyethers 1, 2, 3 [Ba^{2+}] = 1.0×10^{-5} M [1, 2, 3] = 5.0×10^{-5} M, [Triton X-100] = 2.0×10^{-5} M.

pH	Ba^{2+}					
	Maximal Percent Removal, W, %/Rate Constant, k, min^{-1}					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>
4.0	-	-	2.18	0.0019	-	-
5.0	6.27	0.0012	14.9	0.0064	14.1	0.0039
6.0	81.4	0.0581	60.8	0.0517	95.2	0.1304
7.0	81.7	0.0527	72.6	0.0612	97.5	0.1665
9.0	86.8	0.1667	99.4	0.3616	99.3	0.2498

It was found that pH has a strong influence on the course of the flotation process. The dependence of the increasing separation of Ba^{2+} with increasing pH is shown in the graph (Figure 4).

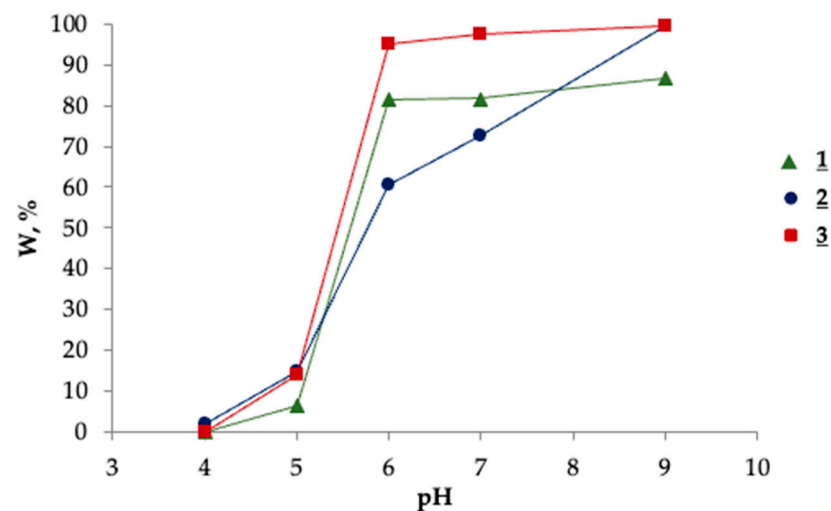


Figure 4. Influence of pH on the barium(II) ions flotation process by ionizable acyclic polyethers 1, 2, 3.

At pH = 4, the flotation process for collector 1 does not involve, while at pH = 5, the degree of separation is very low (approx. 6%). At pH = 6, the process yield rises sharply to 81%, and the highest degree of separation is about 87% at pH 9. The results for polyether 2 show a gradual increase in the efficiency of the flotation process. The highest degree of Ba^{2+} separation, around 99%, was obtained at pH = 9. Similar with compound 1, for compound 3, no flotation process was observed at pH = 4, while at pH = 5, the degree of ion separation is low. Meanwhile, at pH = 6, the process yield increases rapidly and is maintained at $97 \pm 2\%$ for the next two flotations conducted in an inert environment and alkaline conditions.

Additionally, the study concluded the influence of pH on the rate constant of the flotation process. The rate constant for all collectors increased with increasing the solution pH (Figure 5).

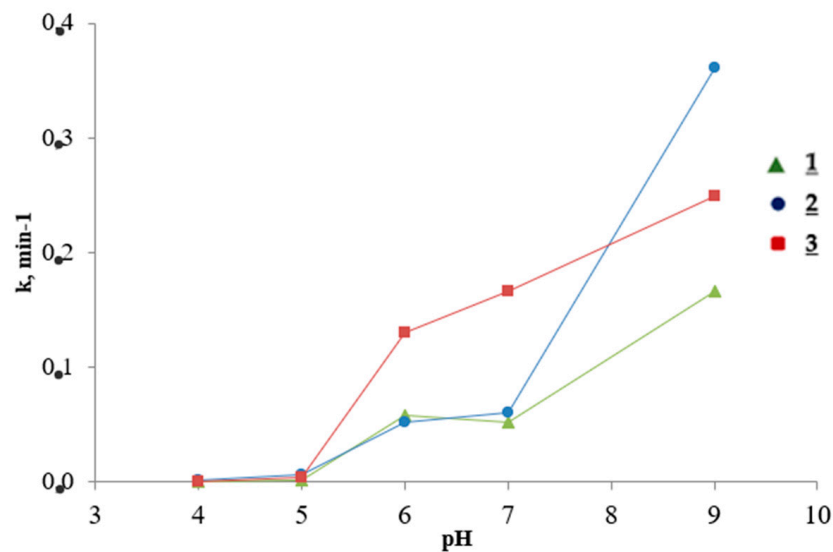


Figure 5. Influence of pH on the rate constant of barium(II) ions flotation process by ionizable acyclic polyethers 1, 2, 3.

The best degrees of separation of Ba^{2+} were obtained at pH 9. The speed and efficiency increase in the following order of end groups: $-\text{CH}_3$ (1) < $-\text{C}_6\text{H}_4\text{-pNO}_2$ (3) < $-\text{CF}_3$ (2). Comparison of the results shown by curve flotation (Figure 6).

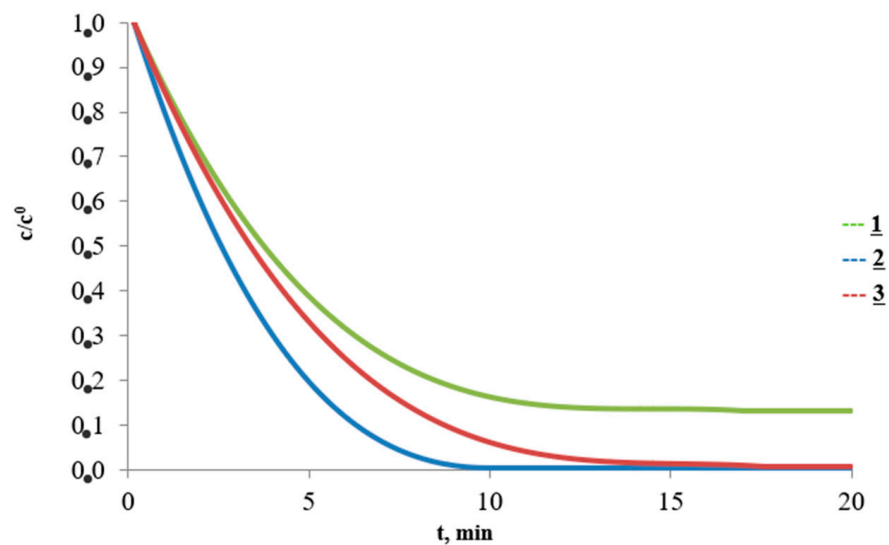


Figure 6. Curve flotation barium ions (II) at pH = 9 by ionizable acyclic polyethers 1, 2, 3.

Similar conclusions were obtained by Walkowiak et al. [42], which investigated the separation of Ra^{2+} and Ba^{2+} from aqueous solutions using ionizable acyclic polyethers (4–11, 12, 13) by competitive solvent extraction in a liquid–liquid, presented in Table 3. It was found that with the increase in pH, the Ba^{2+} extraction degree increases. The collectors 5, 9, 2 extract ions gradually and give the best performance at pH 8.5. But for polyether 4, 6–8, 10, 11, 1, 12, 3, extractions occurred at $\text{pH} \geq 6$, and the highest value was reached in an alkaline environment. The best results were obtained for collector 2.

Table 3. Structures of lipophilic, di-ionizable, acyclic polyethers [40].

Number of the Chemical	Structural Formula	-R	-Y	-X	
<u>4</u>		-C ₈ H ₁₇	-(CH ₂) ₂	-CH ₃	
<u>5</u>				-CF ₃	
<u>6</u>				-C ₆ H ₅	
<u>7</u>				-C ₆ H ₄ -pNO ₂	
<u>8</u>				-CH ₃	
<u>9</u>				-CF ₃	
<u>10</u>				-C ₆ H ₅	
<u>11</u>				-C ₆ H ₄ -pNO ₂	
<u>1</u>				-CH ₃	
<u>2</u>				-CF ₃	
<u>12</u>				-(CH ₂ CH ₂) ₂ O	-C ₆ H ₅
<u>3</u>				-C ₆ H ₄ -pNO ₂	
<u>13</u>				-C ₁₄ H ₂₇	-CF ₃

3.2. Effect of Collector Concentration

Measurements of the influence of concentration were carried out at pH = 9, as previous studies showed that this pH value gives the best results. The initial accepted concentration of collectors were 5.0×10^{-5} , 4.0×10^{-5} , 3.0×10^{-5} ; 2.0×10^{-5} M. The results are shown in the following table (Table 4).

Table 4. Influence of collector concentration on the barium(II) ions flotation process by ionizable acyclic polyethers 1, 2, 3. [Ba²⁺] = 1.0×10^{-5} M, [Triton X-100] = 2.0×10^{-5} M, pH = 9.

Collector Concentration [M]	Ba ²⁺					
	Maximal Percent Removal, W, %/Rate Constant, k, min ⁻¹					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>
5.0×10^{-5}	86.8	0.1667	99.4	0.3616	99.3	0.2498
4.0×10^{-5}	98.5	0.2459	98.6	0.3273	98.2	0.3007
3.0×10^{-5}	99.8	0.2053	95.3	0.2383	97.3	0.2963
2.0×10^{-5}	99.7	0.1583	94.2	0.1817	96.3	0.2939

For polyether 1, the results indicate an increased degree of Ba²⁺ separation as the collector concentration decreases. This suggests that even at the stoichiometric cation concentration to polyether, nearly 100% efficiency and a favorable flotation rate can be achieved. In the case of polyether 2, both the yield and flotation rate slightly declined as the collector concentration decreased (Figure 7). Ten minutes after the measurement began, the separation degree decreased to 99.0%, 98.5%, 95.0%, and 86.0% with decreasing concentration.

The measurement results for polyether 3 remained practically the same (Figure 8). The maximum percentage of removal for the stoichiometric value of the cation concentration to the collector slightly decreased by 3%. After 10 min for each process, efficiency for decreasing concentration amounted to 94.0%; 98.0%; 97.0%, and 96.0%. This means that despite the highest degree of separation, the flotation rate for the ion concentration of 5.0×10^{-5} M was lower than for the other concentrations.

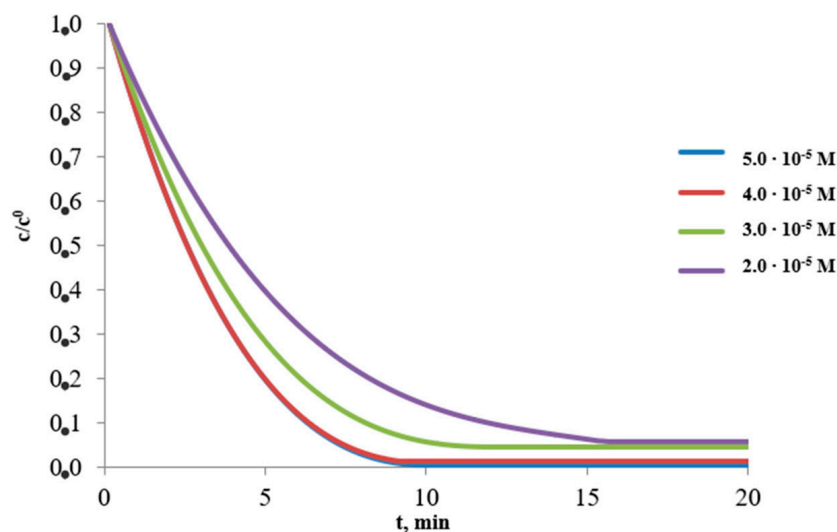


Figure 7. Curve flotation barium ions (II) at different concentrations of collector **2**.

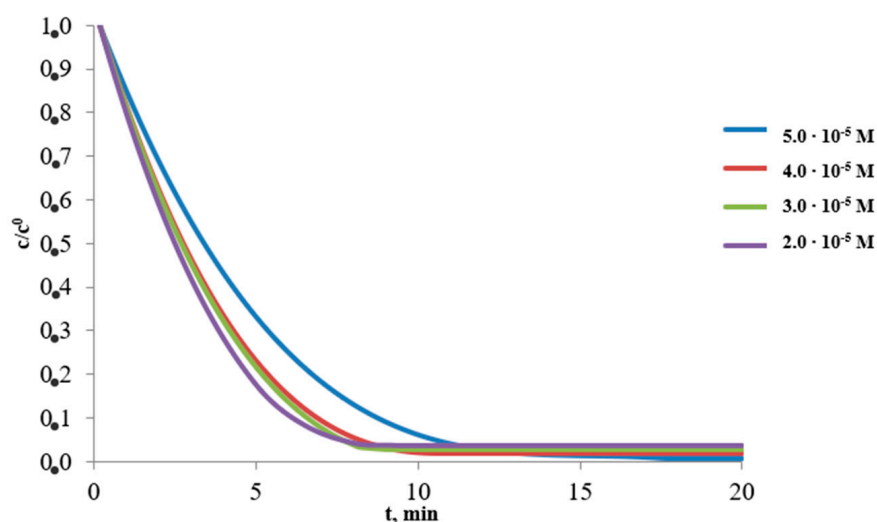


Figure 8. Curves flotation barium ions (II) at different concentrations of collector **3**.

Comparing ionizable acyclic polyethers (**1**, **2**, **3**) to lariat ethers shows similarity to the impact of the increase in collector concentration to increase the efficiency of the flotation process. It is small deviations from this correlation, but when concentrations of ether increased from 2.0×10^{-5} M to 5.0×10^{-5} M it showed a significant increase in the degree of separation, close to 100% [43].

3.3. Effect of End-Group

Analyzing the results obtained for the best efficiency of the flotation process, i.e., for pH = 9 and the initial collector's concentration equal 5.0×10^{-5} M, we can show that end-group has influence. The acidity of these groups decreases in the series: CF_3 (**2**) > $\text{C}_6\text{H}_4\text{-pNO}_2$ (**3**) > CH_3 (**1**). Comparison of the results is shown by curve flotation (Figure 4) and a graph (Figure 9).

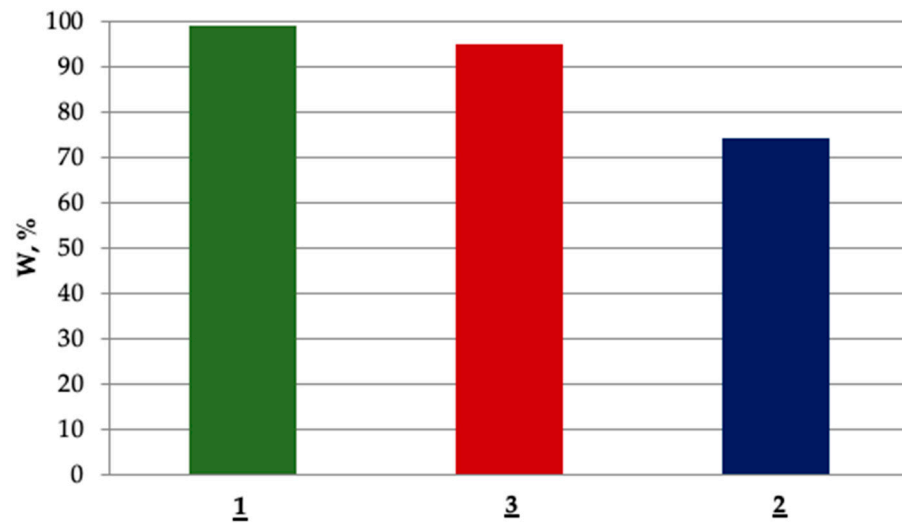


Figure 9. The dependence of attached end-groups with separation Ba^{2+} degree using acyclic polyethers, **1**, **2**, **3** after 10 min from the start of the flotation process. $[\text{Ba}^{2+}] = 1.0 \times 10^{-5} \text{ M}$ [**1**, **2**, **3**] = $5.0 \times 10^{-5} \text{ M}$, $[\text{Triton X-100}] = 2.0 \times 10^{-5} \text{ M}$, $\text{pH} = 9$.

Based on this result, it was observed that the increasing acidity of the polyether molecule attached increased the flotation rate constant **1** (0.1667 min^{-1}) < **3** (0.2468 min^{-1}) < **2** (0.3616 min^{-1}), and the degree of separation Ba^{2+} : **1** (86.8%) < **3** (99.3%) < **2** (99.4%).

4. Summary

Climate and environmental action based on energy efficiency contribute to the sustainable management of nonrenewable raw materials by using renewable energy sources instead, and the entire energy system is focused on maximum efficiency in a closed-loop model [44]. The change in the approach to energy raw materials has determined the replacement of fossil fuels with other options, including nuclear sources. Nuclear power plants have been operating around the world for many years, and new power plants of this type are still being planned. This involves reducing excessive greenhouse gas emissions, but at the same time affects waste management systems. Radioactive waste, due to its specific physicochemical properties, must be properly processed so as not to pose a threat to the environment. Despite progress in the management of very low and low-level radioactive waste, the management of spent nuclear fuel and other waste with high radioactivity still focuses mainly on long-term wet storage. This leads to the formation of liquid waste contaminated with various radionuclides. Selective removal of radionuclides from this type of waste is particularly important.

The results obtained in this paper confirm that the ion flotation method using ionizable acyclic polyethers can efficiently remove toxic metal cations from aqueous solutions. The acidity of the attached polyether molecules increases the flotation rate constant **1** (0.1667 min^{-1}) < **3** (0.2468 min^{-1}) < **2** (0.3616 min^{-1}) and the separation degree Ba^{2+} : **1** (86.8%) < **3** (99.3%) < **2** (99.4%), contributing to the selective or collective isolation of Ba-133 radioactive isotopes from radioactive wastewater and simplifying individual utilization and/or recycling processes. The findings derived from this study align with the assumption proposed in the study by Maciejewski P. et al. [45]. Flotation is a hydrometallurgical method that has so far been widely used in processing metal ores from their natural deposits. Nevertheless, due to the visible change in the approach to ecology and climate change in recent years following the principles of sustainable development and the circular economy model, scientists are constantly looking for modern and effective methods of selective removal of undesirable pollutants that may pose a particular threat to the environment. Thanks to the wide possibilities of using chemical methods in the context of waste processing and disposal, an example of which is the flotation process, their use in laboratory tests and on an industrial scale is becoming more widespread. An example of such achievements is the

development of technologies based on flotation using dedicated organic extractors for the selective recovery of critical metals, including zinc (Zn), copper (Cu), cobalt (Co), lithium (Li), manganese (Mn) and nickel (Ni), from waste zinc-carbon (Zn-C) and zinc-manganese (alkaline, Zn-Mn) as well lithium-ion (Li-ion, LIBs) batteries [41]. The authors of the review article on “Bubbles to batteries: A review of froth flotation for sustainably recycling spent lithium-ion batteries”, published in April 2024, clearly indicated that it is possible to use flotation methods for new polymetallic LIB waste [46]. This will require an in-depth analysis of the scaling and automation of this unitary process; however, the development of flotation methods in the area of topics related to the processing of secondary raw materials is inevitable. Because nowadays the progress of process technologies is so fast that the problems indicated by the authors of the works related to, among others, environmental factors and/or influence, selectivity, synthesis of new flotation compounds or solvents and high water consumption will be solved. The use of this process may also be a promising prospect in the context of processing radionuclides from synthetic solutions and real environmental samples. Therefore, the method presented in this paper can be adapted as either a continuous or batch process, enabling the effective and notably selective concentration of undesirable components from large volumes of aqueous solutions. Hence, it is justified to further explore the research mentioned above approach for both synthetic and real aqueous solutions with complex chemical compositions utilizing organic compounds. A particular challenge seems to be the synthesis of new organic compounds dedicated to the processing of selected waste streams that are complex in terms of chemical composition. Therefore, the future research concept includes not only scaling the process to the semi-technical and then industrial phase, but also examining the possibility of using new extractants in the process of selective barium(II) removal from radioactive waste using the flotation method.

Currently, the research team has started research on the use of ionizable lariat ethers for the recovery of metals from solutions obtained after acid reductive leaching of lithium (LIB) and non-lithium (CIB, FIB, ZIB, AIB) battery masses in order to investigate the selective and/or collective recovery of metal cations. The results of the first promising experimental work will be presented in subsequent publications.

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