Investigating the Efficacy of Activated Carbon/Palmitic Acid as Collector for Rare Earth Element Separation by Froth Flotation

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**Abstract.** Residual materials produced from tin ore extraction commonly known as tailings often contain rare earth minerals such as monazite. However, the selective separation of monazite from tailings remains challenging due to the presence of gangue minerals. Froth flotation offers a promising approach for monazite enrichment in which the type and composition of the collector plays a crucial role in flotation efficiency. This study investigates the effectiveness of composite collectors of activated carbon and palmitic acid (AC/PA) at varying ratios 100:0, 75:25, 50:50, and 0:100 for the flotation of monazite from tailings. The elemental composition of the tailing sample was analyzed using X-ray fluorescence (XRF), which confirmed a cerium content of 23.9%. The FTIR spectra of AC/PA collectors with ratios of 25:75, 50:50, and 75:25 exhibited main adsorption peaks consisting of asymmetric and symmetric stretching vibrations of –CH₂ groups for palmitic acid at wavenumbers 2918 cm⁻¹ and 2846 cm⁻¹, indicating the successful presence of functional groups associated with the collector. Flotation experiments resulted that the AC/PA collector with a ratio of 75:25 produced the monazite recovery reaching 28.18 %. The enhanced performance at the 75:25 collector ratio is attribution of the interaction between activated carbon which provides a high surface area to distribute palmitate molecules, thus maintaining the stability and activity of the collector within the flotation process.

**Keyword**: activated carbon; palmitic acid; froth flotation; waste; tailing

# INTRODUCTION

The global production and supply of rare earth elements (REEs) are currently dominated by four countries such as China, which contributes approximately 60% of total global production, followed by the United States with about 16%, and Burma and Australia with around 9% and 8%, respectively [1]. The increasing demand for REEs, coupled with the decline in high-grade ores, has led to the growing consideration of low-grade ores, mine wastes, and other unconventional resources as alternative feedstocks to supplement the current supply. Over the last two decades, the evaluation of mining tailings as a potential secondary source of REEs has attracted significant attention [2]. Generally, the recovery of mineral processing and purification processes reaches only up to 80%, leaving approximately 20% as tailings [3]. Tailings, as by-products of mining and mineral processing, are often regarded as hazardous waste with environmental implications. On the other hand, tailings still contain various strategic minerals that can be purified into high-value metals with appropriate beneficiation methods [3,4].

Based on the 2017 study of potential associated minerals in tin tailings, tailings contain significant amounts of strategic mineral carriers, such as ilmenite (32.43%), zircon (16.65%), cassiterite (12.59%), monazite (11.76%), and xenotime (10.82% of monazite). Among these minerals, monazite is one of the most important REE-bearing minerals. Monazite is a phosphate mineral containing light rare earth elements (LREEs) such as Ce, La, and Nd [5]. In general, the rare earth oxide (REO) content in monazite ranges between 65–70%, with compositions of 20-30% Ce2O3 and 10-40% La2O3 depending on the deposit location [6]. In addition, monazite often contains minor elements such as aluminium (Al), iron (Fe), bismuth (Bi), gallium (Ga), and thallium (Tl). Therefore, separation processes are required to extract the REEs from monazite for their further applications.

The separation of REE-bearing minerals such as monazite can be achieved using froth flotation, a physicochemical technique that exploits the differences in surface wettability of minerals [7,8]. Froth flotation involves complex interactions among solid particles (minerals), liquid (water), and gas (air). Its advantage lies in its effectiveness for the beneficiation of REE minerals from both high-grade and low-grade ores with complex mineralogy. Hydrophilic minerals exhibit rapid wetting by water, whereas hydrophobic minerals exhibit resistance to wetting. In a mineral suspension containing both hydrophilic and hydrophobic particles, the hydrophobic particles preferentially attach to air bubbles. The implemented use of reagents such as collectors is essential in flotation processes to enhance the hydrophobic characteristics of mineral particles. Fatty acids such as palmitic acid have been reported as effective collectors for the flotation of monazite and other REE minerals [7,9].

The selection of palmitic acid as a collector is supported by its environmentally friendly characteristics and its wide applicability in the flotation of various mineral systems [10]. Palmitic acid is a heteropolar organic reagent containing both polar and non-polar groups with the non-polar substance being significantly larger than the polar component. This structure enhances its hydrophobic characteristic over hydrophilic ones, allowing palmitic acid molecules to adsorb onto the surface of hydrophilic minerals and modify their surface properties to turn into more hydrophobic. On the other hand, activated carbon can serves as an adsorbent that effectively removes impurities and organic compounds that disrupt flotation processes [11]. The incorporation of activated carbon improves the purity and potency of palmitic acid as a collector, thereby enhancing flotation efficiency and product quality. The addition of activated carbon and palmitic acid as a composite collector is supposed to enhance the recovery and selectivity of monazite flotation.

Therefore, this study aims to investigate the effectiveness of composite collectors consisting of activated carbon and palmitic acid (AC/PA) at various ratios (100:0, 75:25, 50:50, 25:75, and 0:100) for the flotation of monazite from tin tailings. By combining the high surface area and stability of AC with the collecting ability of PA, this research seeks to provide new insights into improving monazite recovery through a more selective and sustainable flotation process.

# MATERIALS

Materials used in this work are tailing as raw materials contain monazite minerals, hydrochloric acid (HCl, Smartlab Merck, 37 %), sodium hydroxide (NaOH, Merck, ≥ 98 %), palmitic acid (C16H32O2, Merck Chemical Retal, 65%) and deionized water.

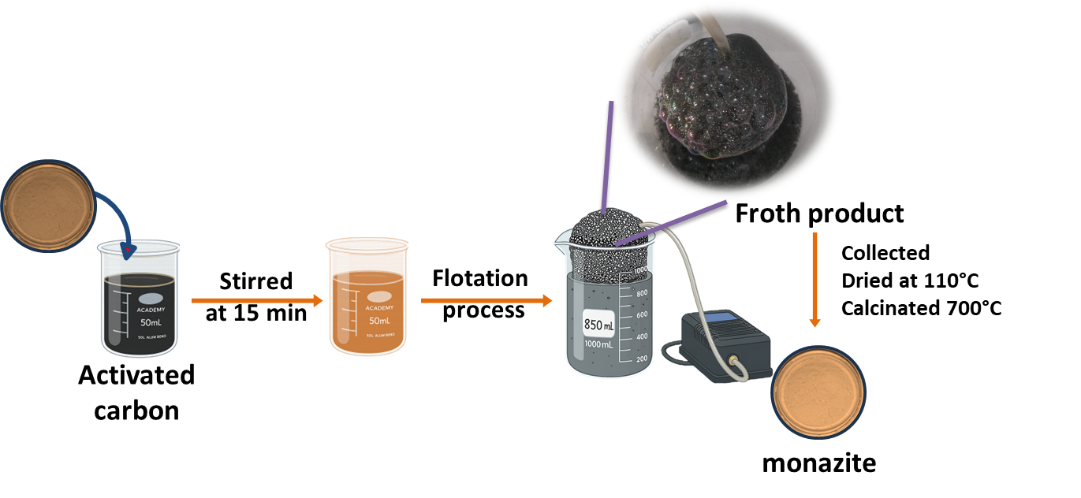
# EXPERIMENTAL

## Preparation of AC/PC Collector

## The collector was prepared by physically mixing bamboo-derived activated carbon with palmitic acid. The activated carbon was initially dried in an oven at 70 °C for 6 hours to enhance its adsorption capacity and optimize its operational performance. The dried activated carbon was then placed into a 50 mL beaker, and the appropriate amount of palmitic acid was evenly coated onto its surface. The beaker containing the composite was covered with aluminium foil and heated in an oven at 70 °C for 24 hours. During this period, the mixture was stirred every 8 hours to ensure uniform dispersion and absorption of the palmitic acid onto the activated carbon surface. After the impregnation process, 5 grams of AC/PA composite were prepared with varying mass ratios of 0:100, 25:75, 50:50, 75:25, and 100:0 (activated carbon to palmitic acid)

## Froth Flotation Process

## The separation of rare earth elements from tin tailings was carried out using the froth flotation method. The collector used in this flotation process was a composite of activated carbon and palmitic acid (AC/PA). The flotation process began by contacting tin tailings (sieved to 120 mesh) with the AC/PA composite at a mass ratio of 50:50, followed by stirring for 15 minutes to ensure thorough mixing. After contact was completed, distilled water was gradually added while stirring until a pulp was formed. Subsequently, an aerator was introduced to generate air bubbles within the slurry inside the flotation cell. The fine air bubbles captured the hydrophobic mineral particles, resulting in the formation of froth that rose to the surface of the solution. The floating froth was collected as concentrate, whereas hydrophilic or less hydrophobic particles remained at the bottom as tailings. The collected froth was then dried in an oven at 105 °C for 12 hours and subsequently calcined at 700 °C for 4 hours to remove residual carbon content. The collected froth was dried in an oven at 105 °C for 12 hours and subsequently calcined at 700 °C for 4 hours to remove the remaining carbon content. Illustrates the flotation process was shown in Figure 1.



**FIGURE 1**. Illustrates the froth flotation process using the composite collector of activated carbon and palmitic acid (AC:PA)

## Materials Characterization

To determine the rare earth element (REE) content in the initial samples was characterized by X-ray fluorescence (XRF). The XRF analysis was performed XRF PANalytical with accelerating voltage 30 kV. This analysis provided essential information on the elemental composition and content of the investigated specimen. The Fourier-transformed infra-red (FTIR) analysis was performed using Shimadzu using conventional KBr pellets at a wavenumber of 400–4000 cm-1 [12,13].

# RESULT AND DISCUSSION

## The AC/PA composite was prepared by mixing activated carbon (AC) and palmitic acid (PA) using the dry impregnation method. The mass ratio variations between AC and PA, as presented in Table 1. Table 1 shows the variation of activated carbon and palmitic acid composites with different mass ratios ranging from 100:0 to 0:100. This variation was designed to determine the optimal composition of AC/PA that can effectively use as a collector in the froth flotation process of rare earth element (REE) bearing minerals, particularly monazite. Activated carbon possesses a high specific surface area and a porous structure, permitting it to adsorb and stabilize palmitic acid molecules, which enhances their dispersion and interaction with mineral surfaces. On the other hand, palmitic acid contributes the hydrophobic functional groups (–CH₂ stretching vibrations) responsible for enhancing the attachment of REE minerals to air bubbles during flotation. The combination of AC and PA is expected to create a synergistic effect with AC enhances the stability and distribution of PA molecules, while PA provides hydrophobicity necessary for selective separation. As observed in similar studies, composite collectors often demonstrate better selectivity and efficiency compared to single-component collectors [8]. Sodium oleate, a commonly utilized fatty acid collector, has been shown to enhance flotation recovery of rare earth minerals, however its effectiveness is frequently constrained by stability issues under different pulp conditions [14]. In this context, the addition of AC provides a structural platform that minimizes reagent loss and maintains collector activity during flotation. Palmitic acid and other long-chain fatty acids have been evaluated in the literature as environmentally sustainable collectors, owing to their biodegradability and selective adsorption properties on rare earth element mineral surfaces. Meanwhile, activated carbon has been investigated not only as an adsorbent for impurities but also as a frother-support material capable of stabilizing bubbles in flotation processes [15]. Other examples of collectors-frothers used in flotation include methyl isobutyl carbinol (MIBC) as a conventional frother to stabilize bubbles and dodecylamine as a cationic collector for silicate minerals [16]. However, the use of AC/PA composites represents a novel approach, potentially offering higher selectivity and improved environmental compatibility compared to conventional reagents. Therefore, varying the AC/PA ratios as shown in Table 1 allows systematic evaluation of the synergistic effect of carbon support and fatty acid molecules in enhancing the flotation performance of monazite from tailings. The experimental results, supported by FTIR characterization, confirm that optimal hydrophobic interactions are achieved when AC and PA are combined at specific ratios, particularly at 75:25, which yielded the highest recovery.

Table 1. Variation Data of AC/PA Composites

|  |  |
| --- | --- |
| **Rasio (%)** | |
| **AC** | **PA** |
| 0 | 100 |
| 25 | 75 |
| 50 | 50 |
| 75 | 25 |
| 100 | 0 |

The impregnated AC/PA composite was subsequently characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify the chemical bonds formed. Spectra IR generates molecular vibration spectra that are used to identify chemical compounds based on the absorption bands of infrared energy produced by the molecules within the AC/PA composite. This instrument can be employed to detect functional groups and identify chemical compounds in a sample, since each compound possesses a unique infrared absorption pattern, thereby providing a characteristic signature of the sample’s chemical composition. The FTIR spectrum of the AC/PA composite is presented in Figure 2.

A graph of different colored lines

AI-generated content may be incorrect.

**FIGURE 2**. Spectra IR of AC/PA Collector

The impregnated AC/PA collector was then characterized using Fourier Transform Infra-Red (FTIR) spectroscopy to analyze the chemical interaction between activated carbon and palmitic acid. The FTIR spectra of AC/PA collector with ratios of 25:75, 50:50, and 75:25 exhibited main adsorption peaks consisting of asymmetric and symmetric stretching vibrations of -CH2 groups at wavenumbers 2918 cm-1 and 2846 cm-1. Another absorption peak observed at 1699 cm⁻¹ indicated the stretching vibration of the carbonyl (C=O) group. Additionally, the peak at 1465 cm⁻¹ represented bending vibrations of -CH₂ and -CH₃ groups. The absorption peak at 936 cm⁻¹ corresponded to the out-of-plane bending vibration of the -OH functional group, while the peak at 718 cm⁻¹ was attributed to in-plane rocking vibrations. Furthermore, the spectrum revealed a characteristic absorption peak at 1570 cm⁻¹, indicating the presence of the carbonyl (C=O) functional group, which is typical for activated carbon. These spectra feature collectively demonstrate the incorporation of palmitic acid into the activated carbon framework through the dry impregnation method, while the persistence of hydroxyl bands indicates that the AC structure retained surface functional groups. The combination of the high surface area and porosity of activated carbon with the hydrophobic long-chain characteristics of palmitic acid highlights the potential of the AC/PA composite as a promising collector-frother material for monazite flotation.

## Froth Flotation Process

## The extraction of rare earth elements from tin tailing samples was carried out using the froth flotation method. This process involves the formation of froth on the surface of a solution, where hydrophobic particles attach to air bubbles and are lifted to the surface, while hydrophilic particles remain in the liquid phase. Froth flotation typically requires the use of a frother and a collector to facilitate bubble formation and the selective separation of target minerals [17]. In this study, the flotation process was conducted using a collector composed of activated carbon and palmitic acid (AC/PA), without the addition of a frother. All experiments were performed at room temperature with a flotation time of 2 hours. The flotation data using various AC/PA collector ratios are presented in Table 2.

Table 2. Flotation results at ratios of AC/PA Composite Collectors

|  |  |  |
| --- | --- | --- |
| **Ratio Collector (%)** | **Froth Mass (g)** | **Recovered material (g)** |
| 100:0 | 0,3006 | 0,0027 |
| 75:25 | 0,5006 | 0,4647 |
| 50:50 | 1,0001 | 0,0751 |
| 25:75 | 1,0001 | 0,0227 |
| 0:100 | 1,0003 | 0,0050 |

The flotation product that underwent calcination was subsequently characterized using X-Ray Fluorescence (XRF) to analyse the composition of rare earth elements (REEs) contained within the material. The XRF analysis results of the calcined flotation product are presented in Table 3.

Table 3. XRF Elemental Analysis Data of Flotation Products

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Samples** | **Ce** | **Si** | **Fe** | **Sn** | **Ti** | **Others** |
| (%) | | | | | |
| AC/PA 100:0 | 16.80 | 5.40 | 30.60 | 3.10 | 6.15 | 37.90 |
| AC/PA 75:25 | 1.80 | 26.40 | 33.70 | - | 0.72 | 37.40 |
| AC/PA 50:50 | 3.20 | 20.00 | 36.10 | - | 1.20 | 39.50 |
| AC/PA 25:75 | 6.22 | 9.94 | 49.20 | - | 1.91 | 32.72 |
| AC/PA 0:100 | 3.70 | 4.20 | 65.50 | - | 1.30 | 25,25 |

The XRF elemental analysis of the flotation products with different AC/PA collector ratios (Table 3) reveals significant variations in elemental composition, particularly in cerium (Ce), iron (Fe), and silicon (Si) contents. For the AC/PA 100:0 sample, Ce reached 16.80%, indicating that activated carbon alone had a relatively high affinity toward Ce species. Similar results have been reported where activated carbon provided strong adsorption sites due to its large surface area and functional groups, which enhanced the collection of REE bearing minerals [18]. However, when the AC/PA ratio was adjusted to 75:25, the Ce concentration decreased sharply to 1.80%, while Si increased markedly to 26.40%. The combination of activated carbon and palmitic acid modified surface interactions during flotation, resulting in enhanced adsorption of silicate gangue minerals over Ce. Interestingly, at the AC/PA 25:75 ratio, Ce concentration increased to 6.22%, indicating that higher concentration of palmitic acid could enhance selective binding to Ce-bearing minerals. Fatty acids such as palmitic and oleic acids are known to chemisorb on the surface of monazite and other REE phosphates through carboxylate functional groups, increasing their hydrophobicity and floatability [19]. In contrast, the highest Fe content was observed at AC/PA 0:100 (65.50%), suggesting that pure palmitic acid promoted the flotation of Fe-bearing minerals, thereby reducing the selectivity for Ce. The data indicate that collector composition significantly affects the flotation behaviour of monazite and related minerals. The addition of activated carbon improved the recovery of both Ce and Sn. The optimal ratio for enhancing Ce separation is 25:75 AC/PA, which facilitates a balance between adsorption selectivity and surface modification. The results correlate with prior research emphasizing the significant role of mixed collectors in improving flotation selectivity for rare earth element minerals [20]. Based on the XRF elemental analysis results, the percentage of mineral content in the froth after calcination was calculated using Equation 1 as follows:

(1)

The percentage data of mineral content in the separation of monazite by froth flotation using activated carbon/palmitic acid (AC/PA) collector is presented in Table 4.

Table 4. XRF mineral analysis data of the calcined froth

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Coesite** | **Hematite** | **Monazite-Ce** |
| (%) | (%) | (%) |
| AC/PA 100:0 | 19,6 | 87,5 | 28,18 |
| AC/PA 75:25 | 95,85 | 96,37 | 3,02 |
| AC/PA 50:50 | 72,61 | 103,23 | 5,36 |
| AC/PA 25:75 | 39,09 | 140,69 | 10,43 |
| AC/PA 0:100 | 15,25 | 187,3 | 6,21 |

The XRF mineral analysis data of the calcined froth (Table 4) reveals significant variations in the content of coesite, hematite, and monazite-Ce depending on the AC/PA collector composition. The sample with AC/PA 100:0 (pure activated carbon) yielded the highest recovery of monazite-Ce (28.18%), suggesting that activated carbon can effectively adsorb and promote the flotation of rare earth-bearing minerals. However, when AC was partially replaced with PA at the 75:25 ratio, the monazite-Ce content decreased drastically to 3.02%, despite the increase in coesite (95.85%) and hematite (96.37%). The strong affinity of palmitic acid for silicate and iron oxide minerals, such as coesite and hematite, could inhibit the selective flotation of monazite. At intermediate ratios (AC/PA 50:50 and 25:75), the recovery of monazite-Ce was relatively low, at 5.36% and 10.43%, respectively. This observation further supports the assumption that excessive palmitic acid results in non-selective adsorption. The AC/PA 0:100 sample, consists purely of PA, exhibited a monazite-Ce concentration of 6.21%. However, the hematite content was significantly higher at 187.3%, indicating the low selectivity of PA as a collector in separation.

The results highlight that activated carbon plays a dominant role in enhancing monazite flotation, likely due to its high surface area, adsorption ability, and capability to stabilize collector molecules on mineral surfaces [8,14]. The combination of AC and PA shows potential; however, the ratio requires thorough optimization to achieve adsorption selectivity between REE-bearing minerals and gangue minerals. The study identified the optimal condition for monazite recovery at an AC/PA ratio of 100:0, indicating that activated carbon exceeded the composite collector system.

# CONCLUSION

# This study indicates the potential of using activated carbon (AC) combined with palmitic acid (PA) as an effective collector in the froth flotation process for the separation of monazite-Ce from tailings. XRF analysis of the calcined froth revealed that the mineral phases predominantly consisted of coesite, hematite, and monazite-Ce. The incorporation of AC into PA significantly influenced the mineral distribution, enhancing the selectivity toward monazite recovery. The AC/PA ratio of 100:0 showed the highest performance among the examined collector ratios, resulting in a monazite recovery of 28.18%. The results indicate that the AC/PA system performs not only as a collector but also effectively functions as a frother, enhancing both particle selectivity and froth stability. These dual roles underline the novelty of the AC/PA collector system in enhancing flotation efficiency.

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