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Emulsified Collectors in Coal Slime Flotation: Linking Collector Dispersion, Flotation Performance, and Microbial Survival

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Abstract

Emulsified collectors (ECs) have attracted increasing attention in coal slime flotation because of their superior dispersion characteristics and collecting performance compared with conventional hydrocarbon collectors. However, the relationship between flotation performance and the effects of ECs on microorganisms in circulating water remains poorly understood. In this study, four ECs were prepared using cationic (dodecyltrimethylammonium bromide (DTAB)), anionic (sodium dodecyl sulfate (SDS)), nonionic (Tween-80), and solid particle-based (β-cyclodextrin (CD)) emulsifiers. The droplet size distribution, flotation performance, adsorption behavior, and microbial response were systematically evaluated. The results showed that ECs significantly improved coal slime flotation compared with conventional kerosene. Among the surfactant-based ECs, smaller oil droplet sizes resulted in higher clean coal recovery, demonstrating the critical role of collector dispersion in flotation performance. Fourier transform infrared spectroscopy provided qualitative evidence of stronger relative adsorption of ECs on coal surfaces than that of conventional kerosene. Yeast survival tests revealed that all ECs exhibited less adverse impact on microorganisms than kerosene. However, for surfactant-based ECs, microbial survival decreased as flotation performance increased. A preliminary negative correlation (R^2 = 0.9323, n = 4, where "n" denotes the number of collector formulations tested) was observed between the yeast survival rate and the number of oil droplets, suggesting that fine oil droplets remaining in the aqueous phase may have contributed to reduced microbial viability. In contrast, the β-CD-stabilized Pickering emulsion achieved both the highest flotation efficiency index (56.22) and the highest yeast survival rate (66.49%), outperforming Tween-80-EC (54.90 and 58.65%), SDS-EC (50.95 and 61.45%), DTAB-EC (50.08 and 63.31%), and conventional kerosene (40.32 and 53.35%). These findings demonstrate the importance of balancing flotation performance and environmental compatibility in the design of sustainable flotation collectors for coal processing.

Keywords: coal slime flotation; emulsified collectors; Pickering emulsion; droplet size; microbial survival; flotation reagents

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1. Introduction

Driven by the "Carbon Neutrality" and "Dual Control of Energy Consumption" policies, the development of environmentally friendly flotation reagents is key to achieving a green transformation in mineral processing. Currently, research on bio-based/environmentally friendly flotation reagents has become a cutting-edge hotspot [1]. Scholars have developed various bio-friendly reagents, including bio-based collectors derived from waste coffee grounds and sophorolipids [2,3], green frothers derived from vitamin E [3], cellulose, lignin, and their derivatives used as depressants and flocculants [4–6], local microorganisms utilized to modulate mineral surface properties [7], and bio-based emulsifiers prepared from materials such as cardanol polyoxyethylene ether (CPE) [8]. Additionally, studies on local microbial communities in mineral processing systems (e.g., coal preparation plants) have revealed the strong impact of microorganisms on flotation efficiency, offering new perspectives for bio-modulation [9,10].

Non-polar hydrocarbon oils (such as kerosene and diesel) are commonly used collectors in the flotation of coal, graphite, and similar minerals, but they suffer from poor dispersibility in water [11,12]. Emulsification of collectors is a core technology [13] for improving the dispersibility and collecting efficiency of non-polar hydrocarbon oils [14–16]. Conventional processes widely employ synthetic surfactants—including non-ionic, cationic, and anionic types—as emulsifiers [17–20]. In addition to the influence of emulsifier type (single emulsifier), researchers have also extensively studied the synergistic mechanisms of mixed emulsifiers, as well as the effects of different emulsion types, such as oil-in-water (O/W) and water-in-oil (W/O), on flotation performance [21–23]. However, these chemically synthesized emulsifiers often cause excessive foaming, which interferes with downstream processing of flotation products. Moreover, the environmental and biosafety risks associated with conventional emulsifiers are becoming increasingly prominent [17].

In response to the shortcomings, research has shifted toward developing more environmentally friendly alternative systems. On the one hand, the use of bio-based surfactants, such as alkyl polyglucosides (APG), to construct biodegradable composite emulsifiers can markedly enhance the flotation efficiency of low-rank coal [14,15]. Similarly, micro-emulsified collectors constructed using CPE have also demonstrated high-efficacy performance [8]. On the other hand, solid-particle-stabilized Pickering emulsion technology has gained attention due to its ability to avoid the use of traditional surfactants [24,25]. In the present study, the term "Pickering emulsion" refers specifically to the pre-prepared collector emulsion (β-Cyclodextrin (CD)/kerosene) used as a feed reagent, which is formulated and characterized prior to its introduction into the flotation cell. The stabilization mechanism of this emulsion by solid β-CD particles at the oil–water interface has been well documented [24]. Our focus is on how the droplet characteristics of this pre-formed emulsion influence flotation performance and the subsequent biological availability of residual oil in the aqueous phase, rather than on the stabilization of the flotation froth itself. Regarding the emulsification of kerosene, the β-CD/kerosene Pickering emulsion prepared by Gao et al. [24] effectively improved the beneficiation efficiency of fine graphite through flotation. Similarly [12], systematically studied the mechanism by which β-CD/kerosene Pickering emulsion improves the flotation of cryptocrystalline graphite [26], confirming its role in enhancing hydrophobicity by reducing oil droplet size and promoting spreading. β-CD stabilizes the oil-water interface by forming amphiphilic inclusion complexes with kerosene alkanes, which greatly facilitates the spreading and adsorption of oil droplets on the mineral surface [27].

However, most existing studies have focused on the preparation processes and flotation efficacy of these reagents, leaving a notable gap in the assessment of their biosafety impacts after they enter aquatic environments as residual substances. The circulating water

systems in coal preparation plants inherently host complex microbial communities [7,10,28]. The addition of residual reagents may further alter their structure and function, potentially leading to unforeseen ecological risks. Because flotation plants increasingly operate under closed-water-circuit conditions, residual collector accumulation may become an important factor influencing microbial communities involved in organic matter degradation and water quality maintenance. Surfactants in water bodies pose potential hazards such as altering soil properties, affecting the survival of microorganisms and algae in aquatic systems, and inhibiting plant growth [29–31], while their metabolites exhibit even more direct toxicity to aquatic organisms. Studies have shown that surfactants containing nonylphenol functional groups can accumulate in organisms and cause organ damage [32,33]. Therefore, systematic evaluation of environmental and biological toxicity is a critical step toward the environmentally friendly application of ECs, yet current research in this area remains relatively scarce.

In selecting a biological endpoint for this preliminary assessment, we chose yeast survival rate as a rapid and reproducible indicator of acute toxicity. Yeast (Saccharomyces cerevisiae) is a well-established eukaryotic model organism widely used for initial toxicity screening due to its genetic tractability, rapid growth, and well-characterized stress responses [34]. While other environmental indicators such as odor or phytotoxicity are also practically relevant, the primary concern in closed water-circulation systems of coal preparation plants is the potential accumulation of residual reagents that may adversely affect indigenous microbial communities responsible for water quality maintenance [7,10]. Therefore, the yeast survival rate serves as a useful first-tier screening metric to establish a relative comparison of biological compatibility among different collector formulations, providing a foundation for more comprehensive ecotoxicological assessments in future studies.

To address this gap, this study integrates flotation performance evaluation with environmental biosafety assessment, aiming to establish their correlation and provide a new perspective for the design of green reagents. Four types of emulsifiers (cationic (dodecyltrimethylammonium bromide (DTAB)), anionic (sodium dodecyl sulfate (SDS)), nonionic (Tween-80), and solid particle-based (β-CD) were selected to prepare collectors. After evaluating their flotation performance, the filtrate obtained after flotation was used to simulate circulating water. The acute toxicity was assessed through the yeast survival rate experiments, and the adsorption behavior of the emulsifiers on the coal surface was analyzed using Fourier transform infrared spectroscopy (FTIR). It should be emphasized that the biological assessment employed in this study is proposed as a preliminary, relative screening method for comparing the potential biological effects of different collector formulations, rather than a standardized protocol compliant with regulatory ecotoxicological frameworks. The use of yeast as a model organism provides a rapid and reproducible basis for establishing initial correlations between collector properties and biological response, which can inform the design of more environmentally compatible flotation reagents and guide subsequent, more comprehensive ecotoxicological evaluations. This study aims to preliminarily establish the correlation between emulsifier type, adsorption amount, flotation performance, and microbial toxicity, thereby providing a scientific basis and methodological reference for achieving a balance between the high efficiency and environmental friendliness of flotation reagents.

2. Experimental Materials and Methodology

2.1. Experimental Materials

The coal slime used in the experiments was anthracite from Laos, with an ash content of 11.80%. The oil phase for the flotation collector and emulsion preparation was kerosene. The emulsifiers were DTAB, SDS, Tween-80, and β-CD. The flotation frother was 2-octanol.

All these reagents were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). The water used in the tests was deionized water with a resistivity of 18.2 MΩ·cm, prepared using a Heal Force EASY 15 water purification system from Shanghai Kang Lei Analytical Instrument Co., Ltd. (Shanghai, China).

2.2. Experimental Methodology

2.2.1. Preparation and Droplet Size Characterization of Emulsions

(1) Preparation of emulsions

A 50 mL conical flask was used as the container. According to an oil-to-water volume ratio of 1:4 and an emulsifier concentration of 1 wt%, the emulsifier, deionized water, and kerosene were sequentially added to achieve a total EC volume of 50 mL. The mixture was homogenized using a high-shear disperser (T18 D S25, IKA Guangzhou Instrument Equipment Co., Ltd. Guangzhou, China) at 10,000 rpm for 2 mins to ensure uniform dispersion of the three components in the emulsion system. Subsequently, the emulsion was further processed with an ultrasonic cell disruptor (VCX800, Sonics & Materials, Inc., Newtown, CT, USA) at an amplitude of 60% for 20 s to reduce the size of the oil droplets. Four types of ECs were prepared: DTAB-EC, SDS-EC, Tween-80-EC, and β-CD-EC. Using the same conditions and procedure but replacing the oil-to-water mixture with pure water, four corresponding collector solutions (without kerosene) were also prepared.

(2) Characterization of emulsion droplet size

The droplet size of the EC was characterized using both optical microscopy for droplet morphology observation and laser particle size analysis for droplet size distribution. The specific methods are as follows. Optical Microscopy Observation: A small amount of the prepared emulsion was placed on a glass slide and covered with a coverslip to prevent droplet movement during observation. The slide was then positioned on the stage of a transmitted/reflected polarizing microscope (CX40P, Ningbo Sunny Instruments Co., Ltd., Ningbo, China). Droplet morphology was observed and recorded via a computer connected to the microscope eyepiece.

Laser particle size analysis: One milliliter of the emulsion was dispersed in 500 mL of water. After performing a background measurement using a laser particle size distribution analyzer (GSL-1000, Liaoning Instrument Research Institute Co., Ltd., Shenyang, China), an appropriate amount of the sample was drawn via a plastic pipette and added to the measurement cell. The particle size distribution analysis of emulsion was conducted under the condition that the sample concentration yielded a laser obscuration value between 25% and 35%.

2.2.2. Coal Slime Flotation

Flotation tests were conducted using a 1.5 L single-tank flotation machine (RK/FD II, Wuhan Rock Grinding Equipment Manufacturing Co., Ltd., Wuhan, China). The operating parameters were set as follows: agitation speed of 1900 rpm, flotation air flow rate of 0.5 m^3/h, feed pulp density of 60 g/L, and froth scraping time of 3 mins. Kerosene and the ECs served as flotation collectors, while 2-octanol (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) was used as the frother. The dosage of kerosene was set at 300 g/t and 500 g/t, with the dosage of 2-octanol being half that of the kerosene. It should be noted that, to ensure an equivalent kerosene concentration in the pulp, the addition amount of the ECs was calculated based on a target kerosene concentration in the pulp of 300 g/t or 500 g/t, respectively.

2.2.3. Investigation of the Yeast Survival Rate

(1) Yeast culture

Yeast was selected because it is a widely used eukaryotic model organism for rapid toxicity screening and provides a reproducible indicator of biological response to residual flotation reagents [34]. Preparation of Culture Filtrate: 18 g of coal sample was weighed and placed into a 500 mL beaker. Deionized water was added to a total volume of 300 mL. The mixture was stirred using a magnetic stirrer at 1600 rpm for 4 mins. A collector (at a dosage equivalent to 500 g/t of kerosene) was added, and stirring continued until the total time reached 6 mins. A single dosage level (500 g/t) was selected for this initial screening study to provide a standardized basis for comparing the relative biological effects of different collector types. The pulp was then filtered through qualitative filter paper, and the filtrate was collected. This filtrate was used as a model aqueous phase to simulate the water that would be present in a closed water-circulation system of a coal preparation plant, where residual flotation reagents may accumulate over time and interact with microbial communities.

Yeast Cultivation: Petri dishes were wrapped in kraft paper and, together with clean conical flasks, placed into an autoclave for sterilization at 121 °C and 100 kPa for 20 mins. After sterilization, the vessels were removed and allowed to cool to room temperature on a clean bench. Then, 200 mL of yeast culture medium (Fujian Xijing Biotechnology Co., Ltd., Fuzhou, China) was added to a sterilized conical flask. An appropriate amount of yeast inoculum was added and thoroughly mixed to obtain a yeast suspension. A standardized volume of yeast inoculum (1.0 mL, optical density (OD)600 ≈ 1.0) was added and fully mixed to prepare a homogeneous yeast suspension. Using a sterile pipette, 15 mL of the yeast suspension was aliquoted into each sterilized Petri dish, and 5 mL of the treatment liquid was added to each dish. The Petri dishes were incubated in a constant-temperature incubator at 28 °C for 48 h to obtain reproducible yeast cultures.

(2) Detection of yeast survival rate

Preparation of Methylene Blue (Tianjin Zhiyuan Chemical Reagent Co., Ltd., Tianjin, China) Staining Solution: 0.6 g of methylene blue was dissolved in 30 mL of 95% ethanol. Simultaneously, 0.01 g of potassium hydroxide (KOH) was dissolved in 100 mL of distilled water. The two solutions were then mixed uniformly to obtain the working staining solution. The principle of methylene blue staining for determining yeast survival is based on the difference in metabolic activity: living cells can reduce the dye to a colorless form, while dead cells cannot. Therefore, dead cells are identified by their retained blue color. Survival rate detection: After incubation, samples were taken from each Petri dish to prepare slides. A drop of methylene blue staining solution was added for staining. An optical microscope was used to photograph the staining status of the yeast cells. For each sample, at least five random fields of view were captured to ensure statistical representativeness. The image processing was performed using Python (version 3.10)-based image analysis. A mask segmentation and contour extraction algorithm was employed to automatically identify stained dead yeast and unstained viable yeast cells. The yeast survival rate, presented as a percentage value, was calculated via Equation (1):

$$\text{Survival rate (\%)} = (\text{Number of viable cells}/\text{Total number of cells counted}) \times 100 \quad (1)$$

The numerator represents the number of live yeast cells, and the denominator is the total cell number counted in each microscopic field. At least 200 cells were counted per sample to ensure reliable quantification.

2.2.4. Fourier Transform Infrared Spectroscopy

The coal sample preparation procedures for FTIR analysis followed the same conditioning protocol as described in the flotation procedure (Section 2.2.2), except that the flotation air supply and froth scraping steps were omitted. Specifically, six grams of coal sample with a particle size of –125 μm was conditioned in a 1.5 L single-tank flotation machine with the collector at a standard dosage equivalent to 300 g/t of kerosene, followed by 2 mins of dispersion. This procedure was applied consistently for all collector conditions (kerosene and the four ECs). The treated coal sample was then filtered and dried at 40 °C to obtain the FTIR test specimen. A small amount of the coal sample was mixed and ground with 100 mg of potassium bromide (KBr, Tianjin Juhengda Chemical Co., Ltd., Tianjin, China). The mixture was pressed into a pellet using a hydraulic press under 20 MPa pressure for 5 mins. The prepared pellet was analyzed using a Fourier transform infrared spectrometer (Nicolet Summit, Thermo Fisher Scientific, Waltham, MA, USA) with a resolution of 4 cm^{-1} over a spectral range of 400 to 4000 cm^{-1}.

3. Results and Discussion

3.1. Analysis of Droplet Size of Emulsified Collectors

Droplet size is a key parameter of EC. Microscopic images of the four prepared emulsified collectors immediately after preparation and after prolonged storage are shown in Figure 1. The droplet size distributions of the four ECs immediately after preparation are presented in Figure 2.

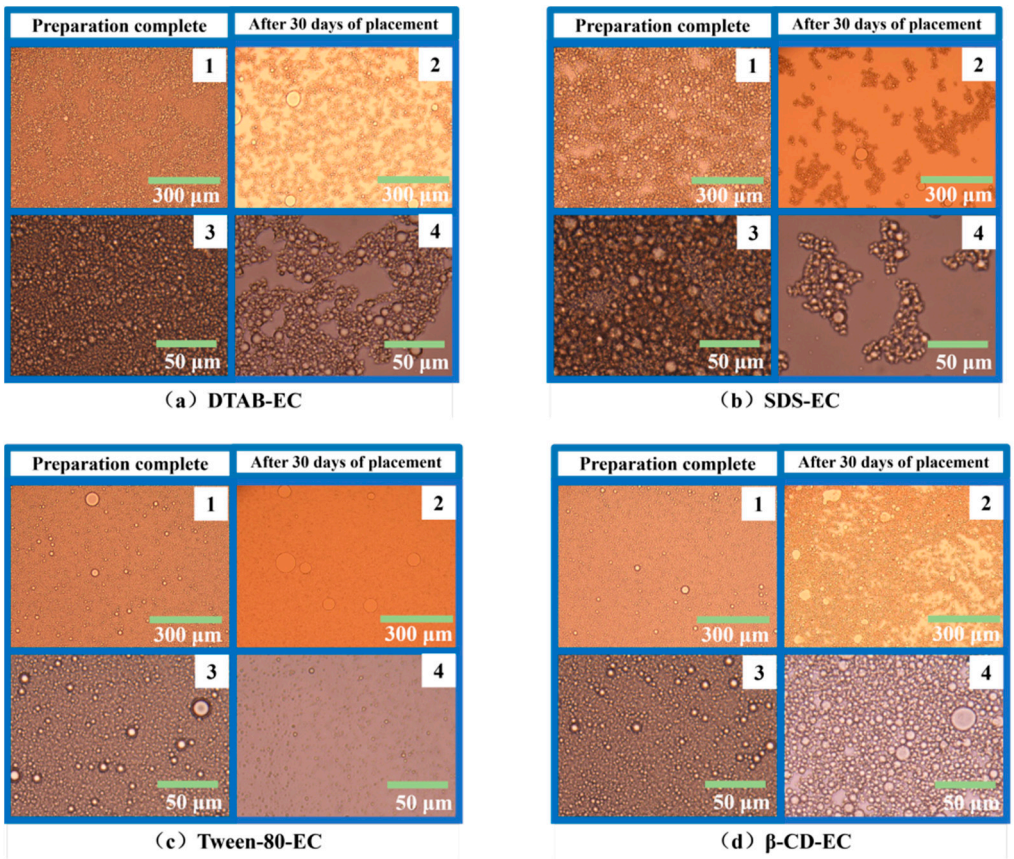


Figure 1. Microscopic images of the various emulsified collectors before and after 40 days of storage. (**a**) DTAB-EC; (**b**) SDS-EC; (**c**) Tween-80-EC; (**d**) β-CD-EC.

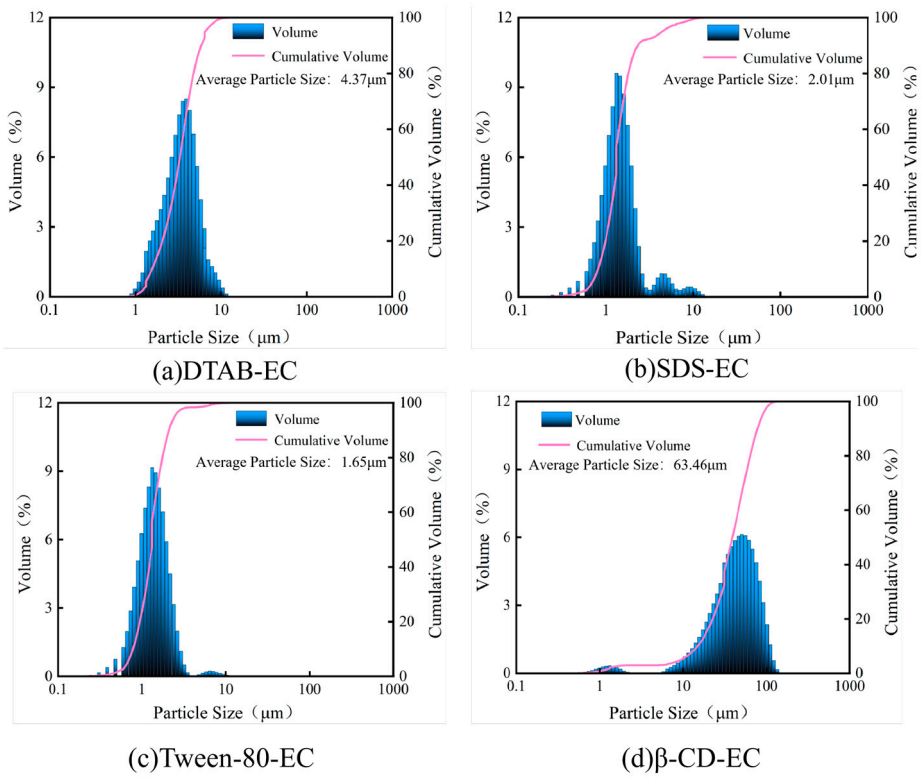


Figure 2. Droplet size distribution of the various emulsified collectors.

As can be seen from Figures 1 and 2, among the four freshly prepared ECs, the Tween-80-EC exhibited the smallest droplet size, followed by the SDS-EC and DTAB-EC. The β-CD-EC showed the largest droplet size. Chemical emulsifiers can produce fine and uniform emulsions, which are more readily dispersed in water, resulting in measured average droplet sizes ranging from 1 to 10 μm. In contrast, the droplet size measured for the β-CD-based emulsion ranged from 10 to 100 μm, which is inconsistent with the droplet sizes observed in Figure 1d. This discrepancy may be attributed to the greater difficulty in dispersing the β-CD-based emulsion in water, leading to the formation of droplet clusters during the measurement process. This phenomenon of droplet clustering is related to the flocculation observed in Pickering emulsions [35,36].

After 40 days of storage, the number of oil droplets in the SDS-based EC decreased obviously, while the distribution of droplets in the Tween-80-based and DTAB-based EC became notably sparser. This indicates that emulsions prepared with chemical emulsifiers possess relatively poor stability. In contrast, the droplets in the β-CD-based EC remained densely populated, demonstrating good emulsion stability, which is associated with the stable particle membrane formed in Pickering emulsions [37,38]. The droplet size and stability characteristics of the four ECs described above serve as the basis for understanding their subsequent flotation performance (Section 3.2) and their potential biological effects (Section 3.3).

3.2. Analysis of Coal Slime Flotation

The four types of ECs exhibited distinct differences in droplet size and ease of dispersion. These differences were expected to influence their collecting performance during the flotation process. Therefore, flotation tests were conducted to compare the performance of the four ECs with that of pure kerosene in coal slime flotation. The test results are presented in Figure 3a.

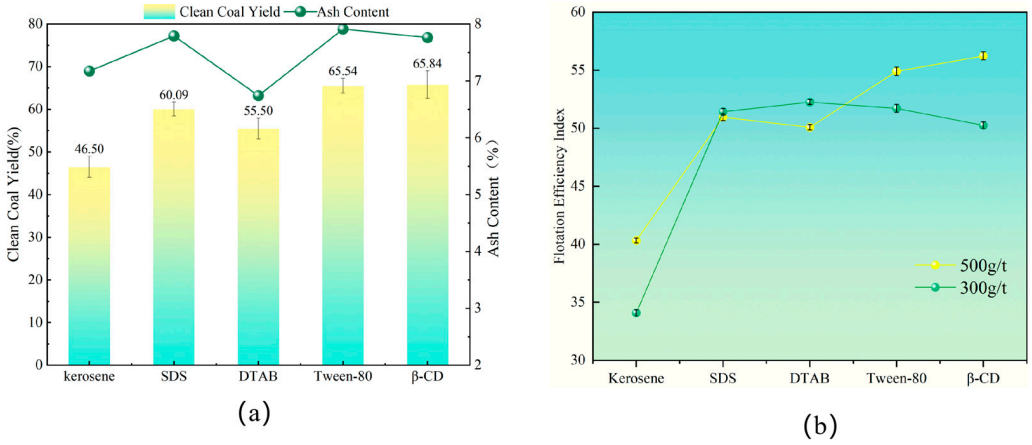


Figure 3. (**a**) Flotation performance with various emulsified collectors, and (**b**) flotation efficiency index of different emulsifiers at varying dosages.

As shown in Figure 3a, among the four ECs, the Tween-80-based EC yielded the highest clean coal recovery (63.02%), followed by β-CD (61.63%), SDS (59.61%), with DTAB yielding the lowest recovery of only 56.61%. Due to the discrepancy between the droplet size distribution data and the microscopic images for the β-CD-based EC, the trend in clean coal recovery among the three surfactant-based ECs aligned with the droplet size distribution pattern: as the oil droplet size of the collector decreased, the flotation performance of the coal slime improved [39]. The improvement in flotation performance can be attributed not only to the reduction in droplet size but also to the corresponding increase in specific interfacial area. Finer droplets provide a larger total oil–water interfacial area at a given collector dosage, thereby increasing the probability of droplet–particle contact and promoting more uniform coverage of hydrophobic sites on the coal surface [40]. Consequently, collector utilization efficiency is enhanced, leading to improved flotation recovery. All four ECs achieved a significantly higher clean coal recovery compared to pure kerosene (48.86%) [41], demonstrating their effectiveness in enhancing coal slime flotation. This interpretation is further supported by the FTIR results, which demonstrate stronger adsorption of emulsified collectors on coal surfaces than conventional kerosene. Enhanced adsorption is consistent with more efficient collector utilization during flotation [42].

Among the four ECs, compared to kerosene, the SDS-, Tween-80-, and β-CD-based ECs increased the ash content of the clean concentrate from 7.03% to 7.39%, 7.70%, and 7.70%, respectively, despite their higher recoveries. In contrast, the DTAB-based EC not only improved the clean coal recovery but also reduced the ash content to 6.67%, indicating its higher selectivity.

In terms of the flotation efficiency index, under the 500 g/t condition, β-CD achieved the highest index (56.22), representing the best overall performance, followed by Tween-80 (54.9). The indices for SDS and DTAB were relatively close at 50.95 and 50.08, respectively, while kerosene performed the worst with an index of only 40.32. Under the 300 g/t condition, as shown in Figure 3b, only DTAB and SDS maintained stable indices with slight increases to 52.25 and 51.42, respectively. In contrast, the indices for β-CD and Tween-80 decreased to 50.25 and 51.71, respectively, showing a notable decline. The index for kerosene further dropped to 34.08, representing the largest decrease.

In summary, β-CD performed optimally at the higher dosage, but its performance was more sensitive to dosage, declining markedly at the lower dosage. DTAB and SDS exhibited more stable performance with some improvement at the lower dosage, demonstrating better adaptability. Kerosene performed the poorest under both dosage conditions.

However, studies have shown that cationic surfactants enhance oil droplet adsorption on the coal surface through electrostatic attraction between their positively charged polar heads and the negatively charged coal surface. Anionic surfactants reduce adsorption due to electrostatic repulsion between their negatively charged heads and the coal surface. Non-ionic surfactants, being uncharged, adsorb via hydrogen bonding with the coal surface. The discrepancy between these established mechanisms and the present flotation results suggests that, compared to the electrostatic interactions between the emulsifier and the coal–oil interface, the oil droplet size exerts a stronger influence on the observed outcomes.

3.3. Analysis of Yeast Survival Rate

The four ECs demonstrated good flotation performance in coal slime flotation. However, their potential hazard to microorganisms in water bodies requires further investigation. The experimental results for yeast survival rates cultured in filtrates under different collector conditions are shown in Figure 4a. According to the data in Figure 4a, the order of yeast survival rates in the different filtrates was no collector > β-CD > DTAB > SDS > Tween-80 > kerosene. The survival rate was highest (73.17%) under the no-collector condition and lowest (53.35%) under the kerosene condition, indicating that kerosene in the filtrate accelerated yeast mortality. In the absence of kerosene, as shown in Figure 4b, the order of yeast survival rates across the different filtrates was largely consistent with that observed in the presence of kerosene.

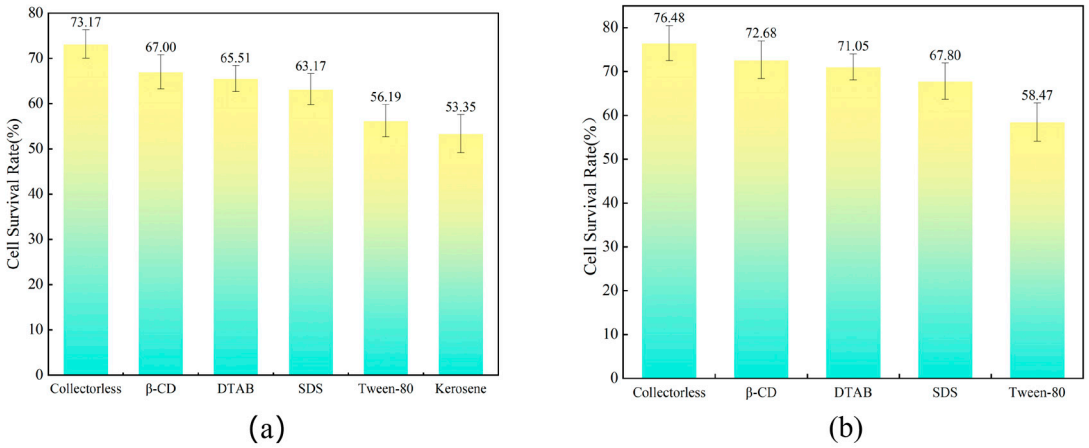


Figure 4. Yeast survival rate with different (**a**) collectors and (**b**) collectors in the absence of kerosene.

The survival rates under EC conditions were higher than those under the kerosene-only condition, suggesting a lower effective concentration of free kerosene in the filtrates from the EC treatments. This inference is supported by the FTIR spectra obtained under different collector conditions, as shown in Figure 5. When ECs were used, the peak intensities for -CH_3 and -CH_2- were much higher than those in the kerosene-only treatment group. Since these are characteristic functional groups of kerosene, the increase in their peak intensities provides a qualitative indication of greater relative adsorption of kerosene-derived components onto the coal sample surface under EC treatments compared with kerosene alone. This supports the interpretation that enhanced collector dispersion through emulsification facilitates more efficient utilization of the hydrocarbon collector. However, it is acknowledged that FTIR analysis is primarily qualitative; future studies employing quantitative adsorption measurements (e.g., total organic carbon analysis or Ultraviolet–Visible (UV–Vis) spectrometry) would be valuable to verify these comparative trends. The enhanced stability of the β-CD-stabilized Pickering emulsion, as observed in Figure 1d after 40 days of storage, is attributed to the formation of a robust interfacial particle layer [37,38]. This stable structure may play a dual role in the flotation system: (i) it promotes more

efficient adsorption of kerosene onto the coal surface during flotation, contributing to the high flotation efficiency index (56.22); and (ii) it limits the release of free kerosene into the aqueous phase, as evidenced by the higher yeast survival rate (66.49%) observed for the β-CD-EC treatment. Thus, the long-term stability of the Pickering emulsion appears to be a favorable characteristic that supports both collector utilization and biological compatibility. Unlike surfactant-stabilized emulsions, the Pickering emulsion stabilized by β-CD forms a relatively rigid interfacial layer that reduces droplet coalescence and may limit the release and bioavailability of free kerosene components. This characteristic likely contributes to the superior balance between flotation performance and microbial compatibility observed in this study. Furthermore, the enhanced stability of the Pickering emulsion may facilitate effective collector utilization during flotation while minimizing the concentration of biologically accessible residual hydrocarbons in the aqueous phase [11,43].

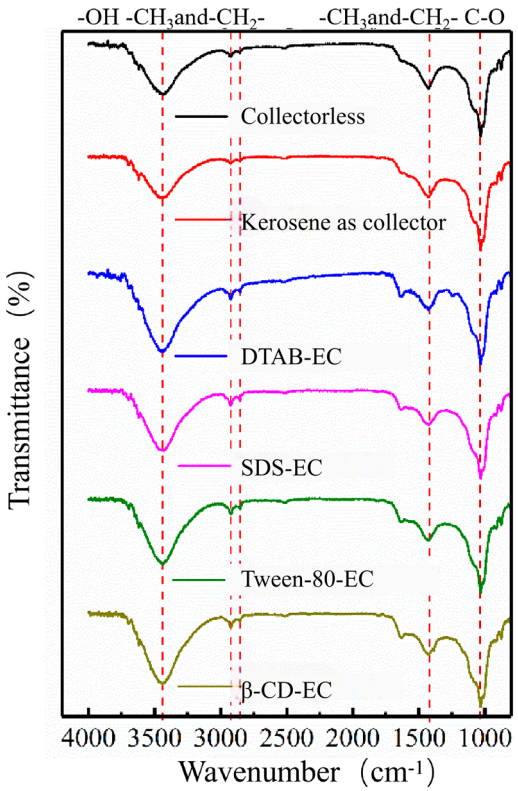


Figure 5. FTIR spectra obtained from experiments with different collectors.

It is also important to acknowledge the limitations of the current biological assessment. The study employed a single collector dosage (equivalent to 500 g/t of kerosene) for the yeast survival assays, and a concentration-dependent toxicity assessment was not performed. The residual collector concentrations in the filtrates were not directly quantified. Therefore, while these results provide a useful relative comparison of biological compatibility among different collector formulations, they do not establish dose–response relationships or definitively confirm ecotoxicological relevance under realistic industrial conditions where collector concentrations may vary over time due to accumulation or degradation. Future work should include quantitative residual analysis (e.g., gas chromatography or total organic carbon analysis) and systematic dose–response studies to evaluate the environmental risks more comprehensively.

It should be noted that yeast was employed in this study as a rapid and reproducible model microorganism to provide a preliminary assessment of the biological effects of residual flotation reagents. While the results offer useful insights into the relative toxicity of different emulsified collectors, they do not fully represent the complexity of microbial

communities present in industrial coal preparation water systems. Therefore, further studies involving indigenous microbial communities, microbial diversity analysis, and standardized ecotoxicological assessments are necessary to comprehensively evaluate the environmental risks associated with these collectors [44].

Among the three surfactant-based ECs, no apparent differences were observed in their adsorption amounts on the coal slime surface. However, the yeast survival rate exhibited an inverse relationship with the clean coal recovery and increased with larger oil droplet sizes. In addition to droplet size, the total number of oil droplets generated by emulsification may also influence the environmental fate of collectors, because finer emulsions contain substantially larger numbers of dispersed droplets at an equivalent oil dosage. Therefore, the relationship between the number of oil droplets and yeast survival rate was further investigated. First, the average particle size of fine oil droplets in four ECs was measured (Figure 2). To facilitate quantitative analysis, the droplet shape was simplified as perfect spheres in subsequent calculations, allowing for the estimation of individual droplet volume and mass. Based on this, the total number of fine oil droplets in the four collectors was further calculated. Subsequently, as shown in Figure 6, the total droplet count was subjected to linear regression analysis against the corresponding yeast survival rate. The results revealed a preliminary negative correlation (R^2 = 0.9323, n = 4) between yeast survival rate and the number of oil droplets, where n represents the number of collector formulations tested (i.e., DTAB-EC, SDS-EC, Tween-80-EC, and β-CD-EC), rather than a variable parameter in the regression equation. Linear regression based on only four experimental groups lacks sufficient statistical power to establish universal quantitative relationships, and the high R^2 value reflects only the monotonic trend observed under the limited test conditions, rather than a general mathematical relationship applicable to all emulsified collectors. This suggests that fine oil droplets remaining in the aqueous phase may have contributed to the reduced microbial viability.

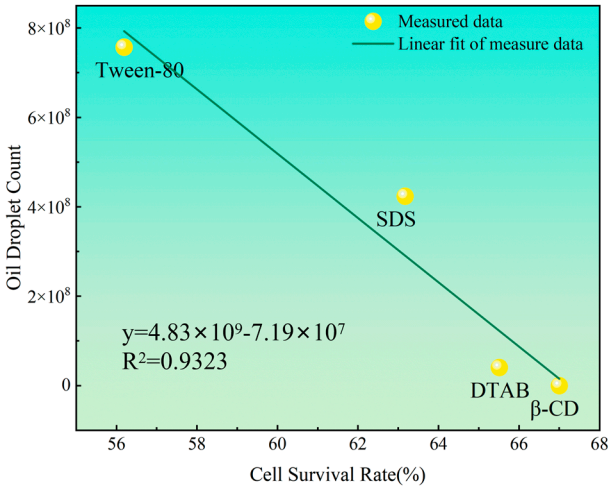


Figure 6. Correlations between the number of oil droplets of each collector and the survival rate. Note: Linear fitting based on only four sample points, this trend is preliminary and requires validation using a larger dataset including additional collector formulations and replicate experiments.

To quantify the correlation between total oil droplet quantity and yeast viability, each emulsion droplet was simplified as a perfect sphere to calculate the total droplet number, followed by linear regression against the measured yeast survival data. This limited sample size means the observed correlation is preliminary and requires further validation with additional collector types and repeated experiments. The fitted linear function is defined as Equation (2):

$$y = 4.83 \times 10^9 - 7.19 \times 10^7 \cdot x \quad (2)$$

where y = total count of oil droplets, and x = yeast survival rate (%). The results revealed a strong negative correlation between the number of oil droplets and yeast survival rate (R^2 = 0.9323), indicating that the yeast survival rate decreased as the number of dispersed oil droplets increased.

These findings suggest that the number of oil droplets may be an important factor influencing cell survival and may partially explain the observed trade-off between flotation efficiency and environmental compatibility. According to Figure 2, a certain proportion of fine oil droplets were present in the SDS- and Tween-80-based ECs. Studies have shown that as oil droplet size decreases, the collision probability between oil droplets and mineral particles is reduced [45,46]. Consequently, fine oil droplets may fail to collide and adhere effectively to coal particles during the relatively short conditioning period, leading to their retention in the pulp and subsequent entry into the filtrate. This explains why, despite the improvement in clean coal recovery with smaller droplet sizes, the increased number of fine oil droplets in the filtrate results in a lower yeast survival rate.

4. Conclusions

This study systematically evaluated the performance of four emulsified collectors (ECs) in coal slime flotation and investigated their potential biological effects using yeast as a model microorganism. The main conclusions are as follows:

(1) All emulsified collectors significantly improved coal slime flotation performance compared with conventional kerosene. Among the surfactant-based ECs, flotation performance generally increased with decreasing oil droplet size, highlighting the importance of collector dispersion and oil–water interfacial characteristics in enhancing coal recovery.

(2) FTIR analysis provided qualitative evidence of stronger relative adsorption of emulsified collectors on coal surfaces compared with direct kerosene addition. Enhanced collector dispersion and adsorption are considered important factors contributing to the improved flotation performance observed for the EC systems.

(3) The biological assessment revealed a potential trade-off between flotation efficiency and microbial compatibility for surfactant-based ECs. Collectors producing finer oil droplets generally achieved higher flotation recoveries but were associated with lower yeast survival rates. A preliminary negative correlation (R^2 = 0.9323, based on four data points) was observed between the number of oil droplets and cell survival. Limited sample quantity restricts the universality of this fitting result, suggesting a potential relationship that requires further validation with a larger experimental dataset and more emulsifier types.

(4) Among the tested collectors, the β-CD-stabilized Pickering emulsion demonstrated the most favourable balance between flotation performance and biological compatibility. Specifically, it achieved the highest flotation efficiency index (56.22) and the highest yeast survival rate (66.49%) among all emulsified collector treatments, compared with Tween-80-EC (54.90 and 58.65%), SDS-EC (50.95 and 61.45%), and DTAB-EC (50.08 and 63.31%). The stable interfacial structure formed by β-CD likely enhanced collector utilization while reducing the biological availability of residual kerosene, resulting in both high flotation efficiency and the highest yeast survival rate.

(5) This study provides preliminary evidence of a relationship between emulsified collector dispersion characteristics and microbial survival, highlighting the number of oil droplets as a potential indicator for evaluating the environmental compatibility of flotation collectors.

Overall, emulsification represents an effective strategy for improving coal slime flotation performance. However, the environmental implications of residual collectors should be considered alongside flotation efficiency when designing sustainable flotation reagents. The present study provides preliminary evidence of the relationship between collector dispersion, flotation behaviour, and biological effects. Further investigations involving indigenous microbial communities, microbial diversity analysis, and standardized ecotoxicological assessments are required to comprehensively evaluate the environmental impacts of emulsified flotation collectors under industrial operating conditions.

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References

1. Oulkhir, A.; Lyamlouli, K.; Bounaga, A.; Danouche, M.; Etahiri, A.; Benhida, R. Green Innovations in Mineral Flotation for Enhancing Sustainability through Enzymatically Synthesized Sugar and Fatty Alcohol Biosurfactants—A Comprehensive Review. *Miner. Eng.* **2025**, *230*, 109415. [CrossRef]
2. Zhai, J.; Chen, P.; Wang, H. Green Flotation of Ilmenite with Bio-Based Sophorolipid: New Insights into the Effects of Temperature on Interfacial Adsorption. *Miner. Eng.* **2025**, *234*, 109742. [CrossRef]
3. Aarab, I.; Amari, K.E.; He, D.; Fu, Y.; Boujounoui, K.; Etahiri, A. Eco-Friendly Apatite Flotation: Unlocking the Potential of Spent Coffee Grounds as a Bio-Based Collector. *Miner. Eng.* **2025**, *233*, 109652. [CrossRef]
4. Bednarek, P.S.; Kowalczuk, P.B. Cellulose and Its Derivatives as a Sustainable Reagent in Mineral Flotation: Mechanisms and Applications. *Sep. Purif. Technol.* **2025**, *378*, 134690. [CrossRef]
5. Yang, X.; Bao, J.; Wu, D.; Cao, Y.; Hao, H.; Zhang, Y. Synergistic Effect of a Bio-Based Mixed Depressant on Flotation Separation of Scheelite from Calcium Gangue. *Colloids Surf. A Physicochem. Eng. Asp.* **2025**, *713*, 136555. [CrossRef]
6. Ludovici, F.; Öktem, G.; Hartmann, R.; Rudolph, M.; Liimatainen, H. Biodepressant Based on Thiol Silylated Cellulose Nanocrystals: Insights into Behavior in a Binary Mineral System of Chalcopyrite and Pyrite. *Miner. Eng.* **2025**, *228*, 109372. [CrossRef]
7. Lu, C.; Tan, J.; Wang, Z.; Luo, M.; Li, J.; Song, S.; Amzil, H.; Benzaazoua, M.; Xia, L. Indigenous Microorganisms Enhance Kaolinite Hydrophobicity with Implications for Coal Slime Flotation. *Colloids Surf. A Physicochem. Eng. Asp.* **2026**, *730*, 138966. [CrossRef]
8. He, M.; Wang, J.; Yang, S.; Wang, F.; Yan, X.; Sun, L.; You, X.; Li, L.; Wang, Q. Preparation of Bio-Based Microemulsion Collector and Its Flotation Performance for Coal Slime. *Sep. Purif. Technol.* **2025**, *354*, 128855. [CrossRef]
9. Wang, X.; Meng, D.; Li, J.; Lu, Z.; Zhang, Z.; Zhang, C.; Song, S.; Peng, Y.; Xia, L. Composition and Dynamics of Bacterial Communities during Flotation in a Coal Preparation Plant. *J. Clean. Prod.* **2023**, *385*, 135691. [CrossRef]

10. Kinnunen, P.; Miettinen, H.; Bomberg, M. Review of Potential Microbial Effects on Flotation. *Minerals* **2020**, *10*, 533. [CrossRef]
11. Zhou, C.; Huang, J.; Yan, Y. Chain Length Dependent Alkane/β-Cyclodextrin Nonamphiphilic Supramolecular Building Blocks. *Soft Matter* **2016**, *12*, 1579–1585. [CrossRef] [PubMed]
12. Bu, X.; Gao, J.; Ni, C.; Chen, Y. Mechanism of β-Cyclodextrin/Kerosene Pickering Lotion for Improving the Flotation Effect of Aphanitic Graphite. *J. China Coal Soc.* **2023**, *48*, 288–295. [CrossRef]
13. Li, Z.; Zhou, B.; Kong, Y.; Ma, Z.; Yang, X.; Wang, L.; Xia, Y.; Zhao, X.; Xing, Y.; Gui, X. Advancements and Prospects for Emulsion Collectors in Low-Rank/Oxidized Coal Flotation Separation. *Adv. Colloid Interface Sci.* **2026**, *348*, 103735. [CrossRef] [PubMed]
14. Li, E.; Xiao, X.; Wang, X.; Pan, Z.; Qin, Y.; Gao, G.; Du, Z.; Cheng, F. Interfacial Interaction of Emulsion Collector in Enhancing Low-Rank Coal Flotation. *Colloids Surf. A Physicochem. Eng. Asp.* **2024**, *692*, 133965. [CrossRef]
15. Cheng, G.; Zhang, M.; Lu, Y.; Zhang, H.; Lau, E.V. New Insights for Improving Low-Rank Coal Flotation Performance via Emulsified Waste Fried Oil Collector. *Fuel* **2024**, *357*, 129925. [CrossRef]
16. Zhou, S.; Wang, S.; Gao, J.; Ni, C.; Xie, G.; Deyab, M.A.; Zaccone, A.; Bu, X. Oily Collector Emulsions in Mineral Flotation: Recent Advances. *Miner. Eng.* **2026**, *240*, 110152. [CrossRef]
17. Cao, L.; Chen, X.; Peng, Y. The Formation and Stabilization of Oily Collector Emulsions—A Critical Review. *Miner. Process. Extr. Metall. Rev.* **2021**, *42*, 388–405. [CrossRef]
18. Fan, P.; Dai, W.; Fan, X.; Dong, L.; Wang, J.; Bao, W.; Chang, L.; Fan, M. Influence Mechanism of Emulsion Collector on the Flotation Effect of Coal Gasification Fine Slag. *Fuel Process. Technol.* **2024**, *263*, 108120. [CrossRef]
19. Ma, S.; Qiao, L.; Liu, X.; Zhang, S.; Zhang, L.; Qiu, Z.; Yu, C. Microbial Community Succession in Soils under Long-Term Heavy Metal Stress from Community Diversity-Structure to KEGG Function Pathways. *Environ. Res.* **2022**, *214*, 113822. [CrossRef] [PubMed]
20. Jiang, H.; Sheng, Y.; Ngai, T. Pickering Emulsions: Versatility of Colloidal Particles and Recent Applications. *Curr. Opin. Colloid Interface Sci.* **2020**, *49*, 1–15. [CrossRef] [PubMed]
21. Gao, J.; Bu, X.; Dong, L.; Qiu, Y.; Xie, G.; Chehreh Chelgani, S. Natural Graphite Froth Flotation-An Overview. *Miner. Process. Extr. Metall. Rev.* **2025**, *46*, 306–323. [CrossRef]
22. Bian, Z.; Yang, Z.; Zhang, Y.; An, Q.; Duan, Z.; Liu, Z.; Fu, P. Synergistic Effects between Binary Nonionic Surfactants Span 80 and Triton X-100 in Stabilizing High Internal Phase Water-in-Oil Emulsions for Coal Slime Flotation. *Chem. Eng. Res. Des.* **2025**, *223*, 763–775. [CrossRef]
23. Qiu, Y.; Mao, Z.; Sun, K.; Zhang, L.; Yang, L.; Qian, Y.; Lei, T. Cost-Efficient Clean Flotation of Amorphous Graphite Using Water-in-Oil Kerosene Emulsion as a Novel Collector. *Adv. Powder Technol.* **2022**, *33*, 103770. [CrossRef]
24. Gao, J.; Bu, X.; Zhou, S.; Wang, X.; Bilal, M.; Hassan, F.U.; Hassanzadeh, A.; Xie, G.; Chelgani, S.C. Pickering Emulsion Prepared by Nano-Silica Particles—A Comparative Study for Exploring the Effect of Various Mechanical Methods. *Ultrason. Sonochem.* **2022**, *83*, 105928. [CrossRef] [PubMed]
25. Ajayi, S.M.; Olusanya, S.O.; Abimbade, S.F.; Faboya, O.L.; Olumayede, E.G.; Akintayo, C.O.; Malomo, D. Pickering Emulsions: Physicochemical Properties and Recent Applications in Engineering. *Hybrid Adv.* **2025**, *11*, 100509. [CrossRef]
26. Chevalier, Y.; Bolzinger, M.-A. Emulsions Stabilized with Solid Nanoparticles: Pickering Emulsions. *Colloids Surf. A Physicochem. Eng. Asp.* **2013**, *439*, 23–34. [CrossRef]
27. Okibe, N.; Johnson, D.B. Toxicity of Flotation Reagents to Moderately Thermophilic Bioleaching Microorganisms. *Biotechnol. Lett.* **2002**, *24*, 2011–2016. [CrossRef]
28. Bomberg, M.; Miettinen, H.; Kinnunen, P. Seasonal Variation in Metabolic Profiles and Microbial Communities in a Subarctic Ore Processing Plant. *Environ. Microbiol. Rep.* **2024**, *16*, e13284. [CrossRef] [PubMed]
29. Badmus, S.O.; Amusa, H.K.; Oyehan, T.A.; Saleh, T.A. Environmental Risks and Toxicity of Surfactants: Overview of Analysis, Assessment, and Remediation Techniques. *Environ. Sci. Pollut. Res.* **2021**, *28*, 62085–62104. [CrossRef] [PubMed]
30. Di Trapani, D.; De Marines, F.; Greco Lucchina, P.; Viviani, G. Surfactant-Enhanced Mobilization of Hydrocarbons from Soil: Comparison between Anionic and Nonionic Surfactants in Terms of Remediation Efficiency and Residual Phytotoxicity. *Process Saf. Environ. Prot.* **2023**, *180*, 1–9. [CrossRef]
31. Chockalingam, E.; Subramanian, S.; Natarajan, K.A. Studies on Biodegradation of Organic Flotation Collectors Using *Bacillus polymyxa*. *Hydrometallurgy* **2003**, *71*, 249–256. [CrossRef]
32. Uguz, C.; Iscan, M.; Ergüven, A.; Isgor, B.; Togan, I. The Bioaccumulation of Nonyphenol and Its Adverse Effect on the Liver of Rainbow Trout (*Onchorynchus mykiss*). *Environ. Res.* **2003**, *92*, 262–270. [CrossRef] [PubMed]
33. Loyo-Rosales, J.E.; Schmitz-Afonso, I.; Rice, C.P.; Torrents, A. Analysis of Octyl- and Nonylphenol and Their Ethoxylates in Water and Sediments by Liquid Chromatography/Tandem Mass Spectrometry. *Anal. Chem.* **2003**, *75*, 4811–4817. [CrossRef] [PubMed]
34. Zhang, L.; Yang, S.; Saleh, A.S.M.; Wang, R.; Xiao, Z. Influence of Emulsifier Type on Sunflower Oil Oleogels Structured with Ethylcellulose. *LWT* **2025**, *238*, 118841. [CrossRef]
35. Abu Zaid, N.S.K.; Nasser, M.; Onaizi, S.A. Pickering Emulsions Stabilized by Metal-Organic Frameworks, Graphene-Based Materials, and Carbon Nanotubes: A Comprehensive Review. *J. Mol. Liq.* **2024**, *393*, 123617. [CrossRef]

36. Kou, X.; Zhang, X.; Ke, Q.; Meng, Q. Pickering Emulsions Stabilized by β-CD Microcrystals: Construction and Interfacial Assembly Mechanism. *Front. Nutr.* **2023**, *10*, 1161232. [CrossRef] [PubMed]
37. Sun, Z.; Yan, X.; Xiao, Y.; Hu, L.; Eggersdorfer, M.; Chen, D.; Yang, Z.; Weitz, D.A. Pickering Emulsions Stabilized by Colloidal Surfactants: Role of Solid Particles. *Particuology* **2022**, *64*, 153–163. [CrossRef]
38. Xiao, M.; Xu, A.; Zhang, T.; Hong, L. Tailoring the Wettability of Colloidal Particles for Pickering Emulsions via Surface Modification and Roughness. *Front. Chem.* **2018**, *6*, 225. [CrossRef] [PubMed]
39. Liu, J.; Zhang, R.; Bao, X.; Hao, Y.; Gui, X.; Xing, Y. New Insight into the Role of the Emulsified Diesel Droplet Size in Low Rank Coal Flotation. *Fuel* **2023**, *338*, 127388. [CrossRef]
40. Sun, K.; Qiu, Y.; Zhang, L.; Liu, Q.; Mao, Z.; Qian, Y. Enhanced Fine Flake Graphite Flotation and Reduced Carbon Emission by a Novel Water-in-Oil Kerosene Emulsion. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *650*, 129603. [CrossRef]
41. Wei, Z.; Yang, M.; Zhang, Z. Interfacial Mechanism of Enhanced Coal Slime Flotation Using Microemulsion Collectors. *Sep. Purif. Technol.* **2025**, *378*, 134747. [CrossRef]
42. Fu, S.-Y.; Feng, X.-Q.; Lauke, B.; Mai, Y.-W. Effects of Particle Size, Particle/Matrix Interface Adhesion and Particle Loading on Mechanical Properties of Particulate–Polymer Composites. *Compos. Part B Eng.* **2008**, *39*, 933–961. [CrossRef]
43. Gao, J.; Bu, X.; Zhou, S.; Wang, X.; Alheshibri, M.; Peng, Y.; Xie, G. Graphite Flotation by β-Cyclodextrin/Kerosene Pickering Emulsion as a Novel Collector. *Miner. Eng.* **2022**, *178*, 107412. [CrossRef]
44. Jafari, M.; Golzadeh, M.; Shafaei, S.; Abdollahi, H.; Gharabaghi, M.; Chehreh Chelgani, S. Effects of Conventional Flotation Frothers on the Population of Mesophilic Microorganisms in Different Cultures. *Processes* **2019**, *7*, 653. [CrossRef]
45. Chen, X.; Peng, Y. Physically Emulsifying Oily Collectors to Produce Optimal Droplet Sizes for Flotation. *Miner. Eng.* **2022**, *184*, 107641. [CrossRef]
46. Gao, J.; Tong, Z.; Bu, X.; Bilal, M.; Hu, Y.; Ni, C.; Xie, G. Effect of Water-in-Oil and Oil-in-Water with Span 80 on Coal Flotation. *Fuel* **2023**, *337*, 127145. [CrossRef]

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