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# Valorization of Heterogeneous Waste Cooking Oils for Efficient Microalgae Harvesting

Xiangjun Li <sup>1</sup>, Hao Wen <sup>2,\*</sup>, Jiahan You <sup>2</sup>, Hongwei Yin <sup>2</sup>

<sup>1</sup> Centre for Human Sciences, Universiti Malaysia Pahang Al-Sultan Abdullah, Pahang 26300, Malaysia

<sup>2</sup> School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, China

\* Corresponding author: 503059987@qq.com

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**Abstract:** To achieve the high-value valorization of waste cooking oil (WCO) and address the economic bottleneck of microalgae harvesting, this study proposes a sustainable buoy-bead flotation strategy. Emulsions derived from three typical WCO sources (Rapeseed, Peanut, and Soybean) were evaluated to optimize this “waste-to-resource” process. Results demonstrated that Peanut Re-Frying Oil Emulsion (P-RFOE) and Soybean Re-Frying Oil Emulsion (S-RFOE) exhibited superior harvesting performance, achieving efficiencies exceeding 92% under optimized conditions. Mechanistic analysis revealed that these substrates formed highly compact aggregates ( $D_f = 1.48$ ) via aluminum sulfate-mediated cationic bridging, marginally enhancing resistance to hydrodynamic shear. The method’s ecological adaptability was validated through the in-situ remediation of natural blooms in three eutrophic lakes, achieving a peak harvesting efficiency of 98.03% (Chaohu Lake) and a high enrichment ratio of 3.21 (Luoma Lake). Furthermore, a gate-to-gate Life Cycle Assessment (LCA) confirmed the system’s sustainability, featuring a competitive operational cost (1.16/m<sup>3</sup>), a minimal carbon footprint (0.066 kg CO<sub>2</sub>-eq/m<sup>3</sup>), and no secondary pollution. This study establishes a cost-effective, eco-friendly solution that simultaneously targets eutrophication control and bioenergy feedstock recovery, exemplifying a circular economy approach.

**Keywords:** microalgae harvesting; waste cooking oil heterogeneity; buoy-bead flotation

## 1. Introduction

Global energy security and environmental sustainability are currently facing dual challenges posed by the depletion of fossil fuels and the intensification of eutrophication in aquatic ecosystems [1,2]. Microalgae, as third-generation biofuel feedstocks, have garnered significant attention due to their high photosynthetic efficiency, rapid growth rates, and ability to accumulate lipids on non-arable land [3]. Furthermore, the cultivation of microalgae can be coupled with wastewater treatment to mitigate nutrient pollution, offering a promising “waste-to-energy” pathway [4]. Despite these advantages, the commercial viability of microalgal biofuels is severely hampered by the downstream processing costs. The harvesting step alone accounts for 20%–30% of the total production cost, primarily due to the dilute nature of algal cultures ( $\rho < 0.5$  kg/m<sup>3</sup>), the microscopic size of cells (2–20  $\mu$ m), and their specific gravity being similar to water [5].

To address this techno-economic bottleneck, various harvesting technologies, including centrifugation, filtration, flocculation, and flotation, have been extensively investigated. Among these, flotation has emerged as a preferred method for large-scale applications due to its high throughput and small footprint [6]. Recently, a novel variant known as buoy-bead flotation has shown demonstrated potential. Unlike

traditional dissolved air flotation (DAF), which relies on energy-intensive microbubbles, buoy-bead flotation utilizes low-density solid or liquid collectors to levitate algal flocs [7]. In this context, WCO represents an ideal candidate for preparing such low-density buoyant collectors, which serve to levitate the micro-flocs pre-formed by chemical coagulants rather than acting as primary flocculants themselves [8,9].

While the feasibility of using WCO-based emulsions for microalgae harvesting has been preliminarily demonstrated [10], a critical scientific gap remains regarding the physicochemical heterogeneity of the waste oil substrate. “Waste cooking oil” is a generic term encompassing a complex mixture of lipids derived from various sources (e.g., rapeseed, peanut, soybean, sunflower) and subjected to different cooking histories. These variations result in significant fluctuations in fatty acid composition, viscosity, acid value, and impurity content [11]. In practical engineering scenarios, this heterogeneity can lead to unpredictable interfacial behaviors, affecting the stability of “oil-algae” aggregates and the overall process stability. Most existing studies have treated WCO as a uniform substrate, neglecting how specific oil sources influence flotation kinetics and separation efficiency. Furthermore, the majority of research has been confined to harvesting laboratory-cultured monocultures [12]. The adaptability of WCO-based flotation to natural eutrophic waters—characterized by complex algal consortia, fluctuating pH, and high turbidity—remains largely unexplored [13]. Validating the technology in-situ is essential for extending its application from bioenergy production to the ecological remediation of harmful algal blooms (HABs).

To bridge these gaps, this study focuses on the impact of waste oil heterogeneity on flotation performance and investigates the potential for in-situ remediation. Three distinct types of Re-Frying Oil Emulsions (RFOEs) were prepared from waste Rapeseed (R-RFOE), Peanut (P-RFOE), and Soybean (S-RFOE) oils to verify the environmental safety and economic sustainability of this “waste-treating-waste” strategy.

## **2. Materials and Methods**

### **2.1. Microalgal Strains and Culture Conditions**

Two freshwater microalgae species, *Chlorella vulgaris* (FACHB-8) were obtained from the Freshwater Algae Culture Collection at the Institute of Hydrobiology (FACHB), Chinese Academy of Sciences, Wuhan, China. The strains were cultivated in BG11 medium within custom-designed photobioreactors (Height = 50 cm, Diameter = 20 cm). The culture conditions were maintained at  $25 \pm 1$  °C under a light intensity of 3000 lux with a 12 h:12 h light/dark cycle. Continuous aeration was provided to prevent sedimentation and ensure sufficient gas exchange. The microalgae were harvested for flotation experiments during the stationary growth phase.

### **2.2. Preparation of Heterogeneous RFO Emulsions**

To investigate the impact of waste oil heterogeneity on flotation performance, three distinct types of waste cooking oils were collected from local catering services:

Waste Rapeseed Oil, Waste Peanut Oil, and Waste Soybean Oil. The oils were pre-treated by simple filtration to remove food residues. The physicochemical properties and quantitative fatty acid compositions of these filtered WCOs were characterized via GC-MS (Agilent Technologies, Santa Clara, CA, USA) and standard titration methods (shown in **Table 1**).

The Re-Frying Oil Emulsions (RFOEs) were prepared via a surfactant-assisted high-shear homogenization process. Specifically, 98 mL of the filtered waste oil was mixed with 2 mL of the non-ionic surfactant Sorbitan oleate (Span 80, CP grade, Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) to form the oil phase. This mixture was then combined with 100 mL of deionized water and emulsified using a mechanical stirrer at 800 rpm for 20 min. The resulting emulsions were designated as Rapeseed Re-Frying Oil Emulsion (R-RFOE), P-RFOE, and S-RFOE, respectively. The emulsions were allowed to stand for 12 h to separate the stable cream layer, which was then collected and stored at 4 °C for subsequent use.

**Table 1.** Physicochemical properties and fatty acid compositions of the three heterogeneous WCOs.

Parameters	Rapeseed WCO (R-WCO)	Peanut WCO (P-WCO)	Soybean WCO (S-WCO)
Acid value (mg KOH/g)	1.82	4.85	1.52
Main Fatty Acids (%)	Erucic acid (45.2%)	Oleic acid (41.3%)	Linoleic acid (52.8%)
Viscosity (mPa·s at 25 °C)	1.15	1.08	1.02
Surface tension (mN/m)	32.4	30.1	28.5

### 2.3. Flotation Apparatus and Experimental Procedure

The flotation experiments were conducted in a polymethyl methacrylate column equipped with a variable-speed agitator and a bottom injection port.

A typical batch flotation test involved the following steps: 1. Coagulation: 200 mL of algal suspension was transferred to the column. Aluminum sulfate was added as the coagulant, and the mixture was stirred at 200 rpm for 2 min to initiate micro-floc formation. 2. Flotation: The prepared RFOE was injected into the bottom of the column using a peristaltic pump. The system was stirred at a predetermined speed (60–160 rpm) for a specific duration to facilitate the collision and adhesion between oil droplets and algal flocs. 3. Separation: The mixture was allowed to stand for 5–10 min. The “Oil-Algae” aggregates floated to the surface due to buoyancy, forming a scum layer.

### 2.4. Characterization and Mechanistic Analysis

#### 2.4.1. Surface Properties

The Zeta potential of algal cells and emulsion droplets was measured using a Zeta potential analyzer (Brookhaven, Nashua, NH, USA). The functional groups on the surface of algae, oil droplets, and their aggregates were analyzed by Fourier Transform Infrared Spectroscopy (FTIR, Nicolet iS50, Thermo Fisher, Waltham, MA, USA).

### 2.4.2. Fractal Dimension Analysis

To quantify the structural compactness of the formed aggregates, microscopic images of the flocs were captured. The fractal dimension ( $D_f$ ) was calculated using the box-counting method via ImageJ software. The relationship is expressed as  $\ln A = D_f \times \ln l$ , where  $A$  is the projected area and  $l$  is the maximum projected length of the floc [14].

### 2.5. In-situ Remediation of Eutrophic Lakes

Field experiments were conducted using natural water samples collected from three eutrophic lakes in China during the algal bloom season: Chaohu Lake, Hongze Lake, and Luoma Lake. Water samples were collected from the surface layer (0–0.5 m depth) at representative bloom sites. The dominant algal species were identified microscopically, and water quality parameters (pH, turbidity) were measured in-situ. The optimized P-RFOE flotation system was applied to these samples. The operational parameters (e.g., emulsion and coagulant dosage) were fine-tuned for each water matrix to validate the method's environmental adaptability.

### 2.6. Life Cycle Assessment (LCA)

A gate-to-gate Life Cycle Assessment (LCA) was performed using SimaPro 9.0 software (PRé Sustainability, Amersfoort, Netherlands) to evaluate the environmental sustainability. The system boundary encompassed emulsion preparation, microalgae harvesting, and wastewater treatment. Notably, the transport and collection costs of waste oil were excluded from this gate-to-gate analysis. The functional unit was defined as the processing of 1 m<sup>3</sup> of algal suspension [15]. Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method, focusing on Global Warming Potential (GWP), Aquatic Eutrophication, and Human Toxicity [16]. To enhance transparency and reproducibility, the detailed life cycle inventory (LCI) of the harvesting process is summarized in **Table 2**, including electricity consumption, Span 80 dosage, coagulant dosage, and water use, together with key assumptions

**Table 2.** Life cycle inventory (LCI) of the S-RFOE harvesting system (functional unit: 1 m<sup>3</sup> algal suspension treated).

Category	Item	Unit	Amount (per FU)
Collector preparation	Soybean oil	kg	1.25
	Span 80	kg	0.027
	Electricity	kWh	0.002
	Water	L	1.39
Coagulation/flotation	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	g	7.78
	Electricity	kWh	6.8
	Water	L	77.78
Wastewater	Effluent treatment	—	Municipal WWTP

## 2.7. Analytical Methods

The  $E_h$  was calculated based on the optical density at 540 nm (OD540) before ( $C_0$ ) and after ( $C_1$ ) flotation (**Equation 1**). The  $E_r$  was defined as the ratio of the initial liquid volume ( $V_0$ ) to the volume of the harvested biomass scum ( $V_1$ ) (**Equation 2**).

$$E_h = \frac{C_0 - C_1}{C_0} \times 100\% \quad (1)$$

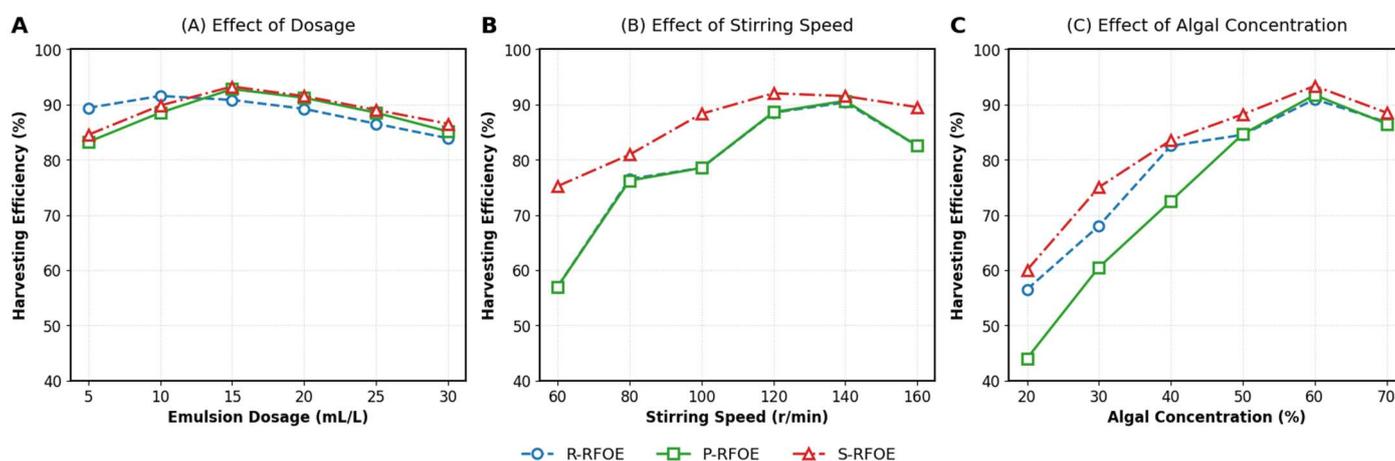
$$E_r = \frac{V_0}{V_1} \times 100\% \quad (2)$$

## 3. Results and Discussion

### 3.1. Impact of Waste Oil Heterogeneity on Flotation Performance

#### 3.1.1. Comparative Efficacy of RFO-Derived Emulsions: Substrate Heterogeneity and Process Optimization

To elucidate the impact of physicochemical heterogeneity inherent in waste cooking oils—specifically the variations in fatty acid composition, viscosity, and surface charge imparted by different source materials—on flotation kinetics, emulsions derived from Rapeseed (R-RFOE), Peanut (P-RFOE), and Soybean (S-RFOE) waste oils were evaluated under varying operational conditions. The comparative profiles of  $E_h$  and  $E_r$ , as illustrated in **Figure 1**, reveal distinct response trajectories for each substrate, underscoring the critical importance of substrate selection in optimizing the “oil-bubble-algae” interfacial interactions.



**Figure 1.** Effects on the harvesting efficiency of different RFO emulsions.

The dosage of the collector serves as a primary determinant of collision probability and hydrophobic modification. As depicted in **Figure 1A**, all three substrates exhibited a characteristic biphasic “rise-and-fall” behavior in harvesting efficiency. R-RFOE achieved its peak efficiency of 91.53% at a relatively low dosage of 10 mL/L; however, a further increase in dosage to 30 mL/L resulted in a significant decline to 83.87%. This deterioration at higher dosages can be attributed to the “overdosing effect”, where excessive oil droplets compete for cationic adsorption sites on the algal surface or induce steric hindrance, thereby restabilizing the suspension rather than promoting flocculation [17]. In contrast, P-RFOE and S-RFOE

demonstrated superior process stability and carrying capacity, attaining higher maximum efficiencies of 92.77% and 93.23%, respectively, at an optimal dosage of 15 mL/L. Furthermore, their enrichment ratios monotonically increased with dosage, reaching peak values exceeding 2.0, suggesting that the specific amphiphilic compounds in Peanut and Soybean oil residues may facilitate the formation of more compact, hydrophobic flocs that effectively exclude interstitial water during the ascent phase.

Hydrodynamic conditions play a pivotal role in modulating the delicate balance between particle collision frequency and aggregate breakage. The experimental data highlighted a divergence in the shear sensitivity of the aggregates formed by different substrates (**Figure 1B**). S-RFOE exhibited superior interfacial adhesion properties, reaching its maximum harvesting efficiency (92.01%) at a lower stirring speed of 120 rpm. This early peak implies that S-RFOE droplets possess a higher affinity for *C. vulgaris* cells, allowing for effective bridging even under lower turbulent kinetic energy, which is advantageous for reducing operational energy consumption. Conversely, R-RFOE and P-RFOE required a higher turbulence intensity to maximize contact probability, achieving peak efficiencies of 90.36% and 90.64%, respectively, at 140 rpm. Beyond these optimal thresholds, excessive hydraulic shear forces universally disrupted the fragile “Algae-Oil-Bubble” aggregates, overcoming the capillary and electrostatic forces holding them together and leading to biomass detachment [18]. The enhanced shear resistance of S-RFOE aggregates at lower speeds may be linked to specific long-chain fatty acids in the soybean oil matrix that enhance the viscoelasticity of the oil-water interface. Specifically, the higher concentration of unsaturated fatty acids (e.g., linoleic acid) in S-RFOE and P-RFOE contributes to a more flexible and tenacious interfacial film compared to the erucic acid-rich R-RFOE [19]. This enhanced interfacial viscoelasticity facilitates more robust bridging between oil droplets and algal cells, forming aggregates that better withstand hydrodynamic stress during the flotation process.

Furthermore, the system demonstrated robust adaptability to varying biomass loads, a crucial parameter for applying this technology to real-world bloom remediation. As shown in **Figure 1C**, the harvesting efficiency for all emulsions showed a strong positive correlation with initial cell concentration up to a threshold of 60% dilution. At this optimal biomass load, S-RFOE outperformed the other substrates with a peak efficiency of 93.34%. Although efficiency declined slightly at higher concentrations (70%) due to an insufficient ratio of buoyant vectors to algal cells, the enrichment ratio continued to climb steeply, reaching a maximum of 2.76 for both R-RFOE and S-RFOE. This trend confirms the method’s efficacy in concentrating high-density algal blooms, as higher cell densities increase the collision frequency per unit volume, promoting the formation of larger, faster-rising flocs via the “sweep flocculation” mechanism. Collectively, these findings validate that the heterogeneity of waste oil sources marginally influences flotation performance, with S-RFOE identifying as the most promising candidate for energy-efficient remediation due to its high performance at lower shear rates and dosages.

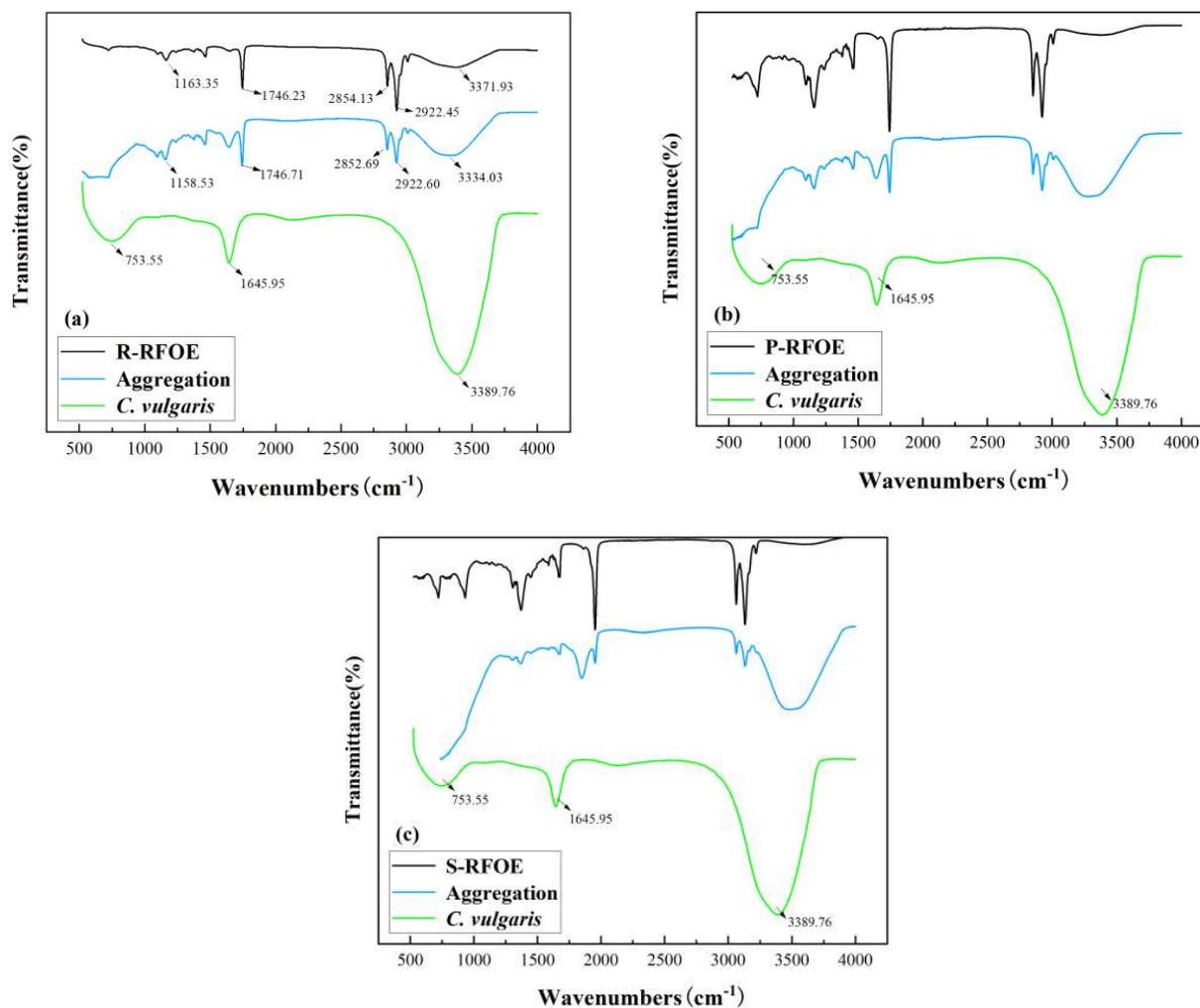
### 3.1.2. Selection of Suitable Collectors

Importantly, S-RFOE displayed excellent operational robustness under

fluctuating environmental conditions, with harvesting efficiency consistently exceeding 90% over 15–35 °C and in the presence of NaCl up to 100 mmol/L. This resilience is particularly relevant for real-world scenarios where water temperature and salinity may vary seasonally or spatially. Although optimal harvesting occurred at pH  $\approx$  8.0, satisfactory performance was preserved over a broad pH range, highlighting the suitability of S-RFOE for practical deployment in diverse hydrochemical environments.

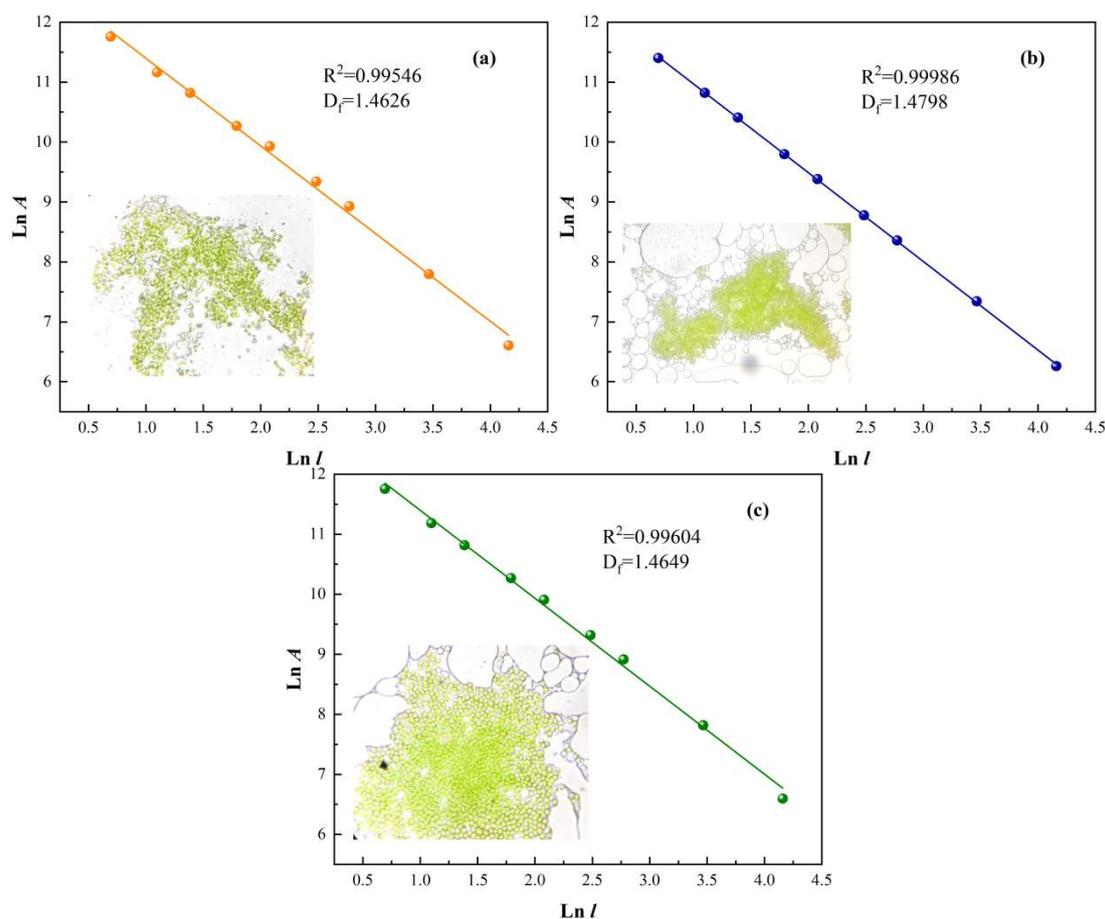
### 3.2. Mechanism of Aggregate Formation

While the macroscopic flotation performance varies, the fundamental chemical mechanism governing the adhesion process remains consistent that aluminum sulfate initiates the primary coagulation, while RFOE droplets function as buoyant vectors that link with these pre-formed aggregates to drive separation. Fourier Transform Infrared Spectroscopy (FTIR, shown in **Figure2**) analysis of the “algae-oil” aggregates revealed a high degree of spectral similarity across R-RFOE, P-RFOE, and S-RFOE systems. The appearance of characteristic ester carbonyl ( $\text{C}=\text{O}$ ) stretching vibrations at  $\sim 1740\text{ cm}^{-1}$  and the shift in hydroxyl ( $\text{OH}$ ) bands provide molecular-level evidence that aluminum sulfate functions as a cationic bridge. This bridge effectively neutralizes the electrostatic repulsion and links the carboxyl-rich interface of the oxidized waste oil droplets with the negatively charged functional groups (carboxyl and amine) on the algal cell walls. Since the surface chemical functionalities are analogous, the observed divergence in flotation efficiency and enrichment ratio must predominantly stem from physical structural differences in the formed flocs.



**Figure 2.** FTIR analysis of R-RFOE (a), P-RFOE (b) and S-RFOE (c) with *Chlorella vulgaris* and its aggregations.

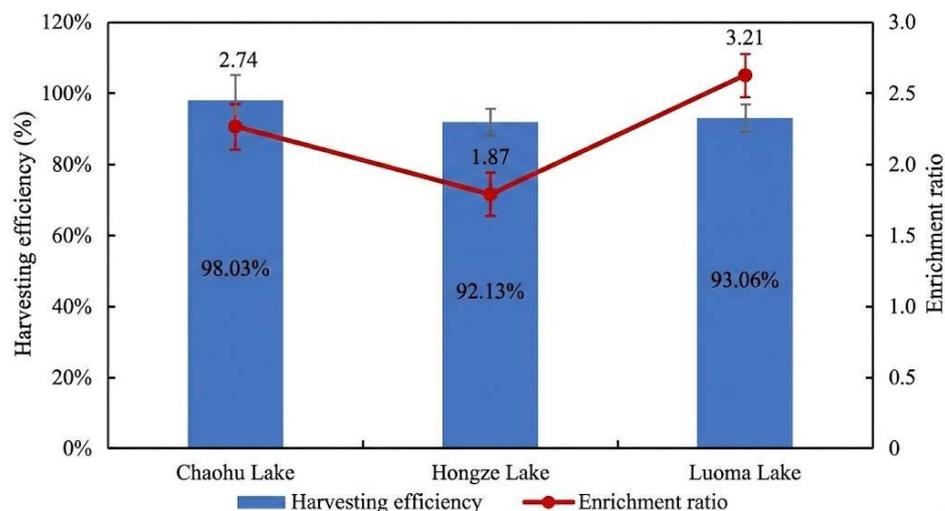
To quantify these morphological variations,  $D_f$  analysis was employed as a descriptor of aggregate compactness. The analysis revealed that the aggregates formed by P-RFOE exhibited a slightly higher fractal dimension ( $D_f = 1.48$ ), followed by S-RFOE ( $D_f = 1.46$ ) and R-RFOE ( $D_f = 1.46$ ). In fractal geometry, a higher  $D_f$  value correlates with a denser, more spherical structure, whereas a lower value indicates loose, porous, and chain-like flocs. The superior compactness of P-RFOE aggregates has profound hydrodynamic implications: it reduces the effective drag coefficient and minimizes porosity, thereby “squeezing out” interstitial water during the ascent phase. This structural densification, qualitatively supported by the more integrated aggregate boundaries observed in **Figure 3**, elucidates why P-RFOE achieved stable performance and a high enrichment ratio in the empirical tests, as the tighter floc architecture naturally enhances dewatering capacity and resistance to hydrodynamic shear forces.



**Figure 3.** Fractal dimensions of aggregations formed by R-RFOE (a), P-RFOE (b) and S-RFOE (c) with *Chlorella vulgaris*.

### 3.3. In-situ Remediation Potential: Performance of P-RFOE in Eutrophic Lakes

To rigorously evaluate the ecological validity and process adaptability of the proposed flotation technology under complex hydrodynamic and hydrochemical conditions, the Peanut Re-Frying Oil Emulsion (P-RFOE)—identified as the optimal substrate in laboratory trials—was deployed to harvest natural cyanobacterial blooms collected from Chaohu Lake, Hongze Lake, and Luoma Lake. Unlike laboratory monocultures, these environmental matrices presented significant challenges characterized by high turbidity, fluctuating pH, and heterogeneous algal consortia dominated by *Microcystis* and *Chlorella*. Despite these complexities, the site-specific multi-objective optimization results, as summarized in **Figure 4**, demonstrated that the P-RFOE system achieved high separation performance across all studied limnetic systems. The system consistently attained  $E_h$  exceeding 92% for all water samples, with the highest efficiency of 98.03% recorded for Chaohu Lake. This consistent high efficacy confirms that the amphiphilic properties of P-RFOE droplets maintain high selectivity and strong interfacial affinity for cyanobacterial cells, even in the presence of competitive dissolved organic matter (DOM), which typically inhibits conventional flocculation.



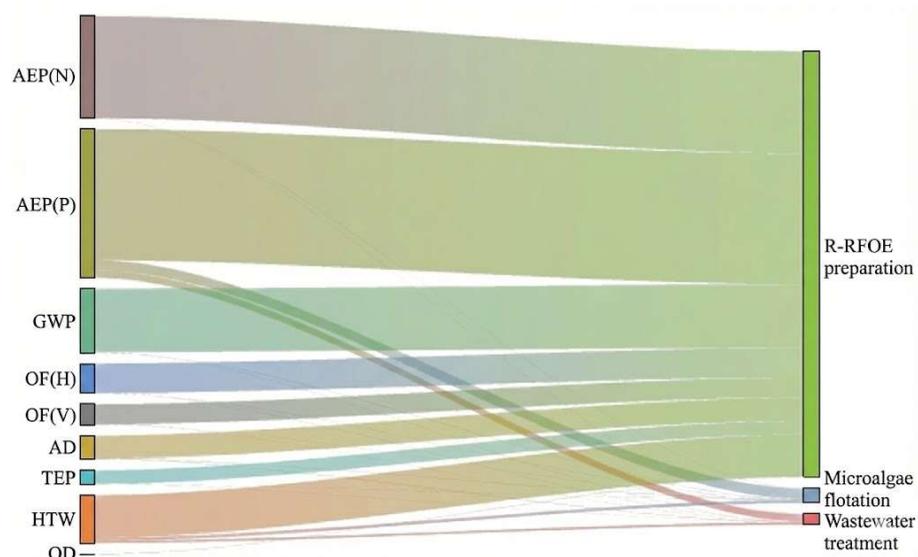
**Figure 4.** In-situ Remediation Performance of P-RFOE (Mean  $\pm$  SD,  $n = 3$ ).

A critical finding from the in-situ trials was the system’s high capability to concentrate biomass under high-load conditions. The Er for the Luoma Lake samples peaked at a substantial 3.21, a value marginally surpassing benchmarks typically observed in laboratory pure cultures ( $\sim 2.0$ ). This counter-intuitive phenomenon highlights a “load-enhancing” effect inherent to natural blooms: the presence of suspended particulate matter and high algal densities appears to increase the collision frequency and effective density of the flocs, promoting a “sweep flocculation” mechanism that aggressively compacts the biomass scum [20]. However, it should be noted that the “sweep flocculation” mechanism in natural waters potentially leads to the co-harvesting of non-algal suspended solids (e.g., silt and organic debris), which could slightly reduce the purity of the collected biomass. For downstream bioenergy applications, a simple washing or sedimentation step might be required to ensure feedstock quality. Furthermore, the operational substrate demand varied marginally depending on the specific water quality characteristics, underscoring the environmental adaptability of the P-RFOE system. The optimized emulsion dosage for Chaohu Lake was remarkably low at 5.00 mL/L, suggesting a synergistic interaction between P-RFOE droplets and natural extracellular polymeric substances (EPS), which likely acted as bio-flocculants. Conversely, Hongze Lake required a higher dosage of 15.00 mL/L to overcome the specific surface charge barriers of its dominant species. Collectively, these findings validate P-RFOE as a versatile and reliable agent for emergency bloom remediation, capable of converting dispersed ecological hazards into harvestable bio-resources with high volume reduction efficiency.

### 3.4. Environmental Impact and Economic Sustainability Assessment

The translatability of waste-to-resource technologies from bench-scale validation to industrial deployment is fundamentally contingent upon their techno-economic feasibility and environmental benignity compared to established paradigms. To rigorously quantify these sustainability metrics, a comprehensive gate-to-gate LCA was conducted, integrating a detailed inventory analysis with a multi-criteria impact assessment. The inventory analysis revealed distinct economic profiles for the three RFO derivatives, primarily driven by the variations in optimal dosage requirements

determined during the mechanistic optimization. R-RFOE exhibited the lowest operational cost at \$1.026/m<sup>3</sup>, largely attributable to its lower raw material consumption in specific experimental scenarios. In comparison, the costs for P-RFOE and S-RFOE were calculated at \$1.164/m<sup>3</sup> and \$1.362/m<sup>3</sup>, respectively. Although the P-RFOE system incurs a marginal cost increment (~3%) compared to the rapeseed-derived substrate, it was ultimately selected as the optimal candidate for scale-up applications [21]. This strategic decision is justified by the trade-off between cost and physicochemical performance: P-RFOE demonstrated superior aggregate compactness ( $D_f = 1.48$ ) and higher process stability in mechanistic studies, characteristics that are critical for minimizing biomass loss and ensuring consistent separation efficiency in dynamic real-world environments. Furthermore, even at the conservative cost estimate of \$1.16/m<sup>3</sup>, the proposed P-RFOE flotation technology demonstrates a strong competitive advantage, representing a cost reduction of over 85% compared to energy-intensive centrifugation (8.0/m<sup>3</sup>) [22] and maintaining economic superiority over dissolved air flotation (7.6/m<sup>3</sup>) [23], thereby confirming its commercial viability for low-value biofuel feedstock production.



**Figure 5.** Results of the environmental impact assessment of P-RFOE harvesting of *Chlorella vulgaris*.

Environmental analysis revealed a carbon emission intensity of 0.066 kg CO<sub>2</sub>-eq/m<sup>3</sup>. **Figure 5** identified emulsion preparation as the primary environmental hotspot, contributing marginally to Global Warming Potential (GWP) and Human Toxicity (HTW). This is attributed to the electricity consumption during homogenization and the chemical synthesis of Span 80. In contrast, the harvesting stage exhibited a negligible footprint due to the buoyancy-driven mechanism. Post-flotation water analysis confirmed that heavy metals and carcinogenic markers remained within environmental safety standards. Future optimizations should focus on process intensification or utilizing bio-based surfactants to mitigate identified upstream impacts [24].

## 4. Conclusions

This study elucidated the impact of waste oil heterogeneity on flotation kinetics, identifying P-RFOE and S-RFOE oil emulsions as superior collectors compared to Rapeseed oil derivatives. Under optimized conditions, P-RFOE and S-RFOE achieved harvesting efficiencies exceeding 92% with enhanced aggregate compactness ( $D_f > 1.46$ ), attributed to the cationic bridging mechanism of aluminum sulfate confirmed by FTIR. The proposed system demonstrated high adaptability for in-situ remediation, effectively harvesting natural cyanobacterial blooms from eutrophic lakes with efficiencies  $>92\%$  and a significant enrichment ratio of up to 3.21. Furthermore, life cycle assessment verified the method's sustainability, revealing a low operational cost ( $\$1.16/\text{m}^3$ ) and minimal carbon footprint ( $0.066 \text{ kg CO}_2\text{-eq}/\text{m}^3$ ). This waste-to-resource strategy offers a cost-effective ( $>85\%$  savings vs. centrifugation) and eco-friendly solution for simultaneous water purification and biofuel feedstock recovery.

**Author contributions:** Conceptualization, X.L. and H.W.; methodology, X.L.; software, X.L.; validation, X.L. and H.W.; formal analysis, X.L.; investigation, X.L.; resources, H.W.; data curation, X.L.; writing—original draft preparation, X.L.; writing—review and editing, H.W., J.Y. and H.Y.; visualization, X.L.; supervision, H.W.; project administration, H.W.; funding acquisition, H.W. All authors have read and agreed to the published version of the manuscript.

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## References

1. Marinič D., Grilc M., Hočevnar B., et al. Liquefaction, cracking and hydrogenation of microalgae biomass resources to CO<sub>2</sub> negative advanced biofuels: mechanisms, reaction microkinetics and modelling. *Renewable energy*. 2023, 203, 382–393. <https://doi.org/10.1016/j.renene.2022.12.055>
2. Khoo K.S., Ahmad I., Chew K.W., et al. Enhanced microalgal lipid production for biofuel using different strategies including genetic modification of microalgae: a review. *Progress in Energy and Combustion Science*. 2023, 96, 101071. <https://doi.org/10.1016/j.peecs.2023.101071>
3. Almomani F., Hosseinzadeh Bandbafha H., Aghbashlo M. Comprehensive insights into conversion of microalgae to feed, food, and biofuels: Current status and key challenges towards implementation of sustainable biorefineries. *Chemical Engineering Journal*. 2023, 455, 140588. <https://doi.org/10.1016/j.cej.2022.140588>
4. Razzak S.A., Lucky R.A., Hossain M.M. Valorization of Microalgae Biomass to Biofuel Production: A review. *Energy Nexus*. 2022, 7, 100139. <https://doi.org/10.1016/j.nexus.2022.100139>
5. Xu K., Zou X., Chang W., et al. Microalgae harvesting technique using ballasted flotation: A review. *Separation and Purification Technology*. 2021, 276, 119439. <https://doi.org/10.1016/j.seppur.2021.119439>
6. Ghazvini M., Kavosi M., Sharma R. A review on mechanical-based microalgae harvesting methods for biofuel production. *Biomass and Bioenergy*. 2022, 158, 106348. <https://doi.org/10.1016/j.biombioe.2022.106348>
7. Jarvis P., Buckingham P., Holden B., et al. Low energy ballasted flotation. *Water Research*. 2009, 43(14), 3427–3434. <https://doi.org/10.1016/j.watres.2009.05.003>
8. Fernández-Silva S.D., Delgado M.A., Ruiz-Méndez M.V. Potential valorization of waste cooking oils into sustainable bio-lubricants. *Industrial Crops and Products*. 2022, 185, 115109. <https://doi.org/10.1016/j.indcrop.2022.115109>

9. Suhendi E., Avina M.N., Andriani K. The effect of operating conditions on the purification of waste cooking oil over a natural zeolite catalyst. *World Chemical Engineering Journal*. 2022, 6, 17–23. <http://doi.org/10.62870/wcej.v6i1.15561>
10. Wen H., Yin H., Qin W., et al. A novel high-value utilization method of re-frying oil in microalgae buoy bead flotation and mechanism analysis. *Algal Research*. 2023, 74, 103233. <https://doi.org/10.1016/j.algal.2023.103233>
11. Potocar T., Leite L.S., Daniel L.A., et al. Cooking oil-surfactant emulsion in water for harvesting *Chlorella vulgaris* by sedimentation or flotation. *Bioresource Technology*. 2020, 311, 123508. <https://doi.org/10.1016/j.biortech.2020.123508>
12. Zhang H., Wen H., Qin W., et al. Multi-objective optimization of a novel microalgae harvesting method based on buoy-bead flotation and feasibility analysis by life cycle assessment. *Separation and Purification Technology*. 2024, 329, 125143. <https://doi.org/10.1016/j.seppur.2023.125143>
13. Tian L., Jiang H., Song N. Comparing the effects of algae and macrophyte residues' degradation on biological nitrogen fixation in freshwater lake sediments. *Science of The Total Environment*. 2022, 809, 151129. <https://doi.org/10.1016/j.scitotenv.2021.151129>
14. Dai D., Qv M., Liu D. Structural insights into mechanisms of rapid harvesting of microalgae with pH regulation by magnetic chitosan composites: A study based on E-DLVO model and component fluorescence analysis. *Chemical Engineering Journal*. 2023, 456, 141071. <https://doi.org/10.1016/j.cej.2022.141071>
15. Gurreri L., Calanni Rindina M., Luciano A. Life Cycle Assessment Based on Primary Data of an Industrial Plant for Microalgae Cultivation. *Chemical Engineering Transactions*. 2024, 109, 493–498. <https://doi.org/10.3303/CET24109083>
16. Zou X., Zhao S., Xu K. Eco-friendly microalgae harvesting using lipid-cored particles with a comparative life-cycle assessment. *Bioresource Technology*. 2024, 392, 130023. <https://doi.org/10.1016/j.biortech.2023.130023>
17. Li S., Hu T., Xu Y. A review on flocculation as an efficient method to harvest energy microalgae: Mechanisms, performances, influencing factors and perspectives. *Renewable and Sustainable Energy Reviews*. 2020, 131, 110005. <https://doi.org/10.1016/j.rser.2020.110005>
18. Jarvis P., Jefferson B., Gregory J. A review of floc strength and breakage. *Water Research*. 2005, 39(14), 3121–3137. <https://doi.org/10.1016/j.watres.2005.05.022>
19. Yalcin H., Toker O.S., Dogan M. Effect of oil type and fatty acid composition on dynamic and steady shear rheology of vegetable oils. *Journal of Oleo Science*. 2012, 61(4), 181–187. <https://doi.org/10.5650/jos.61.181>
20. Demir-Yilmaz I., Ftouhi M.S., Balayssac S. Bubble functionalization in flotation process improve microalgae harvesting. *Chemical Engineering Journal*. 2023, 452, 139349. <https://doi.org/10.1016/j.cej.2022.139349>
21. Rafiq A., Morris C., Schudel A., et al. Life Cycle Assessment of Microalgae-Based Products for Carbon Dioxide Utilization in Thailand: Biofertilizer, Fish Feed, and Biodiesel. *Algal Research*. 2025, 13, 1503. <https://doi.org/10.12688/fl1000research.159019.3>
22. Grima E.M., Belarbi E.H., Fernández F.G.A., et al. Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances*. 2003, 20(7), 491–515. [https://doi.org/10.1016/S0734-9750\(02\)00050-2](https://doi.org/10.1016/S0734-9750(02)00050-2)
23. Hanotu J., Bandulasena H.H., Zimmerman W.B. Microflotation performance for algal separation. *Biotechnology and Bioengineering*. 2012, 109(7), 1663–1673. <https://doi.org/10.1002/bit.24449>
24. Tagne R.F.T., Santagata R., Tchuiwon Tchuiwon D.R. Environmental impact of second-generation biofuels production from agricultural residues in Cameroon: A life-cycle assessment study. *Journal of Cleaner Production*. 2022, 378, 134630. <https://doi.org/10.1016/j.jclepro.2022.134630>