Hue University Journal of Science: Natural Science
Vol. 134, No. 1B, 35–43, 2025

pISSN 1859-1388
eISSN 2615-9678

Cyclone microbubble flotation for enhanced oil recovery from palm oil mill effluent

Le Van Tuan*

Faculty of Environment, University of Sciences, Hue University, 77 Nguyen Hue St., Hue City, Vietnam

* Correspondence to Le Van Tuan <levantuan@hueuni.edu.vn>

(*Received: 13 March 2025; Revised: 08 April 2025; Accepted: 09 April 2025*)

Abstract. In this study, we investigate cyclone microbubble (CMB) flotation for oil recovery from palm oil mill effluent (POME) under batch and continuous operations. Designed to reduce floated waste and enhance oil separation, the process was tested on a real POME from a Malaysian palm oil mill, with high temperature, low pH, and fluctuating oil and grease (O&G), total solids (TS), and chemical oxygen demand (COD) levels. For a mill processing 1,000 tons of fresh fruit bunches (FFB) daily, the POME discharge contained 7.9 tons of O&G, 36.5 tons of TS, and 59.2 tons of COD. Batch flotation achieved ~63.8% of O&G separation with a 60-minute retention time, whereas continuous flotation (flow rate > 20 L/min) showed a lower efficiency (36 ± 9%). However, O&G was enriched 3 times in the recovery tank, demonstrating an effective oil concentration. Economic analysis confirmed that energy costs were significantly lower than the value of recovered palm oil, highlighting CMB flotation's cost-effectiveness. The findings support CMB flotation as a scalable and sustainable POME treatment method, with a potential for further efficiency improvements.

Keywords: cyclone microbubble, flotation, oil recovery, POME

1 Introduction

The Malaysian palm oil industry has seen remarkable growth over the past decades, establishing itself as one of the world's largest producers and exporters of palm oil [1–3]. As of 2022, Malaysia accounted for 25% of global palm oil production and 34% of global exports, producing 18.45 million tons of crude palm oil (CPO). However, this rapid expansion has resulted in a corresponding rise in palm oil mill effluent (POME) generation, a highly polluting by-product of crude palm oil extraction. The number of operational palm oil mills has increased from 10 in 1960 to over 450 in 2023, leading to over 65 million tons of POME discharged annually, making it one of the largest industrial wastewater sources in Southeast Asia [1, 4].

POME is a highly concentrated wastewater consisting of 95–96% water, 4–5% total solids (TS), and 0.6–0.7% oil and grease (O&G). Because of its high biochemical oxygen demand (BOD), chemical oxygen demand (COD), and methane (CH_4) emissions, untreated POME poses significant environmental risks, with CH_4 being 28 times as potent as CO_2 in its global warming potential [2]. Studies estimate that for every ton of crude palm oil produced, 5 to 7.5 cubic metres of water are used, with over 50% becoming POME [1]. Given its low pH (3.5–4.5) and complex organic composition, direct discharge into the environment is strictly regulated because of its detrimental effects on water bodies, soil quality, and atmospheric emissions [1, 5].

Several POME treatment methods have been developed, including open ponding, anaerobic digestion, sedimentation, and chemical coagulation. However, these approaches face significant limitations, such as long retention time (40–120 days), high land requirements, and substantial methane emissions that further contribute to climate change [5–7]. Additionally, physicochemical methods, such as coagulation, flocculation, and adsorption, often coupled with membrane filtration, have been explored for effluent purification and resource recovery, including repurposing solids and O&G as fertilizers or animal feed [1, 8]. However, these approaches require large quantities of coagulants and adsorbents, making them economically unfeasible, while membrane fouling further reduces efficiency [4, 5, 8].

One alternative is the coagulation-flotation approach, which has shown potential for oil-in-water separation. However, this method involves multiple complex steps, including flash mixing, slow mixing, and long retention time, making it challenging for large-scale implementation [4, 9]. Additionally, metal hydroxide- and polymer-contaminated sludge formation hinders dewatering and oil recovery efficiency, further limiting its practical application [10–12].

To overcome these challenges, microbubble (MB) flotation has emerged as an efficient solution for oil recovery from POME [11, 13]. Microbubble flotation employs micron-sized bubbles that enhance oil droplet attachment and flotation, leading to higher separation efficiency compared with conventional methods. Recent advancements, such as lab-scale cyclone microbubble (CMB) flotation, further optimize this process by incorporating hydrodynamic forces that improve oil droplet aggregation, reduce energy consumption, and enhance separation rates [11].

This study investigates the potential of CMB flotation as an innovative and sustainable solution for pilot-scale POME treatment. The primary objectives are to enhance oil recovery and reduce floating waste, contributing to efficient wastewater management in the palm oil industry. Unlike other works using conventional flotation methods, this research develops a novel flotation system that eliminates the need for coagulants, making it eco-friendly and cost-effective.

The treatment efficiency of the newly developed flotation process is evaluated under batch and continuous operational modes, offering insights into its scalability and industrial feasibility. By reducing chemical dependency and optimizing oil separation, this study supports the advancement of green wastewater treatment technologies, aligning with circular economy principles and sustainable palm oil processing. The findings are expected to provide valuable industrial applications, promoting waste-to-resource initiatives and minimizing the environmental footprint of palm oil production.

2 Materials and methods

2.1 Wastewater: POME

In this study, POME was collected after decanter processing at Synn Palm Oil (SPO) Company, located in Simpang Province, Malaysia. The mill processes approximately 1,000 tons of oil palm fresh fruit bunches (FFBs) per day, generating and discharging approximately 600 m^3 of POME.

2.2 Experimental setup

A custom-designed flotation system was developed to evaluate the efficiency of the CMB flotation process in separating O&G from POME. This system integrates multiple interconnected tanks, pumps, and microbubble generators, ensuring optimal fluid circulation, microbubble dispersion, and enhanced oil separation. The system architecture was designed to maximize oil

pISSN 1859-1388
eISSN 2615-9678

recovery efficiency while minimizing sludge formation and chemical dependency. The experimental setup consists of four primary tanks, each serving a distinct function in the flotation process. The POME receiving tank (1,000 L) provides initial storage and allows preliminary sedimentation before treatment. The circulation tank (960 L) stabilizes flow conditions, optimizes the pre-separation of O&G, and ensures steady operation. The flotation tank (670 L) serves as the main separation unit, where MBs facilitate oil droplet flotation and aggregation. Lastly, the oil recovery tank (400 L) collects the floated oil-rich fraction for further processing.

To facilitate fluid movement within the system, a network of five pumps was incorporated, along with an air pump supplying air for MB generation. The piping network and tank configurations were optimized to maintain the desired hydraulic retention time (HRT), turbulence control, and microbubble interaction efficiency.

2.3 MB generation and flotation mechanism

The CMB flotation system utilizes a combination of ejector-based microbubble generators and BT-50 microbubble nozzles to enhance oil recovery from POME. These components work synergistically to maximize bubble-oil interactions and improve flotation efficiency.

Ejector-based MB generation: Five high-speed ejectors were integrated into the system. Four ejectors, positioned at the bottom of the flotation tank at a 45-degree inclination, generate fine microbubbles (<150 µm in diameter). This configuration induces a cyclonic microbubble flow, improving bubble-oil collision, droplet adhesion, and separation efficiency. The swirling motion also enhances the coalescence of smaller oil droplets, accelerating their flotation. The additional ejector was installed in the circulation tank to facilitate the pre-separation of free-floating oil and suspended solids before POME enters the flotation tank. This pre-treatment step helps stabilize system operation and reduces the overall oil load, optimizing the flotation process.

BT-50 MB nozzles: To complement the ejectors, eight BT-50 microbubble nozzles were installed at one-fifth of the flotation tank height. These nozzles ensure uniform microbubble dispersion (<100 µm in diameter), improving oil droplet aggregation and flotation efficiency.

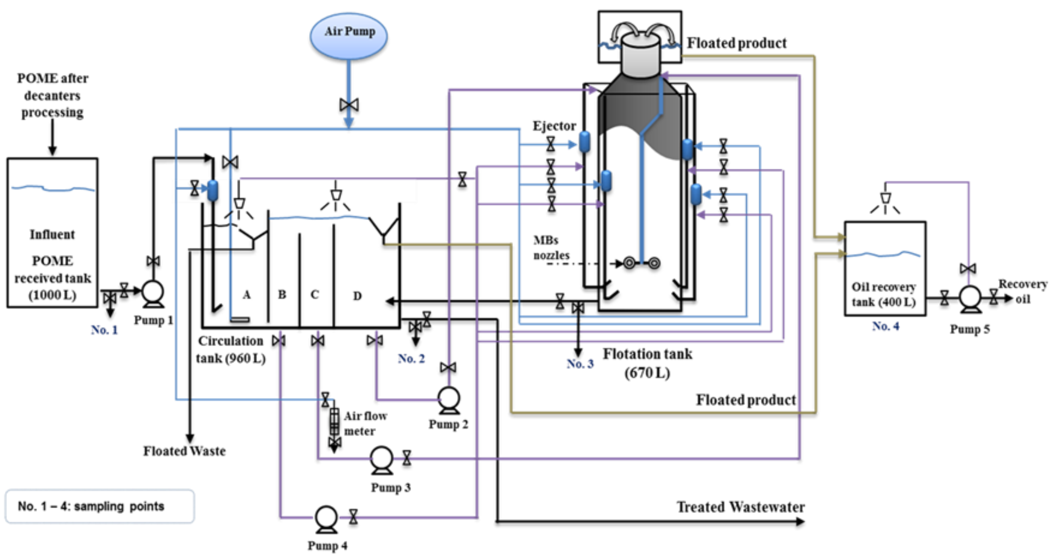

Fig. 1. Experimental setup

2.4 Flotation process operation

The flotation system was operated under both batch and continuous modes to assess its effectiveness under varying process conditions.

Batch mode operation

For batch operation, POME was stabilized overnight (~12 hours) in the circulation tank, allowing its temperature to drop naturally from ~75 to ~45 °C. The flotation process was conducted at different HRT to evaluate oil separation efficiency under controlled conditions (Test 1). Samples were collected at predefined time intervals to monitor treatment performance.

Continuous mode operation

In continuous operation, POME was fed into the flotation system at two different flow rates: 20 L/min (Test 2) and 30 L/min (Test 3). The corresponding HRT was 48 minutes in the circulation tank at 20 L/min and 32 minutes at 30 L/min; 33.5 minutes in the flotation tank at 20 L/min and 22.3 minutes at 30 L/min. The system reached steady-state conditions after 81.5 minutes at 20 L/min and 54.3 minutes at 30 L/min.

Throughout the flotation process, four key sampling points were established:

1) Raw influent POME, sampled after decanter processing (No. 1).

2) Partially treated POME, collected at the bottom of the circulation tank (No. 2).

3) Partially treated POME, collected at the bottom of the flotation tank (No. 3).

4) Finally recovered oil fraction, extracted from the oil recovery tank (No. 4).

Analytical methods

The quality of the treated POME was assessed by using standard analytical methods. pH and temperature were measured in situ by using a calibrated pH meter and thermometer. The removal efficiencies of COD (5,220 C), TS (2,540 D), and O&G (5,520 B) were analyzed following the standard methods [14]. These measurements provided critical insights into the overall performance of the flotation system in recovering oil and improving effluent quality.

3 Results and discussion

3.1 Characteristics and rapid assessment of POME in SPO Company

The characteristics of POME vary depending on processing conditions, oil extraction efficiency, and the operational scale of the palm oil mill. The SPO Company, a high-capacity facility processing 100 tons of FFBs per hour, generates ~600 m^3 of POME per day (m^3/d). Because of their high organic and solid content, the effluents must be subjected to effective treatment to reduce environmental pollution and comply with discharge regulations [15].

Table 1. Characteristics of POME after decanter processing in SPO Company

Parameters	Range	(*) Mean ± SD (*n* = 9)
pH	4.8–5.1	4.9 ± 0.1
Temperature, °C	69–84	74.9 ± 4.6
O&G (mg/L)	8,500–18,900	13,167 ± 4,105
TS (mg/L)	49,000–70,900	60,844 ± 7,194
COD (mg/L)	76,650–109,850	98,697 ± 10,723

Note: (*) Data obtained from on-site sampling and analysis conducted during this study

pISSN 1859-1388
eISSN 2615-9678

Given the daily POME discharge of 600 m³/d, the estimated pollutant load from the SPO mill was:

- 7.9 tons of O&G per day (13.17 kg/m³ × 600 m³/d)
- 36.5 tons of TS per day (60.84 kg/m³ × 600 m³/d)
- 59.2 tons of COD per day (98.70 kg/m³ × 600 m³/d)

These findings emphasize the need for an efficient flotation system to recover oil, reduce solid waste, and lower organic pollutant discharge.

The high temperature (~75°C) of freshly processed POME can enhance oil separation by reducing viscosity and improving flotation kinetics. However, the low pH (4.9) and presence of emulsified oil require micro-bubble-assisted flotation for effective recovery. Given the stable colloidal suspension of fine particulates, an optimized CMB flotation system is necessary to ensure maximum oil recovery and environmental compliance [5, 11]. Under acidic conditions, protonation of surface functional groups reduces electrostatic repulsion, enabling stronger adhesion between negatively charged oil droplets and microbubbles. This electrochemical compatibility, combined with the large interfacial area and high collision frequency of microbubbles, significantly improves attachment efficiency and oil recovery [5, 11]. This study demonstrates the feasibility of CMB flotation as a scalable and eco-friendly solution for POME treatment, supporting circular economy principles and minimizing the environmental footprint of palm oil production.

3.2 Batch CMB flotation: oil recovery efficiency

The batch-mode CMB flotation process was evaluated for oil recovery efficiency from real POME at a pilot scale. While previous studies primarily focused on small-scale, controlled laboratory experiments, this work investigates POME treatment under high operating temperatures (~75 °C) and real industrial conditions, providing a more representative assessment of practical flotation performance.

For batch testing, real POME collected directly from an operating palm oil mill was stabilized overnight (~12 hours) in the circulation tank, allowing the temperature to naturally decrease from ~75 to ~45 °C before treatment. Unlike typical low-temperature laboratory studies, this approach reflects actual mill discharge conditions, ensuring that findings can be directly applied to industrial-scale applications.

The CMB flotation system was operated under a fixed retention time of 120 minutes, with continuous MB generation provided by the ejector-based microbubble generator and the BT-50 MB nozzles. The operating flow rates of pumps and air supply conditions are detailed in Table 2. Flotation duration plays a critical role in separation efficiency because it affects bubble-oil interactions, coalescence, and droplet attachment efficiency. A significant increase in O&G removal efficiency was observed within the first 60 minutes, reaching 63.8% separation efficiency when the initial O&G concentration was ~5,800 mg/L (Figure 2).

Table 2. Operational parameters for batch CMB flotation (Test 1, 120 min, $n = 3$)

Component	Flow rate (L/min)
POME Flow (Pump 2)	290
BT-50 MB Nozzles (Pump 3)	80
Circulation (Pump 4)	30
Ejector MB, air supply/ejector	2.5
BT-50 MB, air supply/nozzle	1.5

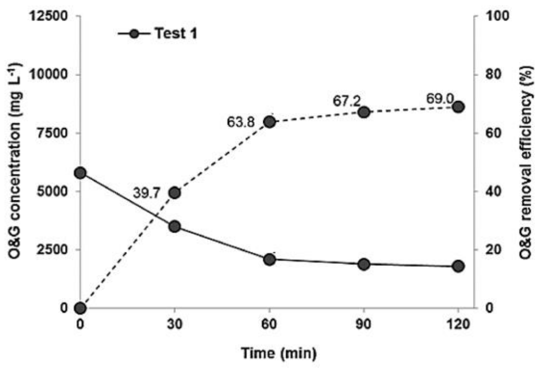

Fig. 2. O&G separation efficiency in batch CMB flotation. Solid line: O&G concetration; Dashed line: O&G removal efficiency.

The high variability in O&G concentrations in real industrial POME caused fluctuations in flotation performance, primarily because of the presence of emulsified oil droplets (<20 μm), which are more difficult to separate than free oil [16]. This aligns with findings from other studies, where prolonged retention time was necessary for achieving efficient oil-water separation in similar batch flotation systems [11].

Batch flotation for oil recovery has been extensively studied, but much research has been conducted under controlled laboratory conditions with synthetic or diluted wastewater at lower temperatures [5, 11]. Several researchers explored POME utilization but relied on bench-scale experiments [4–6, 11, 12, 16], which did not account for high organic loads and fluctuating O&G content found in real mill effluents. By contrast, the CMB flotation system in this study was tested on real mill discharge POME at high operational temperatures and at a pilot scale (hundreds of litres per cycle). This real-world evaluation ensures direct industrial applicability, addressing the challenges of oil separation from high-strength and high-temperature wastewater.

Unlike laboratory-scale studies that often achieve 92–96% separation under ideal conditions [17] or 85% efficiency with flotation pretreatment in vegetable oil wastewater [18], this study provides practical insights under dynamic industrial conditions, high O&G variability, and unmodified wastewater characteristics. The results confirm CMB flotation as a scalable, chemical-free alternative for industrial palm oil wastewater.

3.3 Continuous CMB flotation: oil recovery efficiency

The continuous-mode CMB flotation process was implemented to evaluate its oil recovery efficiency under dynamic operating conditions. Unlike batch-mode flotation, which operates under fixed retention times, continuous flotation enables higher throughput and real-time separation, making it a scalable alternative for industrial wastewater treatment. However, continuous operation introduces new challenges, including fluctuations in O&G concentration, variable retention time, and the need for precise MB distribution to sustain efficient separation.

To ensure process consistency, residual POME was fully discharged, and the system was cleaned before each operation. Fresh POME was continuously fed into the system at two flow rates: 20 L/min (Test 2) and 30 L/min (Test 3). The system consisted of two main processing tanks—a circulation tank (960 L capacity) and a flotation tank (670 L capacity)—where HRT was determined based on the POME flow rate. The system reached steady-state conditions after 81.5 minutes at 20 L/min and 54.3 minutes at 30 L/min, ensuring stabilized operating conditions for performance assessment. During each flotation run, three key sampling points were analyzed to assess O&G removal efficiency: Sampling No.1, Sampling No.2, and Sampling No.4.

The O&G removal efficiency was calculated based on the concentration difference between Sampling No.1 and Sampling No.2, while the recovered oil fraction was analyzed from

pISSN 1859-1388
eISSN 2615-9678

Sampling No.4. The operational parameters for each test are summarized in Table 3, and the corresponding treatment efficiencies are illustrated in Figure 3.

In general, the treatment efficiency in the continuous mode was lower than in batch operation, primarily because of reduced retention time and dynamic process conditions. Increasing the POME feeding flow rate from 20 L/min to 30 L/min led to a decline in O&G removal efficiency, from 36 ± 9% to 25 ± 11% (Figure 3). However, despite the lower separation efficiency, the concentration of O&G in the oil recovery tank was enriched 3 times compared with raw POME, indicating that the flotation system effectively concentrated and recovered oil.

From a hydrodynamic perspective, MB generation is a crucial factor influencing flotation efficiency. Most MB generators involve mechanical components such as pumps and nozzles, where strong shear forces affect the liquid flow, promoting bubble formation through cavitation and decompression. MBs can be generated via pressure drops in nozzle-based injection devices or gas-water circulation mechanisms [19]. Research has shown that higher recycle pressurization leads to the formation of smaller microbubbles, increasing the total air-bubble surface area and enhancing oil droplet recovery and fine particle separation [11, 19]. In this study, the air supply rates were maintained at 1.5 L/min for the pressurized MB generator and 2.5 L/min for the ejector-based MB generator, ensuring a stable pressure range of 200–250 kPa. However, pressure fluctuations were observed as POME flow rates changed, affecting microbubble behaviour and flotation stability.

Table 3. Operational parameters for continuous CMB flotation

Test	POME Flow (L/min)	Air (L/min)	HLR ($m^3/m^2.h$) flotation tank	Floated product (L/min)
Test 2	1.20	2.2.5 (Ejector), 1.5 (BT-50)	3.3.62	4.1.2
Test 3	5.30	6.2.5 (Ejector), 1.5 (BT-50)	7.5.43	8.1.4

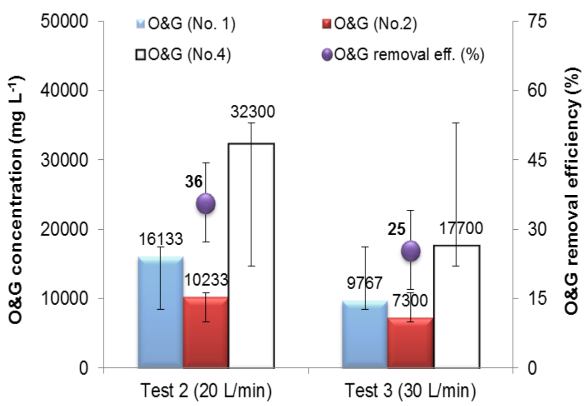

Fig. 3. O&G concentrations in influent (No.1), effluent (No.2), and oil recovery tank (No.4) at different continuous pome feeding flow rates (20 L/min and 30 L/min; temperature: 74.9 ± 4.6 °C)

3.4 Economics of the flotation technique

In wastewater treatment, the economic feasibility of a technique is influenced by multiple cost factors, including equipment purchase, operating expenses, energy consumption, chemical requirements, maintenance, installation, environmental compliance, and disposal costs. This section evaluates the economic viability of the CMB flotation technique for POME treatment, based on energy input (electricity cost) and the value of recovered palm oil. For this assessment, an average O&G concentration of 13,200 mg/L (n =

9) in raw POME was used as a reference. Under continuous-mode operation at 20 L/min, the microbubble flotation system achieved 36% O&G separation efficiency with oil enrichment of approximately 3 times in the recovery tank and a floated product volume of ~72 L after 60 minutes of treatment.

This flotation technique requires about ~6.7 kWh (energy consumption) for the treatment of 1,200 L of POME (to high as 5,400 L, pump 1) (Table 4). However, the palm oil product can be recovered about 1.9 kg O&G [(3 × 13,200 mg/L – 13,200 mg/L) × 72 L × 10^{-6}], and the treatment process can be reduced to more than 5.7 kg O&G (36% × 13,200 mg/L × 1,200 L × 10^{-6}) to discharge to the ponds system.

Presently, the industrial electricity cost per kWh in Malaysia varies from 0.05 to 0.09 USD, and that of crude palm oil is from 900 to 950 USD/ton. Thus, the cost of total energy consumption (6.7 × 0.09 = 0.60 USD to treat 1200 L of POME) was significantly lower than the cost of palm oil recovery (0.9 × 1.9 = 1.71 USD from 1200 L of POME).

Table 4. Total energy consumption of the flotation technique

Unit	Q min – Q max (L min^{-1})	Q operation (L min^{-1})	Power (kW)	Time operation (min)	Energy (kWh)
Pump 1	20 – 90	20	0.68	60	0.68
Pump 2	200 – 700	290	4.1	60	4.1
Pump 3	50 – 180	80	0.95	60	0.95
Pump 4	20 – 90	30	0.68	60	0.68
Pump 5	20 – 90	20	0.68	3.6	0.04
Air pump	200	–	0.21	60	0.21
Total energy consumption for the treatment of 1200 L of POME					6.66

4 Conclusion

This study demonstrates that cyclone microbubble flotation is an effective and scalable approach for oil recovery from POME, offering both environmental and economic advantages. The batch-mode flotation process achieved a high oil separation efficiency (~63.8%), benefiting from extended retention time, while the continuous-mode process exhibited lower efficiency (36%) but enabled higher throughput and process continuity. Despite the variation in efficiency, both flotation modes successfully enriched the oil concentration in the recovery tank 3 times, confirming the system's ability to capture and concentrate valuable oil fractions. Furthermore, the economic assessment demonstrated that the cost of energy consumption (~0.60 USD per 1,200 L of POME) is significantly lower than the monetary value of recovered oil (~1.71 USD per 1,200 L of POME), reinforcing the economic feasibility of the technique. Overall, CMB flotation proves to be a sustainable, cost-effective, and industrially viable method for POME treatment, reducing environmental impact while enhancing oil recovery potential in palm oil mills.

Acknowledgement

The author would like to express their gratitude to Yamaguchi University, Japan, for funding this research.

pISSN 1859-1388
eISSN 2615-9678

References

1. Wu TY, Mohammad AW, Jahim JM, Anuar N. A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME. Biotechnology Advances. 2009;27(1):40-52.
2. Lam MK, Lee KT. Renewable and sustainable bioenergies production from palm oil mill effluent (POME): Win–win strategies toward better environmental protection. Biotechnology Advances. 2011;29(1):124-41.
3. Malaysian Palm Oil Board (MPOB). Industry Performance 2022 – Overview of the Malaysian Palm Oil Industry; 2023.
4. Wu TY, Mohammad AW, Jahim JM, Anuar N. Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. Journal of Environmental Management. 2010;91(7):1467-90.
5. Mohammad S, Baidurah S, Kobayashi T, Ismail N, Leh CP. Palm Oil Mill Effluent Treatment Processes—A Review. 2021;9(5):739.
6. Poh PE, Chong MF. Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment. Bioresource Technology. 2009;100(1):1-9.
7. Foo KY, Hameed BH. Insight into the applications of palm oil mill effluent: A renewable utilization of the industrial agricultural waste. Renewable and Sustainable Energy Reviews. 2010;14(5):1445-52.
8. Ahmad AL, Ismail S, Ibrahim N, Bhatia S. Removal of suspended solids and residual oil from palm oil mill effluent. 2003;78(9):971-8.
9. Fobang E.Y. Application of electro-flotation method to agricultural and livestock wastewater treatment [dissertation]. [Saitama]: Saitama University Graduate School of Science and Engineering; 2023.
10. Frank NK. The Nalco Water Handbook. USA: McGraw-Hill; 1988.
11. Le TV, Imai T, Higuchi T, Yamamoto K, Sekine M, Doi R, et al. Performance of tiny microbubbles enhanced with "normal cyclone bubbles" in separation of fine oil-in-water emulsions. Chemical Engineering Science. 2013;94:1-6.
12. Azmi LHM, Elaissari A, Fatehah MO, Aziz HA, Hung Y-T. Evaluation of Coagulation-Flocculation Treatment Technologies in Palm Oil Effluent Management. In: Wang LK, Wang M-HS, Hung Y-T, editors. Industrial Waste Engineering. Cham: Springer International Publishing; 2023. p. 509-51.
13. Karno R, Arisoesilaningsih E, Purwantari RA, Widiastuti L. Effectiveness of micro-nanobubble aeration and phytoremediation in treating filtered palm oil mill effluent on bacterial diversity and water properties. Biodiversitas Journal of Biological Diversity. 2024;25(1):117-126.
14. American Public Health Association (APHA). Standard Methods for the Examination of Water and Wastewater. 22nd ed. Washington, DC: APHA, AWWA, WEF; 2012.
15. Chan YJ, Chong CH, Chew CL. Effects of operational processes and equipment in palm oil mills on characteristics of raw palm oil mill effluent (POME): A comparative study of four mills. Cleaner Waste Systems. 2023:1-10.
16. Ahmad AL, Sumathi S, Hameed BH. Coagulation of residue oil and suspended solid in palm oil mill effluent by chitosan, alum and PAC. Chemical Engineering Journal. 2006;118(1):99-105.
17. Zhao C, Zhou J, Yan Y, Yang L, Xing G, Li H, et al. Application of coagulation/flocculation in oily wastewater treatment: A review. Science of The Total Environment. 2021;765:142795.
18. Kastali M, Mouhir L, Saafadi L, Yilmaz L, Souabi S. Pretreatment of industrial wastewater by natural flotation: application to pollution reduction from vegetable oil refinery wastewaters. Environmental Science and Pollution Research. 2021;28(26):34598-610.
19. Agarwal A, Ng WJ, Liu Y. Principle and applications of microbubble and nanobubble technology for water treatment. Chemosphere. 2011;84(9):1175-80.