# FLOTATION-BASED TECHNOLOGIES FOR INDUSTRIAL WASTEWATER TREATMENT

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**Abstract:** *Flotation technologies have emerged as key processes for the treatment of industrial wastewater containing oil, grease and suspended solids. This review proposes an academic synthesis of four studies addressing flotation-based separation, unified by their focus on the removal of hydrophobic pollutants from complex industrial effluents. This paper cover: (i) the mechanistic fundamentals and design parameters of flotation processes, (ii) the optimization of dissolved air flotation (DAF) for dairy wastewater, (iii) a comparative assessment of acid-induced flotation and DAF for vegetable oil refining effluents, and (iv) the integration of induced gas flotation (IGF) assisted by micro/nanobubbles (MNBs) with ceramic membrane filtration (CMF) for oil sands process-affected water. Overall, flotation processes are most effective when carefully tailored to the physicochemical properties of the treated effluent and when integrated with complementary pre- or post-treatment steps. Despite their high efficiency, limitations such as membrane fouling, energy demand, and challenges related to large-scale implementation remain critical. This review underscores the need for optimized hybrid systems and emphasizes the central role of physicochemical interactions in improving flotation-based wastewater treatment performance.*
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**Keywords:** flotation; DAF; micro- and nanobubbles; industrial wastewater; oils and fats.

## 1. INTRODUCTION

Industrial wastewater generated from sectors such as petrochemical processing, dairy production, and edible oil refining contains complex mixtures of contaminants, including free oil, emulsified oil, and suspended solids [7,10,11]. These pollutants pose significant environmental challenges due to their stability, persistence, and resistance to conventional treatment methods [19].

Flotation remains one of the most versatile separation technologies for treating such effluents, as it exploits differences in hydrophobicity and density between contaminants and the aqueous phase [3]. Consequently, flotation-based technologies are widely applied for the removal of oil, grease, and fine particles from industrial wastewater [11,19]. Among these, dissolved air flotation (DAF), induced gas flotation (IGF), and emerging micro/nanobubble-assisted systems represent the most relevant and widely studied approaches [3,9,14].

In recent years, research has shifted from general process descriptions toward the optimization of hydrodynamic parameters and the integration of flotation with complementary treatment units, particularly membrane filtration and coagulation or acidification stages [8,15]. Despite these advancements, conventional flotation processes still exhibit limited efficiency in removing fine emulsified droplets (<20 μm), which remain a major bottleneck in wastewater treatment due to their stability and low buoyancy [4,16].

Conceptually, the methodological study on flotation mechanisms and design parameters provides the theoretical framework for interpreting the experimental findings enabling a coherent transition from fundamental principles to practical applications in dairy wastewater treatment, vegetable oil refining effluents, and oil sands process-affected water.

Across these studies, flotation performance is shown to depend critically on several factors, including wastewater characteristics, particle and droplet size distribution, operating conditions, and system design. The integration of flotation with pre-treatment or post-treatment processes further enhances efficiency, highlighting the importance of tailoring the process to the specific physicochemical properties of the treated effluent.

Accordingly, this review aims to: compare flotation technologies across different industrial applications, evaluate the influence of key operational parameters, assess the advantages of hybrid flotation-based systems, identify current limitations and research gaps.

## 2. RESULTS AND COMPARATIVE ANALYSIS

### *2.1. Performance of Dissolved Air Flotation (DAF)*

Dissolved air flotation (DAF) demonstrated strong performance in the treatment of dairy wastewater, achieving removal efficiencies of 97.8% for turbidity, 87.5% for COD, and 83.1% for color [2]. These results confirm that DAF is highly effective for the separation of dispersed oil fractions (20–150 μm) and suspended solids when operating conditions are properly optimized [2,21].

However, as highlighted by the broader mechanistic framework proposed in scientific literature, flotation efficiency is not solely governed by bubble generation, but by a complex interplay of hydrodynamic parameters, including gas holdup, flow regime, bubble size distribution, and mixing conditions [3,30]. In this context, was shown that DAF performance is inherently multi-parametric, with key variables such as air saturation pressure, recycling ratio, and coagulant dosage playing a decisive role [2].

Optimal conditions reported (10 bar saturation pressure, 20% recycle ratio, pH ~4, and 250 mg/L $FeSO_4$) indicate that DAF becomes significantly more robust when coupled with chemical conditioning of the influent [2,5,27]. Nevertheless, despite its effectiveness, DAF remains limited in removing fine emulsified droplets (<20 μm), which reduces its standalone applicability in highly stable emulsions [2,5,27].

### *2.2. Acid-Induced Flotation vs. DAF*

The comparative study on vegetable oil refining wastewater provides further insight into the limitations of conventional DAF [1]. Results show that acid-induced flotation at pH of 3 significantly outperforms DAF, achieving oil removal efficiencies of 99.24% and COD reduction of 93.4% [1,22].

From a mechanistic perspective, this improvement can be attributed to enhanced droplet coalescence, charge neutralization, and increased bubble–oil attachment efficiency under acidic conditions [1,15]. The findings suggest that, in effluents rich in hydrophobic compounds such as vegetable oils, destabilization of emulsions through acidification can be more effective than relying solely on bubble-mediated separation [8,15].

However, these benefits come at the cost of increased chemical consumption and potential corrosion issues, raising concerns regarding operational sustainability and economic feasibility. Therefore, while acid flotation can surpass DAF in performance, its practical implementation requires careful evaluation of trade-offs [1,15].

### *2.3. Induced Gas Flotation with Micro/Nanobubbles*

It was observed that when is used induced gas flotation (IGF) based on the formation of micro/nanobubbles (MNBs) [4]. The incorporation of MNBs extends the operational capability of flotation systems, enabling the removal of much finer droplets [4,9].

Key findings include [4]:

- reduction of minimum floatable droplet size to 7.6 µm
- increase in oil removal efficiency by approximately 11%
- increase in suspended solids removal by approximately 19%

These improvements can be explained by the unique physicochemical properties of MNBs, including increased surface area, prolonged residence time, and enhanced collision probability with fine particles [9,12,14].

Table 4. Effect of operational parameters in IGF [3, 4, 9, 19]

| Parameter | Effect on performance |
|---|---|
| Bubble size | Smaller bubbles → higher efficiency |
| Injection ratio | Higher ratio → improved removal |
| pH | Lower pH → enhanced flotation |
| Gas type | $N_2 \approx$ air > $CO_2$ |

Some studies [3] reveal that bubble size distribution and hydrodynamics are central to flotation performance [3,20]. Unlike conventional DAF, IGF with MNBs partially overcomes the limitation related to fine emulsified droplets, although complete removal remains challenging without additional treatment stages [4,19].

### *2.4. Hybrid IGF–CMF System*

The integration of IGF with ceramic membrane filtration (CMF) represents a shift from standalone flotation toward hybrid treatment systems [4,8]. In this configuration, flotation acts as a pre-treatment step, reducing the load of oil and suspended solids before membrane filtration [4,21].

Table 5. Results of Hybrid IGF–CMF System [4]

| Parameter | IGF only | IGF + CMF |
|---|---|---|
| Oil concentration | 32–106 mg/L | <7 mg/L |
| SS removal | moderate | near complete |

This hybrid approach offers several advantages [4]:

- improved effluent quality
- reduced membrane fouling rate
- elimination of chemical additives

However, a typical trade-off associated with hybrid systems is observed: the presence of residual nanobubbles slightly reduces membrane flux due to partial pore blocking and increased interfacial resistance [4,21]. Despite this limitation, the overall system performance remains superior due to enhanced stability and reduced fouling over time [4].

### *2.5. Integrated Critical Interpretation*

Flotation efficiency is not determined by a single parameter, but by the interaction between hydrodynamics, water chemistry, and pollutant characteristics. In scientific literature is shown that the theoretical backbone for understanding system behavior [3], process optimization and chemical conditioning are essential for high performance [2], highlights the dominant role of pH in destabilizing emulsions [1]. The IGF–CMF study shows that integration with advanced technologies is necessary to overcome limitations related to fine particles and long-term stability [4].

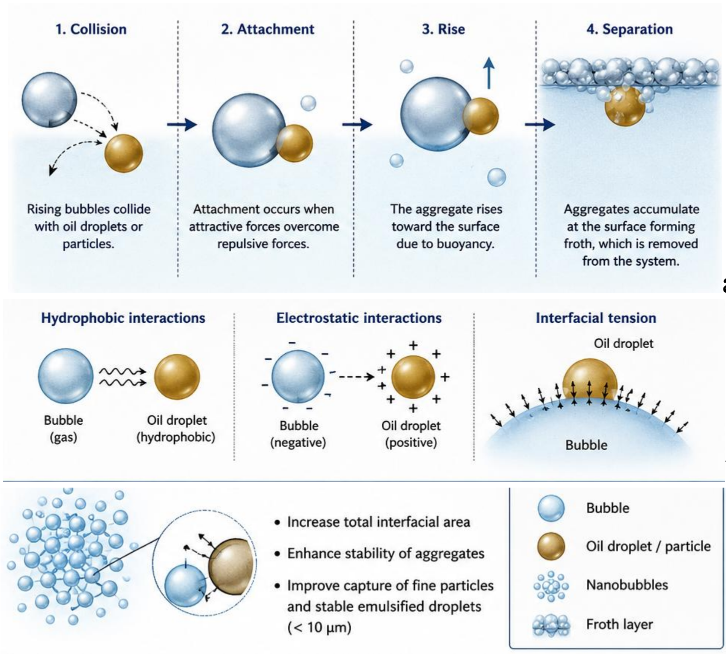
## 3. MECHANISMS

Flotation efficiency is fundamentally governed by microscale interactions occurring at the interface between gas bubbles, oil droplets, and suspended particles [3,13]. At this scale, separation performance is controlled by the balance between hydrophobic forces, electrostatic interactions, and interfacial tension [3]. These physicochemical interactions determine whether particles and droplets will successfully interact with rising bubbles or remain dispersed in the bulk liquid.

The flotation process proceeds through a sequence of key mechanisms. Initially, collisions occur between rising gas bubbles and dispersed oil droplets or solid particles [3,13]. The frequency of these collisions depends on hydrodynamic conditions, including bubble size distribution, gas holdup, and flow regime [3,12,20]. Following collision, attachment takes place if attractive forces overcome repulsive barriers, leading to the formation of stable bubble–particle or bubble–droplet aggregates [9,12]. Once formed, these aggregates rise toward the surface due to buoyancy, where they accumulate and form a froth layer that can be removed, thus achieving phase separation [ 4,9,12,19].

The incorporation of nanobubbles significantly enhances these mechanisms due to their unique physicochemical properties. Their extremely small size increases the total interfacial area available for interaction, thereby improving collision probability. In addition, nanobubbles exhibit high surface energy and stability, which promotes stronger attachment between bubbles and fine particles. As a result, they improve the stability of formed aggregates and enable the efficient capture of fine and stable emulsified droplets, typically below 10 µm, which are difficult to remove using conventional flotation systems. [4,19]

The overall separation performance is determined by the dynamic of bubbles, droplet and particles. The interaction at microscale involves electrostatic and hydrophobic interactions and interfacial tension. At first, suspended particles and oil droplets collide with the rising bubble, being influenced by bubble size, gas holdup and hydrodynamic conditions. The formation of aggregates is influenced by the overcame of repulsive force by the attractive force. These aggregates rise at the surface where they are removed thus achieving the separation of pollutants. Nanobubbles have some advantages: high surface area, high surface energy, strong attachment and stability of aggregates Fig.1.



a) b) c)

Figure 1. a) Mechanisms of flotation; b) microscale interaction and c) the role of micro/nanobubbles in enhancing separation efficiency.

Fig. 1 1 illustrates the fundamental stages of the flotation process, including bubble–particle collision, attachment, rise, and separation through froth formation. At the microscale, flotation efficiency is governed by hydrophobic interactions, electrostatic forces, and interfacial tension between gas bubbles and oil droplets. The lower section highlights the role of micro- and nanobubbles, which increase interfacial area, enhance collision probability, and improve the stability of bubble–particle aggregates. These effects enable the effective removal of fine emulsified droplets (<10 μm), which are typically resistant to conventional flotation processes.

## 4. CRITICAL DISCUSSION

A first key aspect is the dominant role of process parameters controlling bubble-particle interactions. Across all studies, flotation efficiency is strongly influenced by bubble size, gas concentration, residence time, and pH [3,14]. These parameters directly affect collision frequency, attachment probability, and aggregate stability, confirming that flotation is fundamentally governed by hydrodynamic and interfacial phenomena rather than by a single operational variable. [3,20]

A second important observation concerns the role of the wastewater matrix. The results demonstrate that performance achieved in one type of effluent cannot be directly transferred to another. Variations in organic loading, salinity, emulsion stability, and particle size distribution significantly alter separation mechanisms [11,19]. For instance, while DAF performs well in dairy wastewater under optimized conditions [2], acid-induced flotation proves more effective in highly hydrophobic effluents such as vegetable oil wastewater. This highlights the necessity of tailoring flotation processes to the specific physicochemical characteristics of each wastewater stream [1,15].

A third major trend is the transition toward hybrid systems. The integration of flotation with complementary processes-such as coagulation, acidification, or membrane filtration-consistently leads to improved performance [5,6,8]. In particular, the combination of IGF with ceramic membrane filtration demonstrates how flotation can be effectively used as a pre-treatment step to enhance downstream separation efficiency and reduce fouling [4, 21]. This shift reflects a broader evolution from standalone unit operations toward integrated treatment trains.

Despite these strengths, several limitations are consistently reported across the studies. High removal efficiencies (typically exceeding 80–99%) are achievable, but often under controlled or optimized conditions that may not fully reflect industrial complexity. Flotation performance remains highly sensitive to droplet size, especially for stable emulsions below 20 μm [14,19]. In addition, energy consumption associated with pressurization (DAF) or gas injection (IGF), as well as chemical dependency in acid flotation, raises concerns regarding operational sustainability [1,4,15]. In hybrid systems, membrane fouling and flux reduction remain critical challenges, even when flotation is used as a pre-treatment step.

From a research perspective, several gaps limit the direct applicability of current findings. A major issue is the limited validation on real industrial wastewater, as some studies rely on synthetic or controlled systems that do not fully capture real-world variability. Furthermore, there is a lack of standardized comparison metrics, as different studies report performance using non-uniform indicators, complicating direct evaluation. Equally important is the absence of comprehensive analyses of energy consumption and operational costs, as well as a lack of clearly defined scale-up criteria for industrial implementation.

These aspects should be addressed through a unified evaluation framework based on common performance categories, including removal efficiency, operational stability, chemical consumption, energy demand, and impact on downstream processes. Such an approach would enable a more consistent comparison of flotation technologies and support their transition from laboratory-scale studies to full-scale industrial applications.

## 5. CONCLUSIONS

Flotation technologies remain essential for the treatment of industrial wastewater containing oil, grease, and suspended solids, due to their versatility and adaptability to a wide range of effluent characteristics. Flotation processes can be effectively tailored to diverse industrial applications when the underlying mechanisms and control parameters are properly understood.

The study on dairy wastewater confirms that dissolved air flotation (DAF) can achieve high removal efficiencies when supported by careful optimization of operational and chemical conditions. In contrast, the comparative analysis of vegetable oil refining wastewater shows that acid-induced flotation can outperform DAF under specific conditions, particularly in systems dominated by stable hydrophobic emulsions. Furthermore, the investigation of oil sands process-affected water demonstrates the potential of integrating induced gas flotation (IGF) with micro/nanobubbles and ceramic membrane filtration, emphasizing the advantages of hybrid treatment configurations.

Future industrial applications will increasingly rely on hybrid flotation-based systems, designed through an integrated understanding of hydrodynamic behavior and wastewater chemistry.

Future research should therefore focus on: the optimization and scaling of hybrid systems, reduction of energy consumption and chemical dependency, validation under real industrial conditions and development of standardized performance metrics for cross-study comparison.

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