

*Original Research*

# Application of Dissolved Air Flotation in Metal Plating Wastewater Treatment: A Life Cycle Perspective

**Dilsad Elif Ozturk, Baris Canci, Neslihan Manav-Demir\***

Yildiz Technical University, Environmental Engineering Department, Esenler, Istanbul, 34220, Türkiye

*Received: 01 September 2025*

*Accepted: 08 November 2025*

## Abstract

The metal plating industry is among the most rapidly developing and widely used industrial processes worldwide, consuming large amounts of water and generating significant environmental problems due to its wastewater. In this study, real wastewater from the metal plating industry was treated, and heavy metals were removed using a pilot-scale treatment process with a total volume of approximately 2.2 m<sup>3</sup>. The process consisted of sequential coagulation, flocculation, and dissolved air flotation (DAF), which was employed to reduce the area required for sedimentation. Initially, laboratory-scale studies were conducted to optimize the mixing speed, as well as the coagulant/flocculant type and dosage. Pilot-scale studies were then conducted. The study yielded removal efficiencies for COD, Cu, Ni, Zn, CN<sup>-</sup>, Cr<sup>+6</sup>, and SO<sub>4</sub><sup>2-</sup> in the coagulation/flocculation/DAF (CF-DAF) process of 83%, 33%, 94%, 99%, 46%, 99%, and 90%, respectively. Additionally, a life cycle assessment was performed using two different methods (ReCiPe 2016 Midpoint (H) and Environmental Footprint 3.1 (EF 3.1)). Environmental impact categories of the process, such as climate change, eutrophication, human toxicity, and resource depletion, were determined, and the factors that provided the highest contribution were identified.

**Keywords:** metal plating wastewater, dissolved air flotation, life cycle assessment (LCA), wastewater treatment, heavy metal removal

## Introduction

Due to the growing population and developing technology, industrial activities are continuously increasing, leading to the consumption of natural resources. Among these, freshwater is of particular concern, as the amount of readily accessible fresh water worldwide is less than 1% [1], and the treatment and

recovery of wastewater, thereby the protection of water resources, have gained great importance in recent years.

One of the most prominent and rapidly developing industrial sectors that generates considerable wastewater is the metal plating industry. This sector has gained momentum with the rise of the automotive industry in the 1960s and has become one of the leading industrial activities in Türkiye, serving multiple sectors such as automotive, white goods, electronics, and metal products [2].

In the metal plating industry, various materials are processed depending on their intended use, such

\*e-mail: nmanav@yildiz.edu.tr  
Tel.: +90-212-383-5397

as coating and rinsing. Among all, rinsing baths are particularly critical, as the water becomes heavily polluted due to the accumulation of contaminants through repeated bath cycles. Metal plating wastewater (MPW) generated after plating baths and rinsing processes may contain oil, grease, and other organic compounds; heavy metals including chromium ( $\text{Cr}^{+6}$ ), copper (Cu), zinc (Zn), lead (Pb), nickel (Ni), iron (Fe), cyanide ( $\text{CN}^-$ ) compounds [3]; along with various chemicals, organic or inorganic acids and bases, and a range of other cations and anions [4, 5].

Various treatment methods are employed for the treatment of large volumes of MPWs [6] and the removal of heavy metals, which pose a significant threat to the environment. These technologies include chemical precipitation, coagulation-flocculation (CF), ion exchange, adsorption, electrolysis, electrodialysis, evaporation, solvent extraction, flotation, and membrane processes such as ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) [7, 8]. The selection of the treatment method should be based on compliance with the discharge standards, removal efficiency, ease of operation, and cost-effectiveness [8]. Although many of these treatment methods are effective in heavy metal removal, their success in terms of water recovery is limited [9], and chemical precipitation is the most commonly employed method for this reason [10].

Dissolved air flotation (DAF) is a solid-liquid separation process in which particles are removed from the liquid phase by flotation. The underlying mechanism involves the attachment of hydrophobic particles to rising air bubbles through collision [11], followed by the formation and aggregation of small air bubbles (less than 100  $\mu\text{m}$ ) within the foam phase [12]. The buoyancy force acting on these bubble-particle clusters causes them to rise to the water surface, where they are collected and removed as foam [13]. These systems operate in two sequential stages: CF followed by DAF for enhanced particle separation. In the absence of coagulation pretreatment, particles in the feed water predominantly carry negative surface charges, resulting in electrostatic repulsion upon close approach, which inhibits their agglomeration [14]. The efficiency of the process depends on several factors, including bubble size distribution, which influences collision and attachment probabilities; aeration rate; hydrodynamic conditions such as flow regime and residence time; and physicochemical properties of the influent, such as pH, ionic strength, surface charge, and the presence of surfactants and coagulants. In addition, the overall efficiency is a function of tank geometry, baffle configuration, impeller design, and dimensions. These factors significantly influence fluid dynamics and bubble-particle interactions.

DAF is a high-efficiency process that is frequently used in industrial applications as an alternative to final sedimentation [15]. Due to its operational flexibility and superior performance in removing suspended solids, oil, grease, and some heavy metals, DAF has

become a valuable process, particularly in industrial wastewater treatment systems such as food processing, pulp and paper, petrochemicals, and metal plating [16-18]. Compared to conventional systems, the CF-DAF system offers advantages such as improved removal of small and low-density particles [14], a shorter hydraulic retention time, and lower operational costs [19, 20]. As a result, it has found widespread application in treatment systems as an effective alternative to sedimentation-based particle separation techniques.

In industrial applications where heavy metal removal is the primary objective, the integration of advanced treatment methods such as DAF is critical for enabling closed-loop water reuse systems. These systems increase resource efficiency and reduce operating costs by reducing freshwater intake and wastewater discharge [21]. For instance, Barredo-Damas et al. [22] used a CF-DAF system and reported 99% turbidity removal and 84-98% color removal. Similarly, a 90% reduction in marine ecotoxicity and an 84% reduction in aquatic eutrophication were reported for an integrated CF-DAF system in Tüpraş Petroleum Refinery in Kocaeli, Türkiye [23].

Life Cycle Assessment (LCA) is a key tool in environmental impact evaluation, providing a quantitative analysis of the environmental effects associated with all stages of a product or process – from raw material extraction to final disposal [24]. This holistic approach considers factors such as energy consumption, chemical usage, and emissions, helping to identify major sources of environmental impact and supporting decision-making toward the development of sustainable technologies [24, 25]. LCA is widely applied in the wastewater treatment sector as well, enabling a comprehensive assessment of treatment processes and revealing opportunities for environmental performance improvement [25]. In particular, LCA studies on the treatment of metal plating wastewater have shown that innovative processes – such as recovery of plating baths using magnetic nanoparticles – can reduce environmental impacts by up to 98% compared to conventional disposal methods [26, 27].

In this study, a pilot-scale integrated system, which involves  $\text{CN}^-$  and  $\text{Cr}^{+6}$  removal, as well as CF and DAF steps, was developed for treating real MPW. The system's performance was evaluated for the removal of toxic heavy metals. The study first determined the most appropriate coagulant type, dosage, and mixing speed, followed by pilot-scale studies. Furthermore, the entire integrated system was evaluated through an LCA, and its environmental impacts were determined.

## Materials and Methods

### Real Metal Plating Wastewater

In this study, real MPW collected from a plating facility in Istanbul, Türkiye, was used. The wastewater

in the facility originates from three main sources: CN<sup>-</sup>-containing wastewater (20 m<sup>3</sup>/day), Cr<sup>+6</sup>-containing wastewater (20 m<sup>3</sup>/day), and wastewater generated from the metal washing process (60 m<sup>3</sup>/day).

Cyanide oxidation was performed using 0.1 N sodium hydroxide (NaOH) and 1% sodium hypochlorite (NaOCl). Subsequently, Cr<sup>+6</sup> removal from Cr<sup>+6</sup>-containing wastewater stream was carried out using 0.1 N hydrochloric acid (HCl) and 20% sodium metabisulfite (Na<sub>2</sub>S<sub>2</sub>O<sub>5</sub>). After the pretreatment of individual sources, all three wastewater streams are mixed. pH measurements were conducted using an Emec pH meter, while chemical oxygen demand (COD) analysis was performed in the USEPA 410.4 method, utilizing a CHEMetrics COD photometer for the measurements. The Bathocuproine Disulfonic Acid method, Dimethylglyoxime method, 4-(2-pyridylazo)resorcinol (PAR) method, Diphenylcarbazide method, Barium sulfate method, and ISO6703/EPA 335.2 methods were employed for the determination of Cu, Ni, Zn, Cr<sup>+6</sup>, SO<sub>4</sub><sup>2-</sup>, and CN<sup>-</sup>, respectively, using a Hach Lange DR3900 spectrophotometer. The characterization of the mixed wastewater stream was determined as: pH = 2.33±0.11, COD = 415±25 mg/L, Cu = 1.45±0.16 mg/L, Ni = 5.30±0.45 mg/L, Zn = 12.1±0.40 mg/L, CN<sup>-</sup> = 0.25±0.03 mg/L, Cr<sup>+6</sup> = 5.64±0.11 mg/L, and SO<sub>4</sub><sup>2-</sup> = 2395±29.31 mg/L.

### System Description and Operation Conditions

CF-DAF processes were used for the treatment and recovery of metal plating industry wastewater, respectively. The flowchart of the pilot-scale process is shown in Fig. 1. Jar test studies were conducted under laboratory conditions with an active volume

of 250 mL to determine the best coagulant type, optimum coagulant dosage, polyelectrolyte type, and optimum polyelectrolyte dosage. The chemicals used in the study, the conditions applied in each test, and the concentrations were given in Table 1.

The chemicals used in the experiments were selected based on the studies of Zuo et al. [28] (5% CaCO<sub>3</sub>), Ettaloui et al. [29] (40% FeCl<sub>3</sub>), Ebba et al. [30] (0.1 N NaOH), and Gupta et al. [31] (0.1 N Ca(OH)<sub>2</sub>). In addition, Prazeres et al. [32] used doses ranging from 100 to 1000 mg/L for FeCl<sub>3</sub>, Solmaz et al. [33] applied doses between 0.25 and 2 mg/L for AP, Ariase and Wikaningrum [34] used doses of 60 to 150 mg/L for PAC, and finally, Bidhendi et al. [35] used doses ranging from 50 to 500 mg/L for Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>. In the coagulation step, the mixing speed was 1000 rpm, and the mixing time was 6 min, while in the flocculation step, it was 100 rpm and 9 min. After determining the appropriate coagulant type and dosage, two additional mixing speeds (100 and 2000 rpm) were tested in the coagulation step to determine the optimum mixing speed, considering the maximum removal efficiency and minimum chemical use. During the study, flocculation was followed by a half-hour sedimentation process.

### DAF (Dissolved Air Flotation system)

The pilot-scale DAF unit has a width of 0.723 m, a length of 1.708 m, a total height of 1.764 m, and a surface area of 1.23 m<sup>2</sup>. The pilot-scale DAF process was operated at pH 8, 200 µm bubble diameter, 3-4 bar pressure, and approximately 53 min contact time. DAF was operated with a flow rate of 1 m<sup>3</sup>/h, an air flow rate of 1.3 mL/min, and a hydraulic loading rate of 2 m<sup>3</sup>/m<sup>2</sup>h during the study. DAF was operated at 3-4 bar saturation pressure and without water recirculation. Scraper

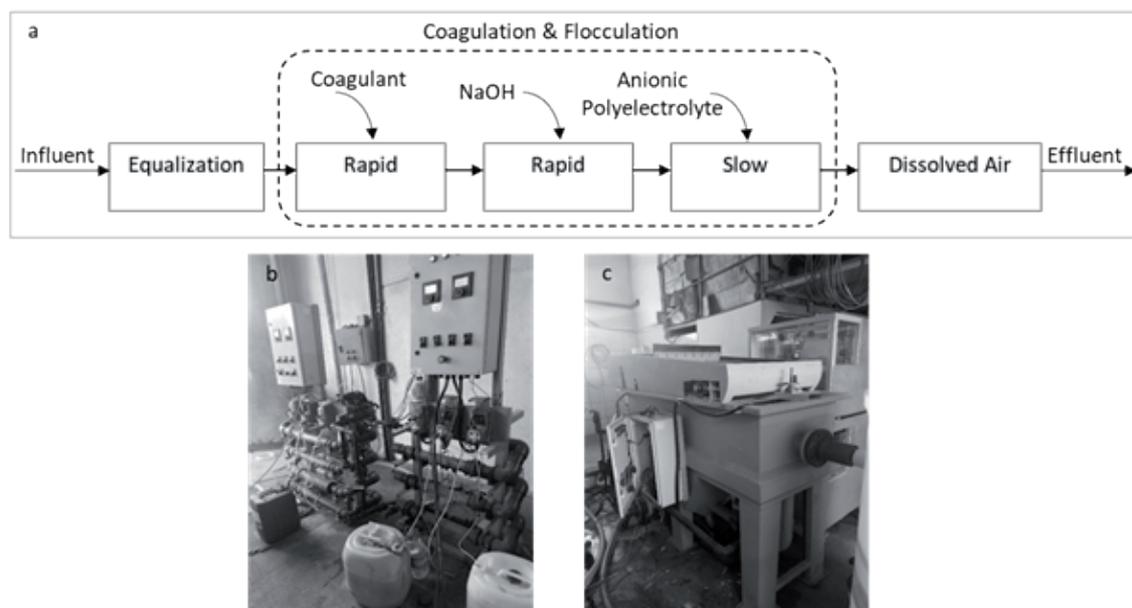


Fig. a) Flowchart of process, b) pilot-scale coagulation & flocculation, and c) pilot-scale DAF.

Table 1. Types and concentrations of chemicals (coagulant, flocculant, and aid) used in the study.

Steps	Coagulant & Flocculant	Dosage (mg/L)
Set 1	CaCO <sub>3</sub> (5%) – FeCl <sub>3</sub> (40%) – AP (%01)	150–280–1.5
Set 2	CaCO <sub>3</sub> (5%) – PAC (17%) – AP (%01)	150–51–1
Set 3	CaCO <sub>3</sub> (5%) – Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (20%) – AP (%01)	150–290–0.5
Set 4	NaOH (0.1 N) – FeCl <sub>3</sub> (40%) – AP (%01)	1.2–240–0.5
Set 5	NaOH (0.1 N) – PAC (17%) – AP (%01)	1–42.5–0.25
Set 6	NaOH (0.1 N) – Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (20%) – AP (%01)	1.2–150–0.25
Set 7	Ca(OH) <sub>2</sub> (0.1 N) – FeCl <sub>3</sub> (40%) – AP (%01)	2.78–180–0.25
Set 8	Ca(OH) <sub>2</sub> (0.1 N) – PAC (17%) – AP (%01)	2.59–42.5–0.5

PAC: Polyaluminium chloride, AP: Anionic polyelectrolyte

engine's power is 0.37 kW@380V AC and 9 rpm. The energy consumption is 2.96 kWh per day for an 8-hour working schedule per day. The wastewater pump is 0.55 kW@380V AC and 1440 rpm. All experiments were performed at room temperature (25±2°C). After every flotation run, the supernatant was collected and analyzed.

### LCA Methodology

In the study, the system boundaries of the process were established in accordance with the LCA main phases, i.e., (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results. All relevant processes, as well as associated inputs and outputs within these boundaries, were identified and defined. The scope was determined in alignment with the objective of the study, ensuring a comprehensive and consistent framework for data collection and analysis. The LCI phase involved the compilation of data on all inputs (e.g., chemicals, fuels, and energy) and outputs (e.g., emissions to air, water, and soil, and solid waste) associated with the defined system. These data were collected from operational records and supported by secondary data sources where necessary. In the LCIA

phase, environmental impacts associated with the system were assessed using characterization models. For this study, the ReCiPe 2016 Midpoint (H) and Environmental Footprint 3.1 (EF 3.1) methods were employed to quantify environmental impact categories such as climate change, eutrophication, human toxicity, and resource depletion. The final phase, interpretation, focused on the analysis of the results in order to identify major contributors to environmental impacts and to propose potential improvement strategies for reducing these impacts within the defined system boundaries.

### Software and Database

The LCA was performed using SimaPro® software (version 9.4.0.3), a widely used tool for life cycle modeling and environmental impact assessment. Inventory data for the inputs were primarily obtained from the Ecoinvent database (version 3.5), integrated within the SimaPro® platform. Environmental impacts were calculated using the aforementioned impact assessment methods. The system boundaries determined in accordance with the study's goal and scope are illustrated in Fig. 2.

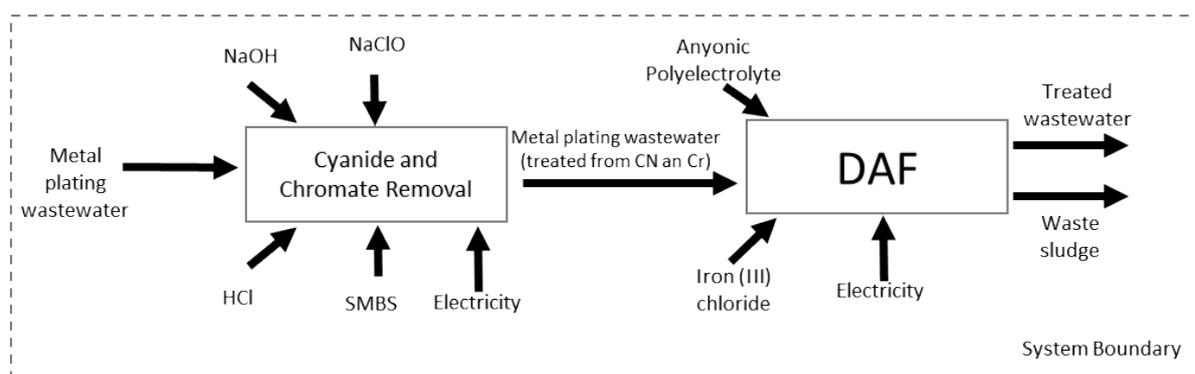


Fig. 2. System boundaries of pilot-scale process.

Table 2. Inputs and outputs within the system boundaries.

Inputs (Chemicals)		
Material	Value	Unit
Anionic Polyelectrolyte	0.036	g
Hydrochloric acid	2.7	g
Sodium hypochlorite	22.5	g
Sodium hydroxide	18	g
Sodium metabisulphite	0.03	g
Iron(III) chloride	17.28	g
Inputs (electricity, heat)		
Material	Value	Unit
Electricity	70	kWh
Emissions to water		
Material	Value	Unit
COD	415	mg
Copper	1.41	mg
Zinc	11.7	mg
Cyanide	200	mg
Nickel	4.99	mg
Sulfate	2430	mg
Chromate	118	mg
Final waste flows		
Material	Value	Unit
Sludge	212.5	kg

The inputs and outputs associated with the processes were determined within the established system boundaries. Accordingly, the inventory corresponding to these boundaries is based on the collected data and is provided in Table 2.

## Results and Discussion

### Jar Test Experiment Sets

The effluent concentrations obtained using different types and dosages of coagulants and flocculants are shown in Fig. 3. The left panel in the figure (Fig. 3a) shows the pH values in all sets while the influent pH is 2.33. The panel on the right-hand side (Fig. 3b) is a combination of bar diagrams showing the percent discrepancies between the influent and the effluent concentrations for seven pollutant species (Cu, Ni, Zn, CN<sup>-</sup>, Cr<sup>+6</sup>, SO<sub>4</sub><sup>2-</sup>, and COD). The values in Fig. 3b) can be interpreted as removal efficiencies. The highest removal efficiencies were obtained for COD at Sets 4 and 5, Cu at Set 4, Ni at Set 7, Zn at Set 4, CN<sup>-</sup> at Set

2, Cr<sup>+6</sup> at Set 6, and SO<sub>4</sub><sup>2-</sup> at Set 2, with high observed removal efficiencies in all sets. In addition to coagulant and flocculant dosage and type, the effect of mixing speed was also investigated at this stage. Although the highest removal efficiencies for the analyzed pollutant parameters were obtained in different sets, the removal efficiencies for COD, Cu, Ni, Zn, CN<sup>-</sup>, Cr<sup>+6</sup>, and SO<sub>4</sub><sup>2-</sup> in Set 4 were determined as 70%, 15%, 88%, 99%, 46%, 99%, and 81%, respectively, and thus, removal efficiencies closest to the maximum values for all parameters were achieved only in Set 4. In this set, flocs were observed to form more rapidly and distinctly. Therefore, Set 4 was selected for mixing speed optimization in the coagulation step, and two additional mixing speeds (100 and 2000 rpm) were tested. At this stage, no conclusive results could be obtained for the applied mixing speeds; however, it was observed that the optimum speed among the applied speeds was 1000 rpm.

### DAF Experimental Analysis Data

In the study, removal efficiency trends for all parameters were observed to be similar in both laboratory- and pilot-scale experiments. While lower removal efficiencies were obtained for Cu and CN<sup>-</sup> in both studies, removal efficiencies for all other parameters were found to exceed 70% in laboratory-scale experiments and 80% in pilot-scale experiments. The effluent concentrations and removal efficiencies obtained from the pilot-scale DAF experiments are presented in Table 3. The pH of the treated effluent remained relatively stable (7.6±0.3), which is important for complying with discharge standards for receiving water bodies. The COD concentration was reduced to 70±5.5 mg/L, with an average removal efficiency of 83±1.3%, indicating that the DAF process was effective in removing COD from this type of wastewater. The removal performance of the DAF process for the analyzed heavy metals varied. The lowest removal efficiency (33±11.1%) was observed for Cu, which may be attributed to its speciation or competition with other metal ions. In contrast, Ni and Zn exhibited very high removal efficiencies of 94±0.4% and 99±0.1%, respectively, demonstrating that the treatment method is well-suited for these specific contaminants. Similarly, Cr<sup>+6</sup> removal reached 99±0.1%, confirming the effectiveness of the applied chemical-physical processes in eliminating this highly toxic metal species. Cyanide (CN<sup>-</sup>), a critical contaminant in MPW due to its acute toxicity, was removed with a moderate efficiency of 46±9.2%. This suggests that while the applied treatment contributed to CN<sup>-</sup> degradation, additional or complementary treatment steps, such as advanced oxidation or specialized chemical oxidation, may be required to meet regulatory limits. SO<sub>4</sub><sup>2-</sup> removal was also high at 90±0.9%, which is particularly important as elevated sulfate concentrations can lead to environmental concerns in receiving water bodies.

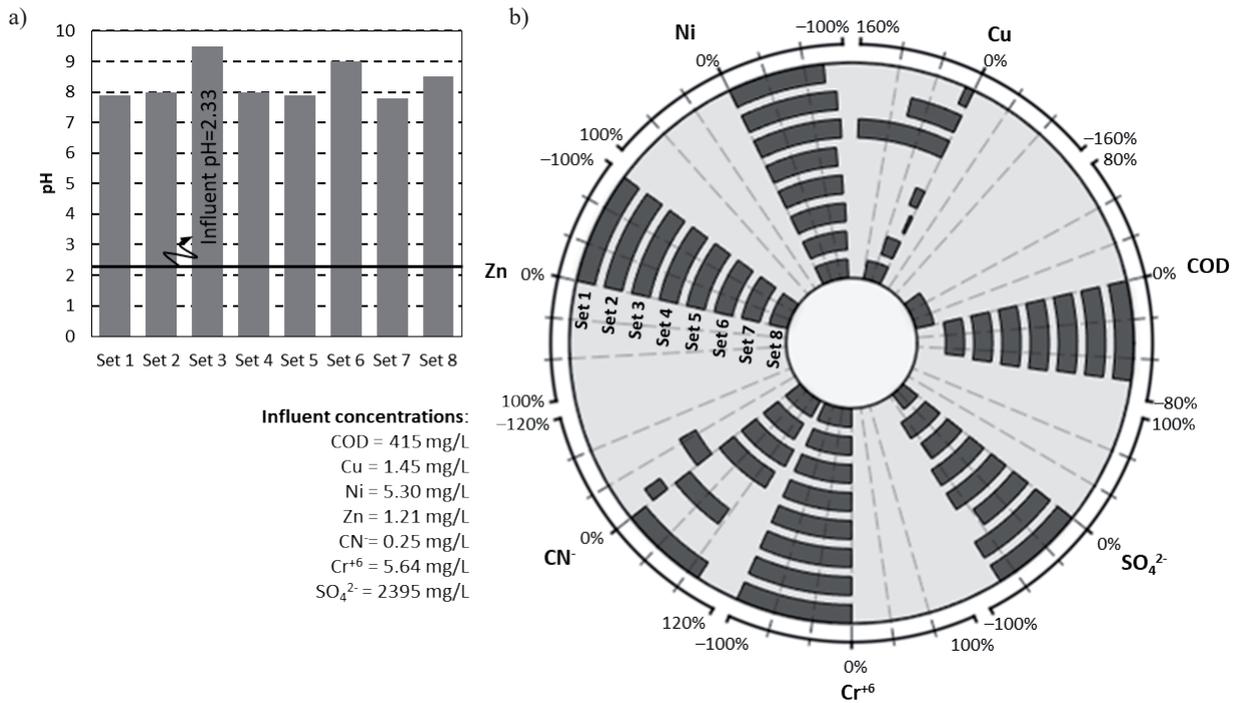


Fig. 3. Influent and effluent characteristics in different steps. a) pH values, b) percent discrepancies with respect to the influent concentrations.

Overall, the DAF process demonstrated high removal efficiencies, particularly for COD, Ni, Zn, Cr<sup>+6</sup>, and SO<sub>4</sub><sup>2-</sup>. However, the relatively low removal efficiencies for Cu and CN<sup>-</sup> indicate that process optimization or integration with additional treatment technologies may be necessary to further improve overall performance. Filho et al. [36] used polyaluminum chloride and cationic polyacrylamide in their study with acid mine drainage. The study reported that the best results were obtained with a polymer flocculant concentration of 20 mg/L, a saturation pressure of 5 atm, and a pH of 4.5, rapidly reducing the sulfate concentration of 1753 mg/L to below 500 mg/L, indicating that the DAF

unit is a suitable process for removing high sulfate concentrations. In another study by Azevedo et al. [37], iron hydroxide and cationic polyacrylamide were used. Pb<sup>2+</sup> and Cu<sup>2+</sup> removal efficiencies of over 95% were achieved in the DAF unit operated at 6 bar saturation pressure and 20% water recycling rate. In another study, it was stated that the use of DAF as a pretreatment for low-pressure membranes provided lower DOC levels compared to the use of a sedimentation tank [14]. Pooja et al. [12] investigated toxic metal removal from electroplating industry wastewater using the DAF process and reported that a maximum removal efficiency of 97.39% was achieved for Cd, Pb, Cu, Cr<sup>+6</sup>, and Ni at pH 8.0, a surfactant dosage of 0.2 g, a contact time of 60 min, and a pressure of 137.89 kPa.

Table 3. DAF effluent pollutant concentrations and removal efficiencies.

Parameter	Effluent conc. (mg/L)	Removal efficiency (%)
pH	7.6±0.3	-
COD (mg/L)	70±5.5	%83±1.3
Cu (mg/L)	0.97±0.2	%33±11.1
Ni (mg/L)	0.318±0.021	%94±0.4
Zn (mg/L)	0.077±0.005	%99±0.1
CN <sup>-</sup> (mg/L)	0.086±0.023	%46±9.2
Cr <sup>+6</sup> (mg/L)	0.021±0.003	%99±0.1
SO <sub>4</sub> <sup>2-</sup> (mg/L)	245±20.9	%90±0.9

### LCA Results

LCA was performed using SimaPro software with the ReCiPe 2016 midpoint and EF 3.1 methods. The characterization and normalization results obtained using the ReCiPe 2016 method are presented in Fig. 4. Fig. 4a) shows that the CN<sup>-</sup> and Cr<sup>+6</sup> removal processes were the predominant factors in all environmental impacts, except the Water Consumption category in the characterization results. The reason for this is probably that the MPW entering CN<sup>-</sup> and Cr<sup>+6</sup> discharge has elevated levels of COD and heavy metals. The input with the second-greatest contribution to the assessed environmental impact is electricity. Notably, the electricity used in the process is generated from fossil

fuels. According to the normalization results in Fig. 4b), a comparison of the environmental impact categories reveals that the foremost five categories in this process are Freshwater Ecotoxicity, Marine Ecotoxicity, Human Carcinogenic Toxicity, Freshwater Eutrophication, and Water Consumption, in descending order. The elevated freshwater ecotoxicity classification is attributed to the detrimental effects of heavy metals present in MPW on the marine ecosystem. Sabeen et al. [38] conducted an LCA of the treatment of Ni-plating wastewater. In the study conducted, the categories of Human Toxicity,

Terrestrial Ecotoxicity, Climate Change, Freshwater Ecotoxicity, and Terrestrial Acidification scored higher than other environmental impact categories, and it was stated that increasing electricity consumption increases environmental impact scores. In this respect, the results obtained are consistent with those obtained in this study. Rodriguez et al. [27] conducted an LCA of the chemical treatment and DAF process for treating MPW. The results obtained showed that in both treatment methods, global warming and human toxicity were the highest categories, while a comparison between the treatment processes indicated that the DAF process

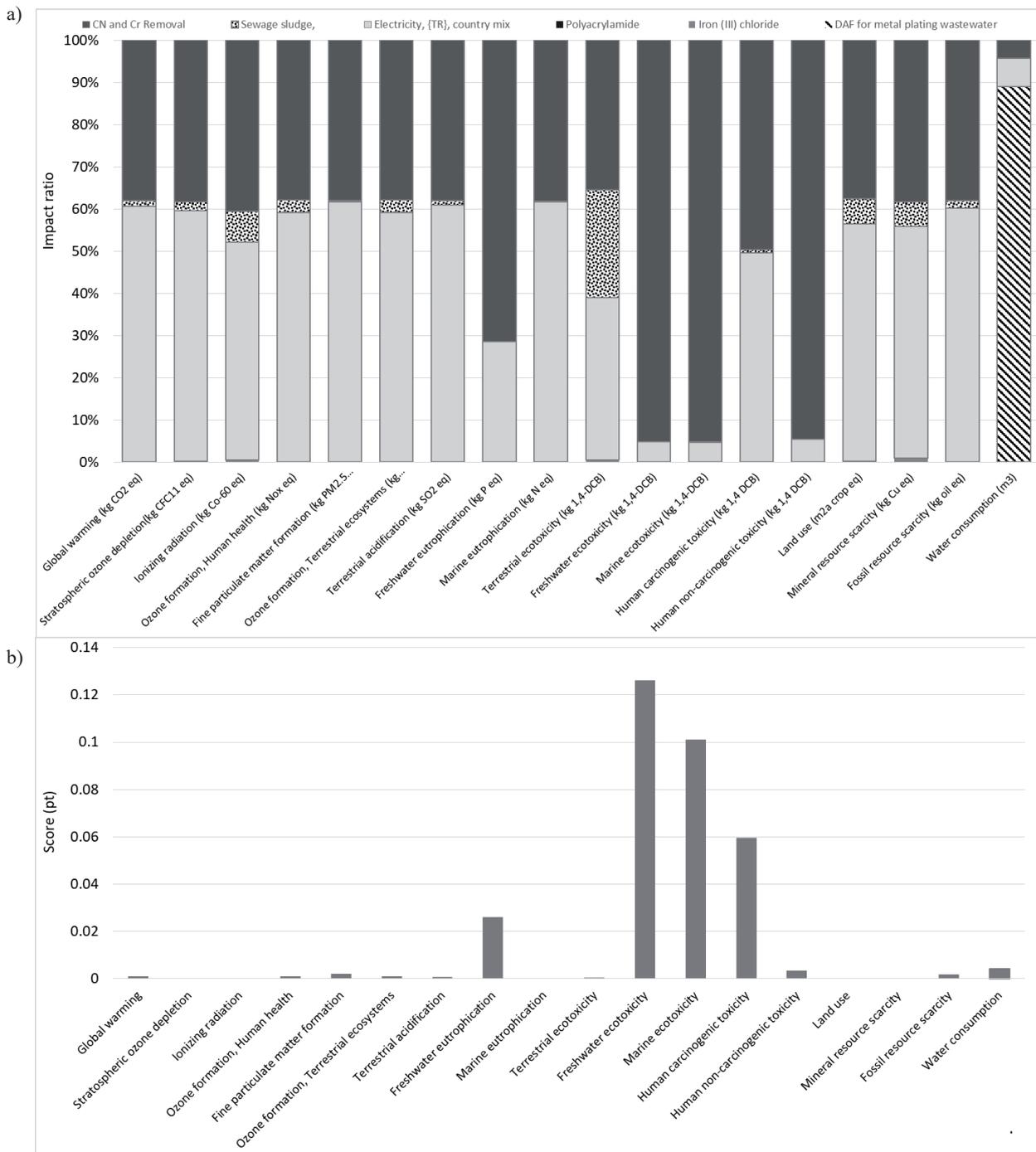


Fig. 4. ReCiPe 2016 method results. a) Characterization and b) Normalization.

caused 85% less environmental damage than chemical treatment. Considering the studies in the literature that involve CF and sedimentation processes, it has been observed that similar environmental impact categories are significantly affected. In the study conducted by Şimşek [39] on a treatment system involving flocculation and sedimentation processes, the environmental impact categories most significantly affected were identified as Global Warming, Fine Particulate Matter Formation, Freshwater Eutrophication, Marine Eutrophication, Freshwater Ecotoxicity, Marine Ecotoxicity, Mineral Resource Scarcity, and Fossil Resource Scarcity. Similarly, in the LCA study carried out by Robles-Bueno et al. [40] on a CF-based wastewater treatment

system, the most impacted categories were reported to be Freshwater Eutrophication, Ecotoxicity, Marine Ecotoxicity, Human Non-carcinogenic Toxicity, Land Use, and Mineral Resource Scarcity. Mohamed-Zine et al. [41] performed an LCA of a drinking water treatment plant and found that the CF unit had the greatest environmental impact in the category of Ozone Layer Depletion. Tran et al. [42] conducted an LCA on an industrial wastewater treatment plant employing CF and identified Freshwater Eutrophication, Freshwater Ecotoxicity, and Human Toxicity as the most affected environmental impact categories. In a similar study, Kartikasari and Santoso [43] assessed a treatment system comprising CF and sedimentation processes, revealing

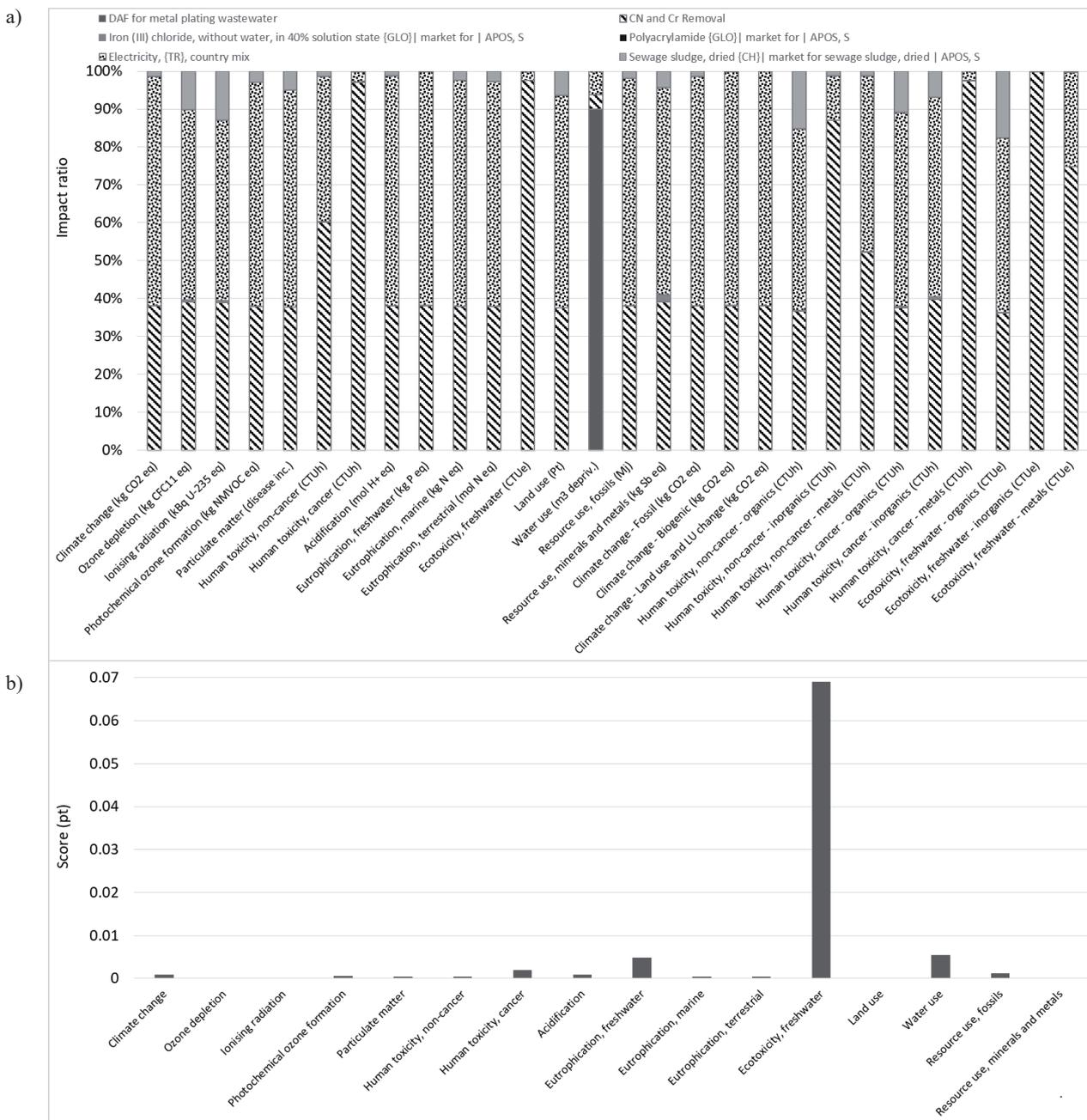


Fig. 5. EF 3.1 method results. a) Characterization and b) Normalization.

that the highest scoring environmental categories were Global Warming and Eutrophication.

Following the assessment of environmental impact categories via the ReCiPe method, the same categories were evaluated using the EF 3.1 approach to facilitate a comparative analysis of the data derived from the alternative method. Fig. 5 display the characterization and normalization results of the environmental impact categories computed using the EF 3.1 approach.

According to the characterization results calculated using the EF 3.1 method (Fig. 5a)), the removal of CN<sup>-</sup> and Cr<sup>+6</sup> was the primary contributor to the generation of environmental impact categories, which is consistent with the conclusions derived from the ReCiPe 2016 method and highlights the greatest environmental risk in the process as the MPW itself. The top five environmental impact categories, in descending order, were freshwater ecotoxicity, freshwater eutrophication, water use, human toxicity (cancer), and resource use (fossils), according to an analysis of the normalization results (Fig. 5b)). Similar to the ReCiPe 2016 method normalization results, freshwater ecotoxicity was the most common environmental impact category in the EF 3.1 method normalization results. The reliability of these results is demonstrated by the consistent score ranking of the same environmental impact categories using both calculation methods.

## Conclusions

In this study, a pilot-scale process consisting of CF-DAF was used for the treatment of real metal plating industry wastewater. The heavy metal removal performance of the process was determined, and the environmental impacts of the process were evaluated by LCA. In the first stage, pretreatment studies were conducted for Cr<sup>+6</sup> reduction and cyanide oxidation of MPW. Following pretreatment, laboratory-scale CF studies were conducted to ensure chemical optimization (ferric chloride and anionic polyelectrolyte). After determining the optimum chemical type and dosage, pilot-scale integrated CF-DAF process studies were initiated. With the CF-DAF process, removal efficiencies of over 80% for COD and over 90% for Ni, Zn, Cr<sup>+6</sup>, and SO<sub>4</sub><sup>2-</sup> were achieved at pH 8, 200 µm bubble diameter, 3-4 bar pressure, and approximately 53 min contact time. The study showed that the DAF process yielded higher removal efficiencies than the conventional CF-sedimentation process, making it a suitable solution for the treatment of MPW. LCA studies have revealed that MPW is the most hazardous input for all living organisms. It has been predicted that environmental impacts can be reduced by using different plating techniques during production in the metal plating industry to produce wastewater with lower pollutant concentrations. Furthermore, environmental impact values can be reduced by using electricity generated from renewable energy sources instead of fossil fuels,

and the scores for environmental impact categories can be lowered. The environmental impact of MPW treatment can be optimized by using different chemicals or by minimizing sludge production in DAF processes.

## Acknowledgments

The authors would like to thank the Scientific and Technological Research Council of Türkiye (TUBITAK) for financially supporting this study under the project number of 119C080. The authors also thank Artemis Treatment, Project, Construction, Analysis, Consultancy Services, Industry and Trade Co. Ltd.

## Conflict of Interest

The authors declare no conflict of interest.

## References

1. RAJORIA S., VASHISHTHA M., SANGAL V.K. Treatment of electroplating industry wastewater: A review on the various techniques. *Environmental Science and Pollution Research*. **29**, 72196, **2022**.
2. SARI B. The use of bioleaching in removal of heavy metals from metal industry waste sludges", PhD thesis, Çukurova University, Graduate School of Science and Engineering, Adana. **2005** [In Turkish].
3. WU L. Metal plating wastewater treatment using an electrochemical advanced oxidation process (EAOP). PhD thesis, School of Civil and Environmental Engineering, Faculty of Engineering, The University of New South Wales, Sydney. **2024**.
4. SHEN J., LIU B., LIU C., CHENG C., WU J. Characterizing fluorescence fingerprints of different types of metal plating wastewater by fluorescence excitation-emission matrix. *Environmental Research*. **194**, 110713, **2021**.
5. PETRINIC I., KORENAK J., POVODNIK D., HELIX-NIELSEN C. A feasibility study of ultrafiltration/reverse osmosis (UF/RO)-based wastewater treatment and reuse in the metal finishing industry. *Journal of Cleaner Production*. **101**, 292, **2015**.
6. KAMAR M.T., ELATTAR H., MAHMOUD A.S., PETERS R.W., MOSTAFA M.K. A critical review of state-of-the-art technologies for electroplating wastewater treatment. *International Journal of Environmental Analytical Chemistry*. **104** (6), 4143, **2024**.
7. POPURI S., VIJAYA Y., BODDU V.M., ABBURI K. Adsorptive removal of copper and nickel ions from water using chitosan coated PVC beads. *Bioresource Technology*. **100**, 194, **2009**.
8. ADELI M., YAMINI Y., FARAJI M. Removal of copper, nickel and zinc by sodium dodecyl sulphate coated magnetite nanoparticles from water and wastewater samples. *Arabian Journal of Chemistry*. **10**, 514, **2017**.
9. BENITO Y., RUIZ M.L. Reverse osmosis applied to metal finishing wastewater. *Desalination*. **142**, 229, **2002**.
10. YANG X.J., FANE A.G., MACNAUGHTON S. Removal and recovery of heavy metals from wastewaters by

- supported liquid membranes. *Water Science and Technology*. **43** (2), 341, **2001**.
11. PRAKASH R., MAJUMDER S.K., SINGH A. Flotation technique: Its mechanisms and design parameters. *Chemical Engineering & Processing: Process Intensification*. **127**, 249, **2018**.
  12. POOJA G., KUMAR P.S., PRASANAMEDHA G., VARJANI S., VO D.N. Sustainable approach on removal of toxic metals from electroplating industrial wastewater using dissolved air flotation. *Journal of Environmental Management*. **295**, 113147, **2021**.
  13. POOJA G., KUMAR P.S., INDRAGANTI S. Recent advancements in the removal/recovery of toxic metals from aquatic system using flotation techniques. *Chemosphere*. **287**, 132231, **2022**.
  14. LADOUCEUR J.D., NARBAITZ R.M., LAN C.Q. Dissolved air flotation pretreatment for low-pressure membranes in water treatment: A review of fouling mitigation and product water quality. *Journal of Water Process Engineering*. **56**, 104391, **2023**.
  15. RAJAPAKSE N., ZARGAR M., SEN T., KHIADANI M. Effects of influent physicochemical characteristics on air dissolution, bubble size and rise velocity in dissolved air flotation: A review. *Separation and Purification Technology*. **289**, 120772, **2022**.
  16. UMMALYMA S.B., SAHOO D., PANDEY A., SUKUMARAN R.K., SAHOO N. Wastewater treatment technologies and new trends towards sustainable management. *Chemosphere*. **271**, 129589, **2021**.
  17. TEIXEIRA M.R., ROSA M.J. Comparing dissolved air flotation and conventional sedimentation to remove cyanobacterial cells of *Microcystis aeruginosa*: Part I: The key operating conditions. *Separation and Purification Technology*. **52** (1), 84, **2006**.
  18. ZAMBOULIS D., PATAROUDI S.I., ZOUBOULIS A.I., MATIS K.A. The application of sorptive flotation for the removal of metal ions. *Desalination*. **162**, 159, **2004**.
  19. KURNIAWAN T.A., CHAN G.Y.S., LO W., BABEL S. Physico-chemical treatment techniques for wastewater laden with heavy metals. *Chemical Engineering Journal*. **118**, 83, **2006**.
  20. ATAMALEKI A., MIRANZADEH M.B., MOSTAFAII G.R., AKBARI H., IRANSHAHI L., GHANBARI F., SALEM A. Effect of coagulation and sonication on the dissolved air flotation (DAF) process for thickening of biological sludge in wastewater treatment. *Environmental Health Engineering and Management Journal*. **7** (1), 59, **2020**.
  21. SUDILOVSKIY P.S., KAGRAMANOV G.G., KOLESNIKOV V.A. Use of RO and NF for treatment of copper containing wastewaters in combination with flotation. *Desalination*. **221**, 192, **2008**.
  22. BARREDO-DAMAS S., ALCAINA-MIRANDA M.I., BES-PIÁ A., IBORRA-CLAR M.I., IBORRA-CLAR A., MENDOZA-ROCA J.A. Ceramic membrane behavior in textile wastewater ultrafiltration. *Desalination*. **250** (2), 623, **2010**.
  23. MUNOZ I., AKTÜRK A.S., AYYILDIZ Ö., ÇAĞLAR Ö., MEABE E., CONTRERAS S., TOSCANO A., TORNE V., LLOPART N., ROMA C.S., FERRER O., JIMÉNEZ-BANZO A. Life cycle assessment of wastewater reclamation in a petroleum refinery in Turkey. *Journal of Cleaner Production*. **268**, 121967, **2020**.
  24. RASHID S.S., HARUN S.N., HANAFIAH M.M., RAZMAN K.K., LIU Y., THOLIBON D.A. Life cycle assessment and its application in wastewater treatment: A brief overview. *Processes*. **11** (1), 208, **2023**.
  25. MENESES M., CONCEPCIÓN H., VRECKO D., VILANOVA R. Life cycle assessment as an environmental evaluation tool for control strategies in wastewater treatment plants. *Journal of Cleaner Production*. **107**, 653, **2015**.
  26. MOURA B., PAPAIOANNOU E., GRIGOROPOULOS A., ZOIKIS-KARATHANASIS A., MONTEIRO H. Sustainability of spent nickel-based electroplating baths: An innovative valorisation process. *Sustainability*. **15** (21), 15366, **2023**.
  27. RODRIGUEZ R., ESPADA J.J., GALLARDO M., MOLINA R., LÓPEZ-MUÑOZ M.J. Life cycle assessment and techno-economic evaluation of alternatives for the treatment of wastewater in a chrome-plating industry. *Journal of Cleaner Production*. **172**, 2351, **2018**.
  28. ZUO W.Q., CHEN C., CUI H.J., FU M.L. Enhanced removal of Cd(II) from aqueous solution using CaCO<sub>3</sub> nanoparticle modified sewage sludge biochar. *RSC Advances*. **7**, 16238, **2017**.
  29. ETTALOU Z., SALAH S., AGUELMOUS A., JADA A., TALEB A. Use of ferric chloride contained in the rejects from the steel industry as a coagulant for the fuel washing wastewater treatment. *Desalination and Water Treatment*. **234**, 68, **2021**.
  30. EBBA M., ASAITHAMBI P., ALEMAYEHU E. Development of electrocoagulation process for wastewater treatment: optimization by response surface methodology. *Heliyon*. **8**, e09383, **2022**.
  31. GUPTA N., THAKUR A., BHARDWAJ P. Oxidative transformation of alcohols and organic halides in aqueous solution. *New Journal of Chemistry*. **38** (8), 3749, **2014**.
  32. PRAZERES A.R., FERNANDES F., LUZ S., JERÓNIMO E. Simple processes for contamination removal in cheesemaking wastewater: CaCO<sub>3</sub>, Mg(OH)<sub>2</sub>, FeSO<sub>4</sub> and FeCl<sub>3</sub>. *Journal of Environmental Chemical Engineering*. **8** (4), 104034, **2020**.
  33. SOLMAZ A., BÖLÜKBAŞI Ö.S., SARI Z.A. Green industry work: Production of FeCl<sub>3</sub> from iron and steel industry waste (mill scale) and its use in wastewater treatment. *Environmental Science and Pollution Research*. **31**, 19795, **2024**.
  34. ARIASE N.I.P., WIKANINGRUM T. Optimization of Coagulation and Flocculation in Concrete Wastewater of Precast Industry. *Journal of Environmental Engineering & Waste Management*. **6** (1), 58, **2021**.
  35. BIDHENDI N., GH. R., TORABIAN A., EHSANI H., RAZMKHAH N., ABBASI M. Evaluation of Industrial Dyeing Wastewater Treatment with Coagulants. (2007). *International Journal of Environmental Research*. **1** (3), 242, **2007**.
  36. FILHO J.A., AZEVEDO A., ETCHEPARE R., RUBIO J. Removal of sulfate ions by dissolved air flotation (DAF) following precipitation and flocculation. *International Journal of Mineral Processing*. **149**, 1, **2016**.
  37. AZEVEDO A., OLIVEIRA H.A., RUBIO J. Treatment and water reuse of lead-zinc sulphide ore mill wastewaters by high rate dissolved air flotation. *Minerals Engineering*. **127**, 114, **2018**.
  38. SABEEN A.H., IBRAHIM Z., KHAN M.A., OTHMAN N. Environmental impacts assessment of industrial wastewater treatment system using electroless nickel plating and life cycle assessment approaches. *International Journal of Environmental Science and Technology*. **16** (7), 3171, **2019**.

39. SIMSEK M.E. Comparative life cycle assessment on a drinking water treatment plant. Degree Project in AL250X (Strategies for Sustainable Development), KTH Royal Institute of Technology, School of Architecture and Built Environment, Department of Sustainable Development, Environmental Science and Engineering, Stockholm, Sweden. **2024**.
40. ROBLES-BUENO Y., CASTILLO-SUÁREZ L.A., LINARES-HERNÁNDEZ I., MARTÍNEZ-MIRANDA V., GARDUÑO-PINEDA L., ALANIS C., NATIVIDAD R. Denim washing wastewater treatment by coupling coagulation–flocculation/Fe-garnet filtration: Life cycle assessment and the fertilization with the sludge. *International Journal of Environmental Science and Technology*. **21**, 6109, **2024**.
41. MOHAMED-ZINE M.B., HAMOUCHE A., KRIM L. The study of potable water treatment process in Algeria (Boudouaou station) — by the application of life cycle assessment (LCA). *Journal of Environmental Health Science & Engineering*. **11**, 37, **2013**.
42. TRAN H.V., PHAN H.A., BUI H.M. Life cycle assessment of industry wastewater treatment plant: A case study in Vietnam. *RSC Sustainability*. **3** (7), 1415, **2025**.
43. KARTIKASARI I.B., SANTOSO R.I.B. Impact of drinking water treatment process using life cycle assessment (LCA) to minimize environmental impact risk. *Journal of Social Research*. **2** (9), 3218, **2023**.