

Decentralized Algae Removal Technologies for Lake Diefenbaker Irrigation Canals: A Review

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ABSTRACT. Lake Diefenbaker Irrigation Canals in Canada are crucial in providing water for irrigation, preventing droughts and floods, and supporting the Saskatchewan agriculture industry and economy. Unfortunately, filamentous algal blooms occur every summer in Lake Diefenbaker Irrigation Canals. These algae are not toxic but a nuisance. They block farmers' pumps and reduce irrigation water flow rates. Currently, the Water Security Agency periodically adds the algaecide Magnacide H. to control the algal blooms, which is costly (i.e., one million dollars per year for the Lake Diefenbaker M1 Irrigation Canal only) and requires effort to dewater the canal to protect fish. Therefore, algae removal before the canal water enters farmer's pumps might be a cost-effective alternative, especially the removal of microalgae during the initial stages of growth in June of each year. This paper has summarized and evaluated algae removal technologies, considering their advantages, disadvantages, and potential solutions for addressing the challenges and limitations associated with these technologies. Five algae removal technologies were identified as promising, which are suspended air flotation (SAF), dissolved air flotation (DAF), hydrodynamic cavitation, spiral blade centrifuge, and coagulation. Among them, SAF seems the most suitable option, while DAF and hydrodynamic cavitation offer eco-friendly advantages. Further research and pilot testing are needed to determine the cost-effective and feasible algae removal technology for Lake Diefenbaker Irrigation Canals.

Keywords: algal blooms, decentralized algae removal technologies, dissolved air flotation, filamentous algae, irrigation water, Lake Diefenbaker Irrigation Canal, suspended air flotation, spiral blade centrifuge

1. Introduction

Algal blooms are global problems and expensive to control. Excessive amounts of the algae produce toxins in sufficient concentrations that can kill fish and poison people who consume shellfish fed on the algae. Algal blooms may also reduce dissolved oxygen concentrations in water due to their oxygen consumption overnight. This may affect the health of aquatic life and produce offensive odours around water systems. Therefore, algal blooms must be prevented and controlled (Wurtsbaugh et al., 2019). The growth and distribution of algae will be impacted by several environmental parameters (including sunlight intensity, temperature, nutrient concentration, and pH), and hydrological parameters (such as water residence time and flow rates) (Abirhire et al., 2015; Hariz et al., 2023).

Aquatic algae can be classified into planktonic, filamentous, and plant-like macroalgae. The planktonic algae group can form harmful algal blooms (HABs) due to their toxin production, contribution to eutrophication, and change in food web dynamics. Among them, *Microcystis aeruginosa* blooms are the most regularly poisonous blue-green algae detected in severely

eutrophic water bodies. They are responsible for the formation of microcystins (MCs), a deadly toxin that is hazardous to both animal and human health (Diaz et al., 2019).

Filamentous algae, mainly green due to the presence of chlorophyll a and b, are colonies of microscopic plants connecting to form mesh-like filaments typically on hard surfaces. Cotton-mat is one of the most prevalent freshwater filamentous green algae. Its dead and dying masses turn gray or brown and look like portions of a woollen blanket. *Cladophora*, *Spirogyra*, and *Oedogonium* are notable examples of green filamentous algae. Rocks of streams and quick-flowing rivers and the shallow edges of nutrient-rich lakes mostly experience plenty of *Cladophora* (John and Rindi, 2015; Ge et al., 2018).

Chlorophyll a concentration is used to indirectly quantify the biomass of micro and macroalgae in the water column and streambed (Morgan et al., 2006). A direct measurement involves counting the number of cells per unit volume, achievable through microscopy with a counting chamber (Berkman et al., 2007).

Approximately sixty years ago, Saskatchewan province in Canada struggled with severe droughts. Lake Diefenbaker, as a significant water resource in Saskatchewan, was built with the aim of flood control, drinking water supply, hydroelectricity production, water supply for industry, cattle farms, recreational activities, and irrigation of around 2,000 km² of land through Lake Diefenbaker Irrigation Canals. The future of agriculture in Saskatchewan seems promising, increasing food surplus and

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affecting civilization. As irrigation canals play an integral role in the Saskatchewan agriculture industry, their maintenance is important (North et al., 2015).

During summer, the Lake Diefenbaker Irrigation Canals are dominated by green filamentous algae growing at the bottom of the canals (Figure 1), which are semi-attached to the rocks and are more of a nuisance than a threat. When they detach from the rocks, they flow downstream, blocking the irrigation intake pumps (Cota-Sánchez et al., 2007). Consequently, farmers dependent on this water source for irrigation would suffer from a reduced water flow rate. Furthermore, filamentous algae mats can restrict the amount of oxygen exchanged between the atmosphere and the water and stop photosynthesis from generating oxygen in the water. If the canals are coated with algal mats, the lack of dissolved oxygen may cause fish kills and offensive odours. It is noted that excessive algal growth speeds up the dredging time and produces more sediments (Clemson University, 2021).

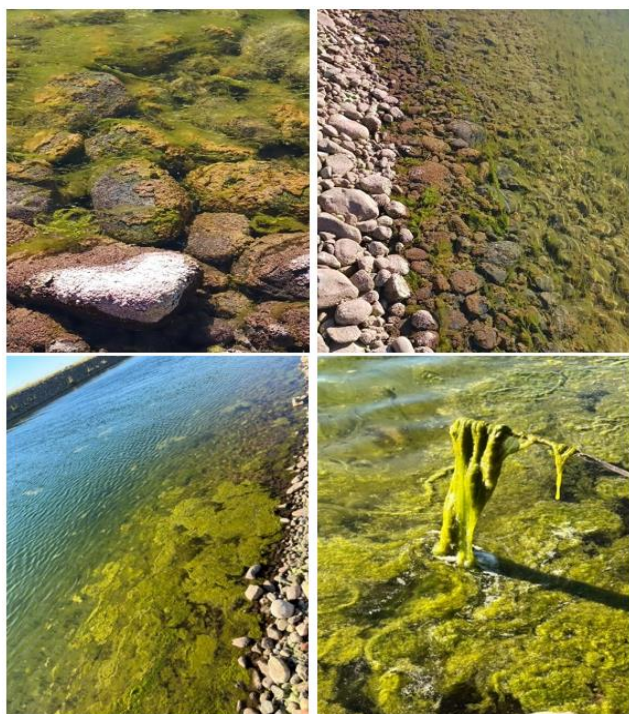


Figure 1. Green filamentous algae in Lake Diefenbaker Irrigation Canal (M1) in July 2022.

Intake screens and periodic algaecide applications (Magnacide H) are the current methods for preventing filamentous algae growth in the Lake Diefenbaker Irrigation Canals. Magnacide H application is costly (around \$1,000,000 a year for Lake Diefenbaker M1 Irrigation Canal), and if it is not appropriately managed, it might pose threats to the aquatic environment and non-target species (Albariño et al., 2007; Cota-Sánchez, 2007; Venturino et al., 2007). Moreover, Magnacide H was inefficient in removing filamentous algae from the canals in 2022. Thus, alternative technology is urgently needed to prevent and control algal blooms in these canals or redesign the canals.

Numerous studies have explored various aspects of algae removal technologies, with some focusing on specific methods like coagulation-based (Ren et al., 2022) and microorganism-based approaches (Sun et al., 2018), while others have provided comprehensive overviews of microalgae harvesting technologies (Kumar et al., 2023; Liu et al., 2023). However, a notable gap exists in the form of a comprehensive review article dedicated to the latest full-scale field applications of freshwater algae removal technologies. Many existing articles lack detailed experimental conditions, hampering effective comparison. This study seeks to fill this gap.

The Lake Diefenbaker Irrigation Canals, operating seasonally with just a six-month window, underscore the need for deployable algae removal technologies. Therefore, this study's primary focus is to review the latest decentralized algae removal technologies suitable for these canals and other shallow surface waters, designed for straightforward installation within this limited timeframe. The environmental characteristics of the Lake Diefenbaker Irrigation Canals have been explained in the following section 2 of this article. It should be noted that, due to the M1 canal's flow into a reservoir, biological methods are not well-suited for this dynamic environment. Hence, Section 3 of this study offers an overview of various algae removal technologies, encompassing physical, chemical, physiochemical, biological, and ecological approaches, but places particular emphasis on exploration of deployable physical, chemical, and physiochemical technologies for effective algae removal.

Due to the scarcity of literature on removing green filamentous algae, the review focused on deployable technologies for removing different types of algae in general, with a particular emphasis on the latest technologies and materials, and pilot-scale solutions. Many studies employ chlorophyll-a concentration measurements to assess the removal efficiency of the target algae using various technologies. This suggests that these technologies could likely demonstrate similar efficacy in removing filamentous algae, as the chlorophyll-a concentration serves as a valid indicator for the removal of filamentous algae as well (Berkman et al., 2007). The reviewed technologies, as shown in Figure 2, have been categorized into laboratory scales and pilot scales technologies, including ultrasonic irradiation, locally enhanced electric field treatment, photocatalytic nanoparticles, magnetic nanocomposites, artificial water mixing, membrane separation, spiral blade centrifuge, hydrodynamic cavitation, air flotation, electrochemical oxidation, coagulation, and electrocoagulation. This article provides laboratory-scale technologies due to their significant potential for further exploration with other researchers to implement them at a pilot scale eventually.

2. The Environmental Characteristics of the Lake Diefenbaker Irrigation Canals

The Lake Diefenbaker Irrigation Canal (M1 Canal, Figure 3), constructed in the 1960s, is a 22.50 km long water supply canal that provides irrigation water for 37,000 acres of land in the Saskatchewan River Irrigation District, connecting Lake Diefenbaker to Broderick Reservoir (Government of Saskatch-

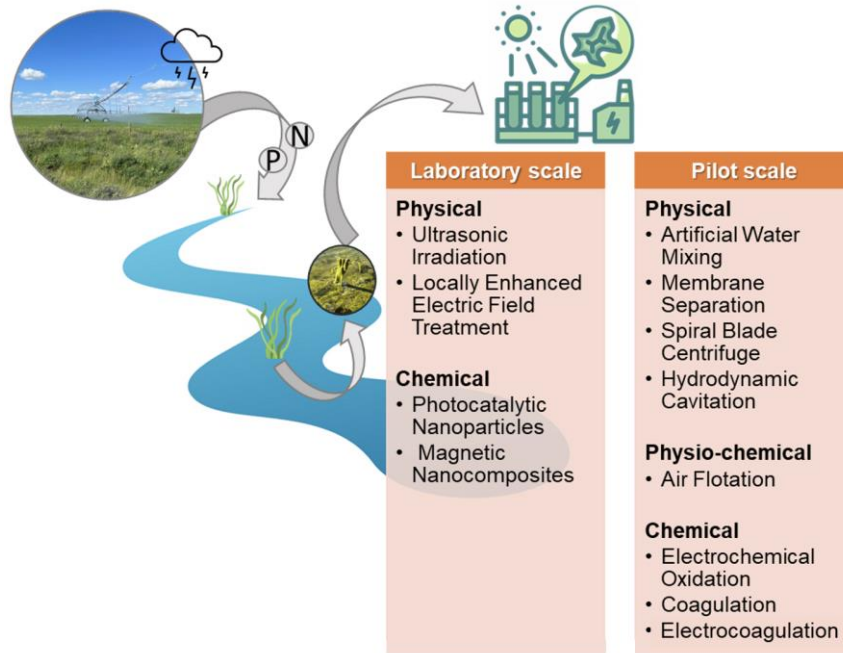


Figure 2. Algae removal technologies from water discussed in this study

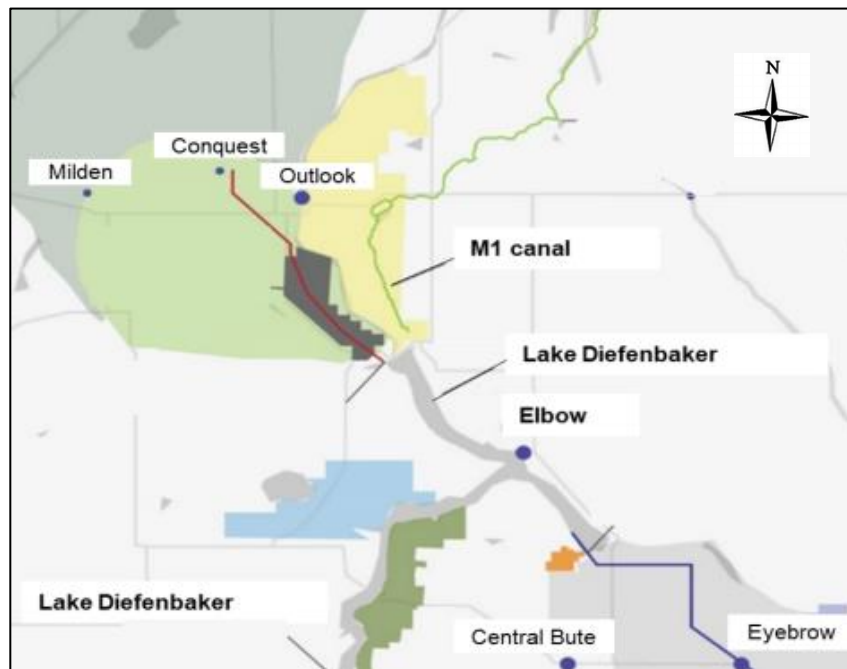


Figure 3. The map of Lake Diefenbaker and its irrigation canal (M1 canal) adapted from Government of Saskatchewan (2021).

ewan, 2014). Based on a water sampling study conducted by Stephanie Young et al. (2022) from the M1 canal in 2022, the average dissolved oxygen (DO) range in the canal was between 9.54 and 10.41 mg/L during summer. The canal water exhibited temperatures of at least 10 °C, favouring algal growth. The turbidity of the canal water was also found to be less than 2 NTU. The pH values remained relatively consistent across sampling

locations, ranging from 8.43 to 8.53, indicating a near-neutral pH. The average water flow rate fluctuated between 0.88 and 2.95 m³/s from June to September 2022. Visible growth of filamentous algae is observed in shallow, slowly flowing water due to favourable nutrient and light conditions. These findings suggest that the canal's acidity and alkalinity levels predominantly support algal blooms (Gebreselassie, 2023).

3. Technology Development for the Control of Algal Bloom and Algae Removal

Various physical, chemical, physicochemical, biological, and ecological technologies have been developed to prevent and control algal blooms. Over the years, it has been shown that using physical technologies such as mechanical mixing, membrane filtration, light shields, and ultrasonic irradiation is beneficial. However, equipment and labour availability are crucial for their practical application. Algicides, copper sulfate addition, herbicides, hydrogen peroxide, and other chemicals are mainly chemical algal bloom removal methods (Zhan et al., 2021). These chemical substances are short-term solutions that may instantly eliminate the target algae species while potentially harming the aquatic environment because of the release of toxins from cell lysis and unwanted effects on non-target species. Also, the efficiency of the process is primarily influenced by the hydrological conditions (Kennedy et al., 2022).

Regarding physicochemical methods, although coagulation-flocculation and flocculation-sedimentation can efficiently control algal blooms, they pose threats to the environment due to chemical addition to the water (Zhan et al., 2021; Tse et al., 2022). The costs associated with these techniques are also high. Biological approaches primarily use aquatic organisms, plants, and the active chemicals they release to inhibit algae growth (Zhan et al., 2021). Bioflocculation is an organic alternative to chemical flocculation, which is more commonly used. It uses various organic flocculants such as bacteria, plant-derived substances, self-aggregating algae, fungi, and microbial-based agents. The method is environmentally friendly with low energy consumption and non-toxic flocculants. However, there are limitations to consider. It requires specialized flocculants for various algal species, operates at a relatively slow pace demands precise control of the environment, and entails an additional step to remove the flocculated algae (Eliasson et al., 2020).

Algal blooms can be controlled using ecological strategies, including constructed wetlands, aquatic vegetation restoration, and plant floating bed technologies. It should be considered that both biological and ecological technologies may have unstable field applications with poor response time (Zhan et al., 2021). Since the Lake Diefenbaker Irrigation Canal is always dewatered in October and left dry for more than six months, biological and ecological technologies might not be appropriate for it. In addition, the permanent installation of algae removal system is challenging. Therefore, on-site deployable physical, chemical, and physio-chemical algae removal technologies have been prioritized and described in the following sections. They have been categorized as laboratory-scale and pilot-scale technologies.

3.1. Laboratory-Scale Technologies

3.1.1. Physical Technologies

Ultrasonic irradiation is a physical algae treatment technology that can rapidly degrade algae in small lakes or larger water bodies. The laboratory-scale of ultrasonic irradiation has been efficient in inactivating *Microcystis aeruginosa*, *Melosira*, and *Spirulina*, whereas it needs ultrahigh frequency in practical applications (Zhan et al., 2021). Ultrasonic irradiation can cause

gas bubbles in algae cells to break down. This disrupts the cell wall and membrane, interferes with photosynthetic activity, slows cell cycle, and controls cell growth. This technology cannot be considered cost-effective because of its high energy consumption. Prolonged exposure to ultrasonic irradiation can lead to cell lysis, an undesirable outcome for cyanobacteria as it may result in the release of microcystin toxins into the water. To address these problems, Huang et al. (2020) assessed the effectiveness of two-cycle low-density, low-frequency and short-duration ultrasonic irradiation for cyanobacteria removal. Various parameters such as ultrasonic densities, frequencies, the duration of irradiation, and distinct time intervals between two irradiation cycles (12 ~ 36 h) were evaluated in this study.

Huang and co-workers reported that 20 kHz, 0.0025 W/mL, and 1-minute radiation duration are optimal conditions for two-cycle ultrasound irradiations with a 36-hour time interval. 86.7% was obtained for *Microcystis aeruginosa* removal under optimal conditions. The experiments were conducted in 500 mL of *Microcystis aeruginosa* with 1.2×10^6 cells/mL initial density and a pH of 7.3 at 20 °C. According to the calculated ultrasound dosage and energy effectiveness factor of sonication, they concluded that this new approach to algae removal was cost-effective due to its low energy consumption, and it has the potential to be utilized in a floating device designed to treat water bodies. They mentioned that this method's performance for removing other algal species should be examined (Huang et al., 2020).

Locally enhanced electric field treatment (LEEFT) is a novel algae control method in water bodies with a low initial density of algae. The primary function of this method is to destroy the algae cell by a generated electric field. This technique needs low voltage and, subsequently, lower energy compared to the pulsed electric field treatment (PEFT). In the LEEFT method, electrode modification with tip structures made of nanomaterials multiplies the local electric field. The LEEFT technique can inactivate algal cells at low voltage since the voltage at the tip of the tip structures can exceed 100 kV/cm. The conductive substrates modified with nanowires, such as copper phosphide, copper oxide, and iron oxide nanowires, are electrode materials utilized in the LEEFT. The long-term practical application of this method needs further studies on its service life and cost-effective electrode fabrication methods (Zhan et al., 2021).

3.1.2. Chemical Technologies

Daniela Diaz and co-workers applied an organic surfactant, silica-modified quaternary ammonium compound (QAC) composite, as an antimicrobial active surface to a fiberglass mesh to disinfect water and control HAB. They reported more than 90% chlorophyll a removal from a sample with an initial chlorophyll a concentration of 150 mg/m³ after a 10-hour treatment (Diaz et al., 2019).

More recently, Kennedy et al. (2022) have investigated the performance of immobilized photocatalytic TiO₂ nanoparticles in 3D printed polymer binder feedstocks to treat HAB and their toxins in both surface water and closed photocatalysis water treatment systems. TiO₂ nanoparticles can degrade HAB and their toxins under solar irradiation (UV light). Owing to their tenden-

cy towards aggregation, they are immobilized in a 3D-printed polymer structure made of biopolymer polylactic acid (PLA) instead of polymers such as polystyrene, which are problematic microplastics in the environment. These retrievable and deployable polymer structures can float at the surface of the water to adsorb UV light, leading to maintaining the photocatalytic effectiveness of nanoparticles. According to the first-year results of laboratory experiments, 3D-printed structures containing TiO₂ nanoparticles eradicated more than 90% of *Microcystis* toxin. It could be noted that 3D printing can be used as a low-cost, fast prototyping research technique to develop field-deployable, configurable, retrievable, and reusable HAB treatment devices (Kennedy et al., 2022). The practical separation of microalgae using nanomaterials is limited due to its high cost, even though it is efficient (Zhan et al., 2021).

Magnetic separation has attracted much interest in recent years because of its high separation efficiency and inexpensive

operating costs. Magnetic nanomaterials developed based on magnetic Fe₃O₄ nanoparticles have simple fabrication procedures and high biocompatibility. Modification of magnetic nanomaterials will decrease their tendency toward agglomeration and keep their effectiveness stable in case the pH of the algal liquid changes. It should be noted that the ability to reuse magnetic nanomaterials frequently limits environmental impacts and lowers operation costs. Graphene oxide has drawn much attention due to its vast surface area and active sites (Zhan et al., 2021). In 2018, Peirui Liu and colleagues evaluated the removal efficiency of chlorella by Fe-based nanomaterials synthesized using an in-situ method. They achieved a high algae removal efficiency in a wide range of pH and temperature, and different algae concentration levels, for \$505 US/tonne of harvested algal biomass (Liu et al., 2018). The advantages and disadvantages of these laboratory-scale algae removal technologies are summarized in Table 1.

Table 1. Advantages and Disadvantages of the Latest Laboratory-scale Algae Removal Technologies

Process	Method	Algae Species	Advantages	Disadvantages	Ref.
Physical	Low-density and low-frequency ultrasonic irradiation	<i>Microcystis aeruginosa</i> ¹	Cost-effective and low energy consumption compared to high and low-frequencies ultrasonic irradiation; Improved environmental protection (i.e., less harm to aquatic species); Increased impact distance; Ability to be used on a floating device	It remains unclear if it is effective on green filamentous algae	Huang et al., 2020
	Locally enhanced electric field treatment (LEEFT)	<i>Chlorella vulgaris</i> ² <i>Microcystis aeruginosa</i>	Lower voltage and energy needed compared to pulsed electric field treatment (PEFT).	Lack of knowledge about its long-term practical application High synthesis cost of the electrode materials; Short-term service life of the existing electrode materials; The hydraulic force, electrophoretic force, and dielectrophoretic force affect its algal inactivation efficiency	Zhan et al., 2021
Chemical	Photocatalytic TiO ₂ nanoparticles immobilized in a 3D printed polymer structure	<i>Microcystis aeruginosa</i>	High <i>Microcystis</i> toxin removal; The use of 3D printing a low-cost and fast prototyping research technique to develop a field-deployable algae removal device	High cost of nanoparticles	Zhan et al., 2021; Kenned et al., 2022
	Magnetic Fe ₃ O ₄ nanoparticles	<i>Chlorella</i>	High algae removal efficiency in a wide range of pH, temperature, and algae concentration levels; Low operating cost	Agglomeration of naked magnetic nanomaterials; Modification needs to improve dispersibility and eliminate interference; Potential environmental and biological toxicity; Repeated reuse is required to minimize harm and reduce cost; Further research is needed on regeneration performance	Liu et al., 2018; Zhan et al., 2021

Note: *Microcystis aeruginosa* is a species of freshwater cyanobacteria; *Chlorella* is a species of green microalgae.

3.2. Pilot-Scale Technologies

3.2.1. Physical Technologies

Although physical approaches are the same for freshwater and marine systems, they have been employed more frequently in freshwater systems. The consequent water consumption has led to the preference for physical over chemical treatments for freshwater (Gallardo et al., 2017).

Several artificial mixing technologies, such as aeration systems, mixers, and bubble diffusers, can prevent cyanobacteria from remaining at the water's surface to absorb the strongest sunlight. Several researchers claim that the mixing systems are more capable of changing the dominant algae species from cyanobacteria to other algae species rather than decreasing total algae biomass (Smithheart, 2018). Mixing systems require 0.53 kWh/m² a year for a 12 h/day operation. Therefore, these processes have high energy consumption (Khatib et al., 2019).

In 2018, Smithheart installed pilot-scale solar-powered circulators (SPCs) in a shallow reservoir located in the US with a surface area of 4.80 km² and a volume of 32.1 × 10⁶ m³ for two years (2014 ~ 2016). The dominant algae species of the reservoir were filamentous and nitrogen-fixing cyanobacteria with chlorophyll a concentration greater than 40 µg/L. They also employed six aeration lines in another reservoir with a surface area of 1.38 km², a volume of 5 × 10⁶ m³, and the same dominant algal bloom. For modeling, they collected physical and biological data from the reservoirs over the years. The main objective of the modeling was to investigate how vertical diffusion, nutrient concentrations and water temperature interact with algal bloom metrics, such as chlorophyll concentration and cyanobacterial biovolume. They concluded that increased water column mixing reduces cyanobacteria biovolume but may slightly increase overall chlorophyll concentration, indicating that cyanobacteria thrive in quiescent water conditions, and while artificial mixing had mixed success in increasing turbulent diffusion, the use of aeration lines was associated with an elevated chlorophyll concentration compared to other reservoirs (Smithheart, 2018).

Surface mechanical mixers and bubble aerators have a single function of increasing dissolved oxygen. In contrast, a water-lifting aerator created by Zhang and co-workers, is a multifunctional system that has been extensively used to reduce phytoplankton in several deep drinking water reservoirs. This system directs the algae to the bottom of the reservoir with the lowest temperature and sunlight. Consequently, the growth of HABs is significantly influenced by thermal stratification and vertical mixing. However, the performance of this water-lifting aerator for shallow reservoirs and other types of algae should be studied (Zhang et al., 2020).

Pumps, hydraulic, and pneumatic mixers can all be used for water circulation to prevent algae growth. In the past, solar-powered systems were costly, and the logistics for large-scale practical applications were challenging. The literature's examples indicated that the cost was reasonable for potable water treatment (Gallardo et al., 2017). Nowadays, solar power seems to be an efficient energy source since it is renewable, silent, widely accessible, and reasonably priced, particularly where the maximum possible direct solar radiation is 1,000 W/m². Kha-

tib et al. (2019) employed a low-cost photovoltaic-based pumping system to pump a chemical substance into an artificial pond to remove algae. Photovoltaic (PV) technology is the foundation of solar water pumps, which transforms solar energy into electricity to operate a DC or AC motor-based pump. There are benefits associated with PV-powered pumps, including simple installation, deployment ability, low maintenance requirements, and zero pollution. However, the system's current drawbacks are the high initial cost and variable water output. The literature shows the effectiveness and viability of PV-based pumping systems for agricultural purposes. The combination of PV-powered pumps with other technologies, such as centrifuges, can remove algae from water bodies.

Membrane separation is a decentralized physical technology whose performance for algal bloom removal is restricted due to membrane fouling. Recently, some studies have been conducted on vibrating membrane separation methods to remove algae. It is noted that the system is a short-term algae removal technology because of its high cost of operation and maintenance (Zhan et al., 2021). Jiang et al. (2020) studied the dynamics model of a vibration membrane filtration system. They reported that membrane fouling would decline by increasing the frequency of the vibration from 1 ~ 5 Hertz, resulting in total and irreversible membrane fouling alleviation and reversible membrane fouling mitigation. Energy consumption increments caused by applying high vibration frequency should be addressed.

Practically all varieties of microalgae can be isolated from the culture medium using centrifugation. A centrifuge functions as an accelerated sedimentation tank, increasing the gravitational force to speed up the settling process. Centrifugation may be a more suitable choice for large-scale production (> 20,000 L), whereas at small scale (< 2,000 L), cross-flow microfiltration may be more attractive (Grima et al., 2003). While centrifugation can achieve algae removal efficiency above 95%, it is acknowledged as an energy-intensive method, requiring about 1 kWh of energy for harvesting 1 m³ of microalgae (Najjar and Abu-Shamleh, 2020).

Alfa Laval's centrifuge, the Clara 701H, is a sizable machine designed to separate algae from water using centrifugal force. It operates at 4,800 rpm, effectively transporting solid algae particles to the sides of the centrifuge bowl, which are then discharged hydraulically. The machine is around 10 m³, weighs 2,800 kg, and has a powerful 37 kW electrical motor. For instance, it is capable of processing particles within the range of 0.40 ~ 200 µm, including microalgae like *Spirogyra*, which typically falls within the 10 ~ 100 µm size range at a rate of up to 75 m³/h (Eliasson et al., 2020).

Tse et al. (2022) reported a deployable algae cleaning system in 2022. This system included a high-capacity and high-throughput (HCHT) spiral blade centrifuge connected to the influent and effluent water tanks, a series of pumps, and piping, all fitted into a standard 20-foot metal shipping container (Figure 4). A metal grid box was employed to protect the water collection pump from blockage by larger items. The spiral blade centrifuge made by Evodos Dynamic Settlers Company was to separate phytoplankton from the influent water, resulting in

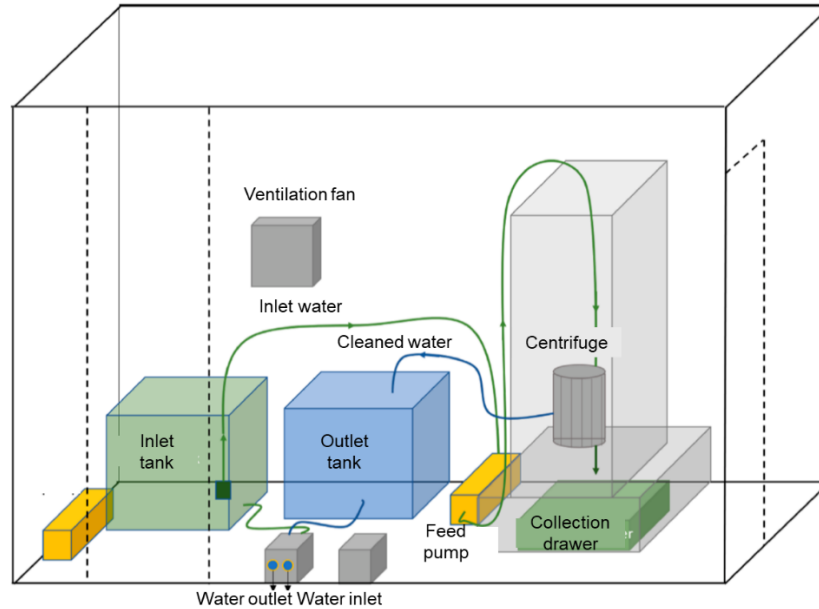


Figure 4. The interior design of the algae cleaning system developed by Tse and co-workers. Reprinted with permission from Tse et al. (2022).

microalgae accumulation on the inside of the drum. Subsequently, this biomass accumulation would be scraped off the drum and collected in the drawer, as illustrated in Figure 4. The collected algae biomass was spontaneously dried in the environment overnight. This gentle technology resulted in a negligible amount of algae cell breakage. Also, there is no need for chemical addition in the process. Consequently, the intact algae collected during the process could be employed for various purposes, such as biofuel and animal feed.

The system was run every 2 ~ 3 days a week from July to the end of August and once a week in September and October of 2017 to treat the algae-laden water of a spot in the proximity of the pumping station in Plover Cove Reservoir. There was a decline in the chlorophyll a concentration of the influent water from 6.8 mg/L to 0.8 ~ 1.2 mg/L over these months. The daily operation time was 4 hours, from 10:30 a.m. to 2:30 p.m. Based on their report, 16 m³ of water with a maximum processing rate of 4,000 L/h (4 m³/h) was processed for one 4-h operation of the algae cleaning system. They concluded that the system could remove more than 90% of microalgae without significantly impacting the quality of influent water, including its pH, chemical oxygen demand (COD), and temperature. In contrary to some physical and chemical algae removal techniques, for instance, chemical flocculation, algicides, and ultrasonic waves, algae biomass would be retrieved in this process, and the most negligible toxic cellular contents from HAB would be released in water. In this research, the actual energy usage of the system during a 4-hour operation was reported as around 23.8 kWh. A diesel-electric generator can generate energy. The authors mentioned that the system could operate even in harsh weather conditions (Tse et al., 2022).

Eliasson et al. (2020) designed a toxic algae harvester con-

taining a centrifuge (Alfa Laval separator, Clara 701H model), a funnel, a pump, an algae tank, and a generator mounted on a boat. They chose centrifuge to remove algae from water among ten technologies, including the inorganic chemical flocculation, bio-flocculation, electrocoagulation, magnetic flocculation, fine mesh filtering, pressure filtering, tangential flow filtration, dissolved air flotation, and roller separation, based on a detailed comparison. The dimensions of the system were 9.40 × 3.00 × 5.07 m (length including the funnel × width × height). Its height might be an obstacle to transportation. Although these experimental results of using a centrifuge for algae removal were successful, they could not manufacture the final design because of its high cost and high carbon dioxide emissions from the generator. The estimated final cost of the system was around \$837,000.

Hydrodynamic cavitation (HC) is a physical process that creates bubbles that burst, generating high temperature and hydroxyl radicals from water molecules. These radicals can destroy enzymes, active substances and proteins in algal cells, affecting their growth. The mechanical, thermal, and chemical effects that occur during cavitation bubble collapse result in HC's ability to fully inactivate different types of bacteria, cyanobacteria, microalgae, and viruses in water (Sun et al., 2020). HC has been proposed as a waste-free and environmentally friendly technology for breaking down various organic compounds that are resistant to traditional treatment methods. However, the cost-effectiveness of the process may vary depending on factors such as the size and complexity of the treatment plant and operating conditions.

Regarding microalgae removal from surface water, HC has been shown to be effective in lowering algal cell growth by destroying gas vacuoles and cell walls and decreasing photo-

synthetic activity. Although HC alone is insufficient to remove contaminants, it can significantly enhance decomposition efficiency when combined with oxidants such as hydrogen peroxide and ozone. This combination has been found to be more effective in removing pollutants from water. The use of oxidants has greatly increased the decomposition rate, making HC a more efficient technology for pollutant and algae removal (Sun et al., 2020; Shokoohi et al., 2023).

A recent study by Reza Shokoohi et al. investigated the effectiveness of HC in removing blue-green alga (*Melosira* and *Oscillatoria*) from water entering a water treatment plant using a 20 L cavitation reactor. HC was combined with ozone and hydrogen peroxide oxidants. The study examined seven factors that affect algae removal, including pH, retention time, flow, cavitation pressure, the distance between the orifice plate and the beginning of the cavitation tube, ozone concentration, and hydrogen peroxide concentration. A cavitation pressure of 5 bar, a retention time of 90 minutes, a pH of 5, a flow of 1 m³/s, the distance of the orifice plate of 25 cm, an ozone rate of 3 g/h, and a hydrogen peroxide concentration of 2 g/L were determined the optimal conditions for removing the dominant algae (38.16% *Melosira* and 35.76% *Oscillatoria*). The results revealed that cavitation pressure was the most effective factor in removing *Melosira* and *Oscillatoria*, while hydrogen peroxide had the lowest effect.

The study also demonstrated that hydrodynamic cavitation can be an efficient treatment strategy for eutrophic water bodies and has the potential to be a sustainable removal technique since it does not produce secondary pollution. However, they also highlighted several challenges and areas for further research. According to their findings, the synergistic effect of combining hydrogen peroxide and ozone with HC was less effective in this study than in previous studies, which could be attributed to changes in the organic load and algae entering the treatment plant. They recommended that future research explore other distances between the orifice plate and the beginning of the cavitation tube and investigate the effect of temperature on the destruction of algae during the cavitation process (Shokoohi et al., 2023).

Waghmare et al. (2019) compared the performance of the optimized probe ultrasonication (US) and HC for cell disruption of *Chlorella pyrenoidosa* strain NCIM 2738, which is a freshwater green alga from the genus *Chlorella*. The initial pH of the influent was adjusted to 7.5. They reported that maintaining a time duration of 180 minutes, applying a pressure of 5 bar, and utilizing a solid load of 0.45% w/v are the optimum conditions for achieving maximum cell disruption using HC, including a cavitation device with a venturi orifice. However, by subjecting the cells to a preliminary treatment of 0.5% w/v sodium hydroxide, the required time for achieving optimal cell disruption with HC decreased to 105 minutes for the maximum cell disruption efficiency of 96.5%. Additionally, an assessment of the energy consumption for cell disruption using both US and HC techniques revealed that HC demonstrated superior energy efficiency, approximately 6.30 times more energy efficiency than the US, and scalability as a treatment method for microalgae cell disruption.

The effectiveness of HC for managing cyanobacterial water bloom was investigated by Jančula et al (2014). The results showed that HC treatment of cyanobacteria disintegrated their gas vesicles, achieving up to 99% removal efficiency without any negative impact on metabolic activity or membrane integrity. HC also did not affect the green algae *C. kessleri*, allowing them to act as natural nutrient competitors in treated bodies of water. However, it remains unclear if HC is effective on green filamentous algae, which has a different morphology than *C. kessleri*. Thus, further experiments are needed to determine its efficacy for green filamentous algae removal.

Flotation is a cost-effective method of producing microalgae concentrate on an industrial scale (Bürger et al., 2020). As algae has low density, leading to its inclination toward floating rather than settling, flotation is a promising technology for harvesting algae (Phoochinda and White, 2003). Gas flotation using air or CO₂ (Kim and Kwak, 2014; Kwak, 2015) can remove tiny particles with a density near that of water. The aggregates formed by the gas bubbles and particles rise to the top of a flotation tank, where a froth layer is scraped off. If the hydrophilic particles have a density greater than water's, they will settle at the bottom of the suspension, where they will be removed in the underflow (Bürger et al., 2020).

3.2.2. Physicochemical Technologies

The flocculation sedimentation technique removes algal cells by injecting flocculants, causing tiny particles to combine into larger ones. When dealing with low algae cell densities, choosing flocculants should be considered based on both choosing and cost. Polyaluminum chloride, polyferric sulphate, polyacrylamide, ferric trichloride, chitosan, polyaluminum ferric silicate, cationic starch, and natural flocculants are examples of commonly used flocculants in this application (Zhan et al., 2021).

Air flotation can be combined with other technologies, such as coagulation, to increase the effectiveness of the removal process. Aluminum sulfate, iron cetyl trimethyl ammonium bromide, ferric chloride, and chitosan are the most often utilized coagulants to neutralize the charge and flocculate algae particles. According to the technique used to create bubbles, the air flotation methods can be classified into dissolved air flotation (DAF), electrolytic air flotation, and dispersed air flotation. Tiny bubbles with an average diameter of 40 μm generated by the dissolved air flotation technique through pressurization stick to algae cells and lift them to the water surface (Zhan et al., 2021). In the DAF process, a fraction of the treated water is recycled and pressurized, regulating the presence of bubbles during the operation. This controlled recycling accounts for approximately 5 ~ 15% of the total volume, while pressurization is maintained within the range of 400 ~ 650 kPa. Upon returning to atmospheric pressure, water naturally releases excess air due to its reduced saturation level (Laamanen et al., 2016). A fine mesh filter should be employed before a DAF system to protect it from large debris in the water.

There are several upsides associated with DAF technology. The price is reasonable as this technology has been industrialized by different companies such as Ecologix Systems (Figure

5) and FRC Company. Also, a high flow rate (a maximum of 29.5 m³/h for a system with volume of 52.64 m³) can be achieved by an example of this technology (model E-405C) developed by Ecologix Systems (Eliasson et al., 2020). The Ecologix System uses countercurrent scraping, the most efficient technique for separating sludge from effluent water, reducing the likelihood of contamination of the effluent water (Ecologix Environmental Systems, 2022). However, the main disadvantage associated with the DAF method is a large quantity of dissolved tiny bubbles generation during the process leading to the destruction of the flakes generated between the algae cells and tiny bubbles. This will reduce the effectiveness of algae removal (Zhan et al., 2021). Furthermore, the characteristics and conditions of the liquid, for instance, temperature and dissolved solids, and the system's design will have an impact on bubble generation (Heron Innovators, 2022).



Figure 5. DAF system developed by Ecologix Systems. Reprinted from Ecologix Environmental Systems (2022).

Martin Page and colleagues from the U.S. Army Engineer Research and Development Center (ERDC) conducted research on considerable HAB mitigation from Lake Okeechobee in Florida using a deployable DAF system developed by AECOM, followed by an ozone system manufactured by HiPOx, Inc. to remove algae toxins. The trailer-mounted DAF system had a footprint of around 10 m² with a reactor depth of 1.82 m. Two chambers comprised the DAF system. The first chamber was utilized to facilitate charge neutralization and flocculation of the algae particles. Aluminum chlorohydrate, with a dose of 30 ~ 50 mg/L, was the inorganic coagulant used to neutralize surface charges. The second chamber was designed for floatation, and the bottom of the chamber was filled with a stream of recirculated air-pressurized water. The injection of the pressurized water into the chamber resulted in nanoscale bubbles released into the non-pressurized water. The neutralized algae flocs bond to the large

surface area of these nanobubbles floating at the water's surface. The concentrated, floating algae are periodically harvested and collected in a hopper by a scraper blade. Prior to oxidation, clarified water was pumped into a holding tank. The flow rate of influent water was 75 gallons per minute (GPM).

It is reported that the treated effluent water contained few toxins and low levels of nutrients, including nitrogen and phosphorous. To be more precise, the system could remove more than 95% of the algae, 95% phosphorous, 65% nitrogen, and 50% organic carbon from the influent water. A belt press filtration was also utilized to achieve high amounts of concentrated algae biomass. According to their study, DAF technology successfully cleaned the algae-laden water and rapidly retrieved a very high proportion of the process water. The amount of produced waste and algae sludge, was limited to 1 gallon for every 400 gallons of water passed through, with an initial algae concentration of around 50 mg/L. The waste sludge had a 2 ~ 3% mass concentration (nearly 20,000 ~ 30,000 mg/L). The concentrated algae sludge was transferred into a biocrude fuel stock (Page et al., 2020).

In another study by Tian et al. (2018), it was proven that DAF technology is viable for algae and other pollutants removal from eutrophic water due to its simplicity of use and low installation and operation costs. It was discovered that managing the coagulant (polymeric aluminum chloride) dose and changing the gas-liquid mixing pump settings of the system would lead to successfully removing chlorophyll a, total phosphorus, turbidity, and chemical oxygen demand from water. A full-scale DAF system with a 50 m³/h treatment capacity was employed in this research that could treat water within 5 min of coagulation. Under the optimal conditions, including a coagulant dose of 220 mg/L, gas-liquid separation pump pressure of 0.38 MP, and dissolved air in a water reflux ratio of 23.81%, the removal efficiencies of turbidity, chlorophyll a concentration, and TP were reported at 80, 71, and 72%, respectively. It is also mentioned that dissolved air would increase dissolved oxygen levels of the water from 0.2 ~ 2 mg/L to 3 ~ 3.5 mg/L in polluted rivers.

During electrolytic air flotation techniques, an electric current break down water molecules. At the cathode, H₂ bubbles develop, and at the anode, O₂ bubbles form (Phoochinda et al., 2005). Aluminum and iron are the most often utilized electrode materials (Zhan et al., 2021). The bubbles typically have a size between 22 and 50 μm (Phoochinda et al., 2005). Although laboratory-scale electrolytic air flotation has succeeded in algae removal, its field application needs further investigation.

Dispersed air bubbles are generated by continually circulating air through porous materials or by introducing air into the system through a diffuser and mixing it at high speed. The interaction between these bubbles and negatively charged microalgae cells will result in algae flotation (Zhan et al., 2021). This method is less energy-intensive compared to DAF but has limited applicability due to the relatively large bubble size, which falls within the range of 700 ~ 1500 μm (Laamanen et al., 2016). Surfactants are frequently used in dispersed air flotation processes to reduce bubble size and coalescence because these pro-

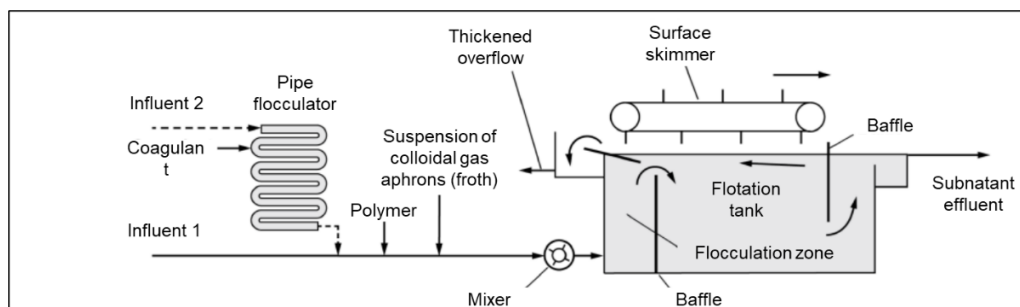


Figure 6. Schematic flow diagram of SAF system. Reprinted from Tchobanoglous et al. (2022).

cesses frequently result in giant bubbles (up to 1 mm in diameter). This method is also referred to as froth flotation (Phoochinda et al., 2005). Alkyl sulfate salts ($R-OSO_3Na$), primary fatty amines ($R-NH_2$) and quaternary ammonium salts ($R-N(CH_3)_3$) are some examples of the surfactants employed in the froth flotation processes (Huang et al., 2019). The difference between DAF and froth flotation is that froth flotation requires a stable foam or froth at the top of the flotation tank. This technology can also be utilized to remove valuable materials, such as metal ions, and hydrophobic minerals from wastewater (Bürger et al., 2020).

The airflow velocity and coagulant dose significantly impact how effectively algae cells are removed from the water. Due to its low cost and excellent effectiveness, the air flotation method has been employed to harvest algae cells. Still, its field application is constrained by the chemical pollution brought on by flotation chemicals (Zhan et al., 2021).

3.2.3. Chemical Technologies

Suspended air flotation (SAF) is another flotation system that typically creates microbubbles chemically rather than mechanically compared to DAF. Instead of utilizing a compressor and saturator for microbubble generation, surfactants are used in SAF units at atmospheric pressure (Wiley et al., 2009). The tiny bubbles with a size of $7 \sim 25 \mu m$ possess the following unique features: a double film wall for chemical reactivity and bubble stability, little to no bubble coalescence, a higher reactive surface area per unit volume, differently charged bubbles (anionic and cationic), and interfacial tension. Low concentrations of surfactant, < 50 parts per million, are required for SAF bubbles (Heron Innovators, 2022). SAF technology is viable due to its low energy consumption, smaller footprint, low chemical use, low investment and operational expenses, zero toxic operational conditions, non-toxic by-products, and the possession of fewer mechanical equipment in comparison with DAF (Wiley et al., 2009; Tchobanoglous et al., 2022). Figure 6 depicts the schematic of the SAF system.

Heron Innovators, a company located in the USA, has developed industrial-scale SAF systems for water and wastewater treatment. They reported that their SAF generators could generate greater than 1 quadrillion bubbles with the size of $7 \sim 25 \mu m$ within 10 gallons of suspended air froth, and nearly ten GPM of froth is required to treat 200 \sim 500 GPM of influent water (Heron Innovators, 2022).

Electrochemical oxidation (EO), an emerging decentralized water treatment technology, has advantages such as high on-site oxidant production, high efficiency, and straightforward operation. Yang et al. (2022) developed an emergency-responsive electrochemical oxidation and filtration (EOF) technology for pumping and treating phytoplankton plumes and cyanotoxins as shown in Figure 7. According to preliminary research, this system showed a solid ability to generate locally concentrated free chlorine, which is > 16 times greater than the bulk chlorine concentration at the porous Ti_4O_7 filter anode surface. This free chlorine destroyed cyanobacterial harmful algal blooms (cHABs) and their toxins when they passed through the porous anode. Also, it is reported that the disinfection by-products from the EOF process were five times lower than those from chlorination to achieve the same degree of treatment.

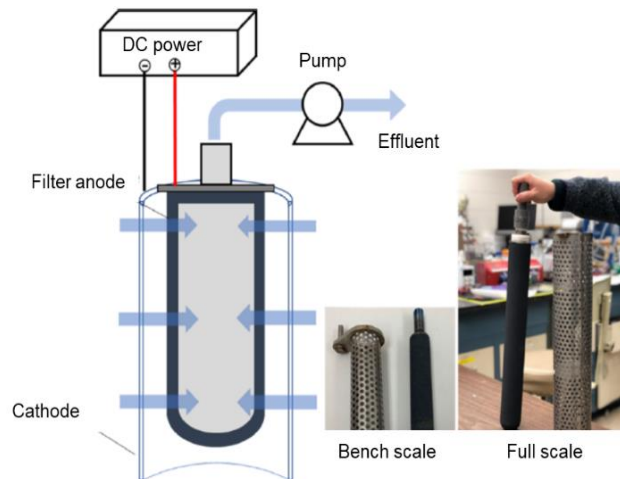


Figure 7. The schematic of EOF system and pictures of small and full-size filter anodes and perforated cathodes. Reprinted with permission from Yang et al. (2022).

Yang and co-workers also designed and deployed a full-scale EOF system mounted on a boat (Figure 8) to treat cHABs on-site in Lake Neatahwanta, USA. The system included three electrode arrays (each of them has 9.0 m long) containing 30 large filter anodes, providing a total geometric surface area of $2.8 m^2$. Arrays were immersed in water and distributed around a pontoon boat. The field experiments were run for five days in September 2020. The power required for all the equipment on

board (pumps, EOF units, and power supplies) was generated by a Honda gasoline generator (EU 7000iS). The lake's chlorophyll concentration was 50 ~ 175 $\mu\text{g/L}$. With a treatment capacity of 110 m^3/day and energy usage of 1.1 kWh/m^3 , the system can efficiently remove more than 50% of phytoplankton and 80% of ambient cyanotoxins. The treatment capacity can be increased by adding more EOF arrays. It should be noted that this EOF process is easy to design and operate and has a quick response in algae treatment (Yang et al., 2022).

Conventional coagulants, although effective under optimized conditions, often require higher dosages for treating water with high algae concentrations, resulting in increased sludge generation and operating costs, while raising concerns about long-term safety and environmental impacts. Aluminum-based coagulants like alum, aluminum chloride (ACl), along with ferric chloride (FC), and ferric sulfate (FS) are commonly inorganic coagulants used in coagulation processes. When aluminum salts are added to water, they undergo hydrolysis reactions, resulting in different hydrolyzed species. The formation of dominant soluble species depends on the pH and temperature of the water. Coagulation is typically favored in the pH range of 6 ~ 7 because it facilitates the presence of positively charged aluminum species. Similarly, iron salts undergo hydrolysis but cover a wider pH range. To achieve more controlled coagulation, prehydrolyzed metal salts like polyaluminum chloride (PACl) have been developed. The choice of the appropriate coagulant depends on factors such as the specific type of algae, its morphology, and the composition of the water (Ren et al., 2022).

Recent interest has focused on titanium-based coagulants as an alternative to aluminum and iron coagulants for algae removal. They form larger, shear-resistant flocs, but may require more chemicals for pH adjustment. Titanium xerogel coagulant (TXC) shows high algae removal efficiencies and can degrade microcystin. Recovered titanium sludges can be converted into valuable photocatalysts. Additionally, silica-containing coagulants enhance aluminum hydroxide precipitation for better algae aggregation. Magnetic coagulation with materials like magnetite is also explored, but efficient recovery remains a challenge (Ren et al., 2022).

Organic polymers utilized as coagulants can be categorized into three groups: cationic, anionic, and nonionic. Cationic polymers are commonly preferred due to the presence of negatively charged impurities in untreated water. Anionic polymers are less effective at coagulating algae but can connect algal cells together under specific circumstances. Organic polymers are often employed as coagulant aids in conjunction with metal salts, reducing the dose of metal coagulants needed and resulting in larger and faster-settling clumps of algae. However, concerns about the environmental impacts and the potential formation of disinfection by-products (DBPs) restrict their usage in drinking water treatment. Natural polymers like chitosan, tannin, and Moringa seed extract show potential as coagulants, but their application in drinking water treatment is limited due to uncertainties about their effects on the ecosystem and human health. Future research should address these concerns and enhance natural polymers' cost competitiveness (Ren et al., 2022).

Electrocoagulation is an efficient way to harvest most algae species that uses less energy and does not require any chemical addition. One study showed that electrocoagulation could totally separate algae only with 0.4 kWh/m^3 energy consumption (Eliasson et al., 2020). In 2017, Sungwook Jung et al. employed an electrocoagulation and flotation (ECF) reactor under a catamaran-type unmanned surface vehicle (USV) to remove HABs from a lake in South Korea with nearly 10.25 g/L cyanobacteria concentration and 22.89 mg/m^3 chlorophyll a concentration. It was the first time an ECF reactor's field application was evaluated. ECF by-products are limited to metal coagulant ions and hydrogen micro-bubbles, which make the process eco-friendly. They designed the pilot-scale system based on their findings from laboratory experiments. This USV was connected to an unmanned aerial vehicle equipped with an image-texture-based object detection algorithm to detect algal blooms and send the location to the USV. The dimensions of the ECF reactor and the total system, including the catamaran-type USV and ECF, were 1.50 $\text{m} \times 0.65 \text{ m} \times 0.35 \text{ m}$, and 3.00 $\text{m} \times 1.40 \text{ m} \times 0.60 \text{ m}$ (length \times width \times height), respectively. The weight of the total system was approximately 50 kg. The velocity of USV was set to nearly 0.50 m/s to optimize the removal efficiency,

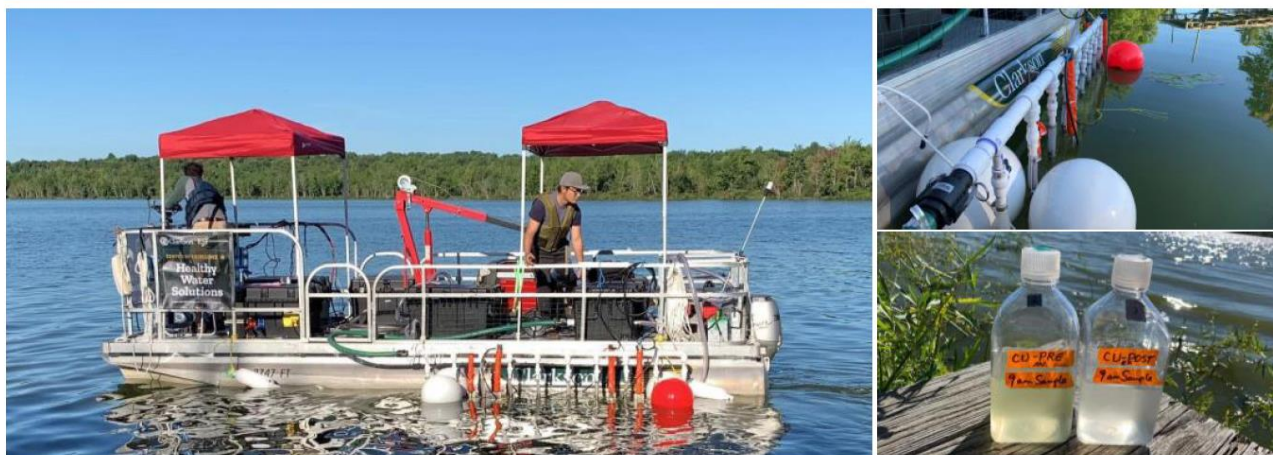


Figure 8. The picture of the boat-mount EOF system. Reprinted with permission from Yang et al. (2022).

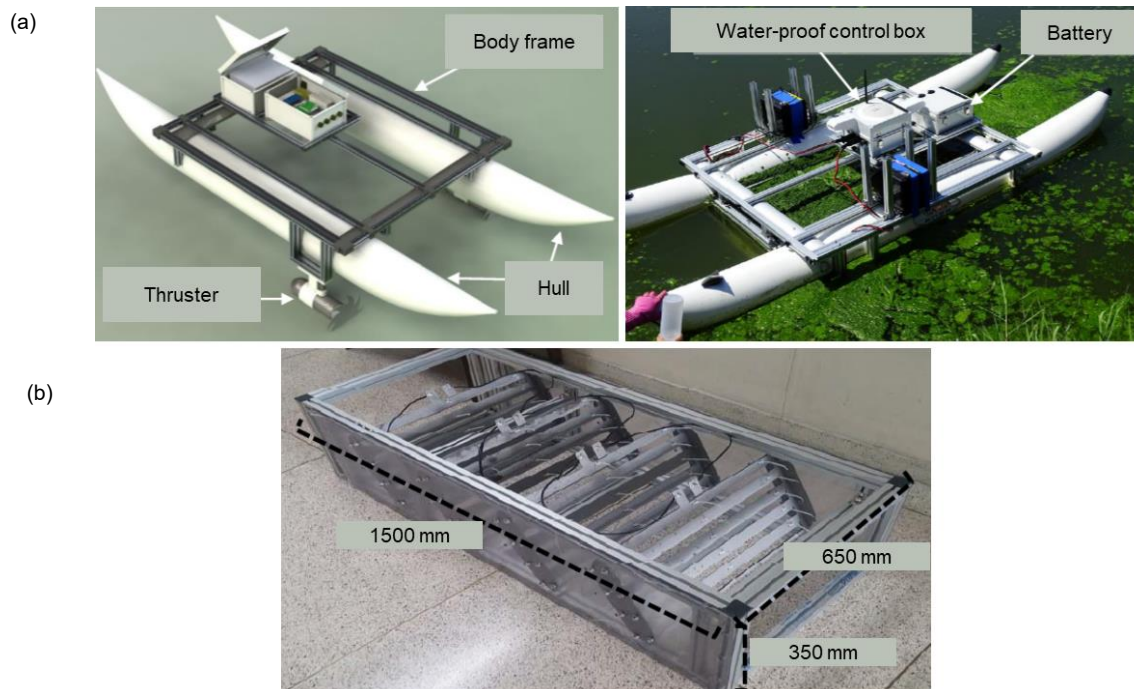


Figure 9. (a) The catamaran-type USV with ECF reactor. (b) The ECF reactor with its dimensions. Reprinted with the permission from Jung et al. (2017).

and it was operating for about 2.50 hours, with a power of 750 Wh (Jung et al., 2017).

The pilot-scale ECF reactor, as shown in Figure 9, contained eight electrode plates with a specific alignment. Metal coagulant ions produced by an anode interact with the algae to form larger flocs. These flocs float on the water surface by oxygen and hydrogen micro-bubbles produced by the anode and a cathode. According to the results, the system achieved 98.53% cyanobacteria removal at a depth of 0.40 m. It is also reported that the ECF reactor is a cost-effective, environmentally friendly, and easy-to-maintenance algae removal system with high efficiency (Jung et al., 2017; Eliasson et al., 2020). However, there are some drawbacks related to this approach. The most notable one is the possibility of effluent water contamination with ions from an anode due to applying more power to the system. Additionally, owing to dissolution, the offering anode must be changed regularly. This adds to the system's cost and may reduce capacity by a certain amount, depending on how long the change interval is. Furthermore, it would cost more money to take an additional step to remove toxic metal ions resulting from the dissolving electrodes (Eliasson et al., 2020).

4. Recommended Algae Removal Technologies for Lake Diefenbaker Irrigation Canals

Farmers are the project's ultimate target market. These stockholders might value feasibility, mobility, costs, and ease of operation more than speedy cleanup. Therefore, decentralized algae removal technologies for Saskatchewan farmers must be determined based on the treatment performance, capi-

tal and operational costs, feasibility, flexibility, deployment ability, operation and maintenance skills, and their advantages and disadvantages. The advantages and disadvantages of all pilot-scale technologies have been summarized in Table 2 for comparison.

It is reported that hydrodynamic cavitation exhibits exceptional energy efficiency, surpassing ultrasonic irradiation by approximately 6.3 times in terms of 96.5% algae cell disruption efficiency (Waghmare et al., 2019). On the other hand, centrifugation stands out as more attractive for large-scale production exceeding 20,000 liters, while the cross-flow microfiltration may be a better choice for small-scale (Grima et al., 2003). In this context, among physical algae removal technologies, this study recommends considering centrifugation, specifically spiral blade centrifuges, and hydrodynamic cavitation to address algae issues in the Lake Diefenbaker's irrigation canals. Furthermore, based on the comprehensive information provided in the previous section, SAF, DAF, and coagulation are identified as chemical decentralized algae removal technologies that this study narrows down as potential solutions among various chemical technologies for the same purpose.

SAF technology is viable due to its low energy consumption, smaller footprint, low chemical use, low investment and operational costs, zero toxic operational conditions, non-toxic by-products, and the possession of fewer mechanical equipment in comparison with DAF (Wiley et al., 2009; Tchobanoglous et al., 2022). However, further research and pilot testing are necessary to confirm its effectiveness and feasibility for specific applications.

Table 2. Advantages and Disadvantages of the Latest Pilot-scale Algal-bloom Removal Technologies

Process	Method	Algae Species	Advantages	Disadvantages	Ref.
Physical	Surface Mechanical Mixers and Bubble Aerators	Mostly <i>cyanobacteria</i>	Increasing the DO concentration of the water	Changing the dominant algae species rather than decreasing it; High energy consumption	Smithheart, 2018; Khatib et al., 2019
	Vibrating Membrane Separation	<i>Chlorella pyrenoidosa</i> ¹	Membrane fouling decrease; High algae removal efficiency	High operation and maintenance cost; Short-term application	Zhan et al., 2021
	Hydrodynamic Cavitation (HC)	Blue-green algae (<i>Melosira and Oscillatoria</i>) ² <i>Chlorella pyrenoidosa</i> <i>Cyanobacteria</i>	Ability to fully inactivate different types of bacteria, cyanobacteria, microalgae, and viruses in water; Waste-free; Environmentally friendly; Energy-efficient	Unclear removal efficiency for green filamentous algae	Jančula et al., 2014; Sun et al., 2020; Shokoohi et al., 2023
	Spiral Blade Centrifuge	<i>Microcystis aeruginosa</i>	High algae removal efficiency without significantly impacting pH, COD, and temperature of influent water; Releases the least toxic cellular contents from HAB during the operation; Operational ability in harsh weather conditions; Direct water discharge back into the water body; No need for flocculants or chemicals; Continuous operation with programmed procedures	High energy intensive; Requires machine maintenance; Algae cell damage probability	Jung et al., 2017; Tse et al., 2022
Physico-chemical	Dissolved Air Flotation	N/A	Ability for operation at high surface loadings; Small footprint; High solid concentration of sludge production without the necessity for thickening prior to dewatering; Efficient in removing flocs and low-density particles; A rapid start-up; Appropriate for treating raw water with low to moderate turbidity water containing algae and natural color	Inappropriate for raw water with high-density solids or turbidity (>100 NTU); Requires protection from freezing and rain; Prevent floating solids from settling; High energy consumption due to using recycle-water pumping and air compressor	Hairom et al., 2021
Chemical	Suspended Air Flotation (SAF)	N/A	Highest product recovery Lowest energy usage compared to DAF; Zero toxic operational conditions; Lowest investment & operational expenses; Non-toxic by-products; Lowest footprint; Greatest water reclamation; Greatest pollutant removal	Addition of coagulants or surfactants	Wiley et al., 2009; Zhan et al., 2021; Heron Innovators, 2022
	Electrochemical Oxidation (EO) Mounted on a Boat	<i>Microcystis aeruginosa</i> <i>Synechococcus</i> ¹	High on-site oxidant production; High removal efficiency; Straightforward operation; Fewer disinfection by-products compared to chlorination	Likelihood of the disinfection by-products released into the water	Yang et al., 2022
	Electrocoagulation and Flotation (ECF) Reactor under a Catamaran-Type Unmanned Surface Vehicle	<i>Cyanobacteria</i>	No need for chemical addition Low energy consumption and cost-effective; High algae removal efficiency	Likelihood of effluent water contamination with ions from an anode; High maintenance cost for replacing the anodes with the new ones; Needs an additional step to remove toxic metal ions generated from the electrode	Jung et al., 2017; Eliasson et al., 2020

Note: *Chlorella pyrenoidosa* is a species of green microalgae; Blue-green algae is from the planktonic group. *Microcystis aeruginosa* and *Synechococcus* are strains of freshwater cyanobacteria.

DAF has also shown to be a more sustainable and eco-friendly option for the algae removal. It does not require harsh chemicals or generate harmful by-products or residues. It also increases the water DO concentration. Nevertheless, its environmental impact can vary depending on the energy source and algae disposal methods, emphasizing the need for careful system design and implementation.

A specific case study comparing SAF and DAF, although not primarily focused on algae removal, demonstrates SAF's superiority in terms of footprint, energy consumption, and required flocculent. In this case study, SAF and DAF were compared for the removal of roughly 1,500 ppm of total suspended solids (TSS) in a flow of 700 GPM (158.98 m³/h) in a brewery. A detailed comparative analysis between DAF and SAF is presented in Table 3 (Heron Innovators, 2019).

Table 3. A Comparative Analysis between DAF and SAF for the Removal of TSS in a Brewery (Heron Innovators, 2019)

Parameter	SAF	DAF
Footprint	20% of DAF's Space	-
Energy Consumption	1/10th of DAF's	-
Flocculent Usage	Horsepower	-
Annual Energy Savings	2/3 of DAF's Flocculent	-
Annual Flocculent Savings	\$31,000	-
Capital Cost	\$60,000	-
Operational Cost	2/3 of DAF's Cost	-
	\$143,000	\$424,000

Another efficient and practical way to remove algae and other particulates from water is with spiral blade centrifuges. They are typically more compact and require less energy compared to other centrifuge designs (Tse et al., 2022). Nevertheless, the capital cost of the equipment is typically higher than other conventional filtration methods. In the algae removal comparison, DAF outperforms the spiral blade centrifuge with higher removal efficiency and lower energy consumption per unit volume, as shown in Table 4.

Hydrodynamic cavitation can generate reactive radicals to remove organic contaminants in water and wastewater without chemical additives. It provides an efficient, eco-friendly, and cost-effective treatment method for large effluent quantities (Zheng et al., 2022). However, its effectiveness in removing algae may depend on several factors such as flow rate, cavitation pressure, and the characteristics of the algae species. Also, this

method has not been implemented to remove green filamentous algae (Sun et al., 2020; Shokoohi et al., 2023).

While effective, coagulation can be more expensive and energy-demanding than SAF. Additionally, it introduces chemicals into the water, which can harm the aquatic ecosystem and water quality. In contrast, SAF combines flotation and sedimentation, requiring fewer chemical doses, minimizing potential harm to the ecosystem, and reducing operational costs.

The cost-effectiveness of the technologies depends on influent algae concentration and operational schedule. Cost efficiency in water treatment is typically assessed in terms of the volume of water treated from an engineering standpoint. Environmentally, cost efficiency can be gauged in relation to the removal of carbon, nitrogen, and phosphorus. In a business context, costs could be adjusted based on the recovery of fuel and nutrient resources from the removed algae. It is crucial to comprehend how changes in a parameter like influent algae concentration can impact these cost considerations, as stakeholders may prioritize different aspects based on their unique circumstances (Page et al., 2021).

The water characteristics of the M1 Canal indicate favorable conditions for algae growth, with sufficient dissolved oxygen, suitable temperatures, low turbidity, and near-neutral pH levels. The water flow rate also fluctuates but remains within manageable limits. Considering the canal water characteristics, cost efficiency, and environmental friendliness, both SAF and DAF appear to be viable options for eliminating filamentous microalgae. A comparison between DAF and SAF shows that the former requires more space and consumes more energy because of the air generation. Hydrodynamic cavitation has eco-friendly benefits as well. However, its effectiveness in removing green filamentous algae is unclear and needs further studies. Pilot testing is suggested for the final implementation of the algae removal technology. It is also recommended to incorporate solar-powered units into the design of the algae removal system, leveraging Saskatchewan's abundant sunlight resources for sustainable and cost-effective operations.

5. Conclusions

Filamentous algal blooms in Lake Diefenbaker Irrigation Canals in Canada pose many challenges to Saskatchewan farmers, such as pump blockages, increased maintenance costs, and reduced irrigation efficiency. Traditional chemical treatments are costly and not environmentally friendly. Since the canals are

Table 4. Comparative Performance Metrics of DAF and Centrifuge Algae Removal Technologies

Technology	Area	Input	Removal Efficiency	Energy Consumption	Ref.
Spiral blade centrifuge	38.54 m ³	4 m ³ /h	Microalgae: > 90%	1.48 kWh/m ³	Tse et al., 2022
Alfa centrifuge	10 m ³	75 m ³ /h	N/A	37 kW	Waghmare et al., 2019
DAF	10 m ²	17.03 m ³ /h	Algae: > 95% Phosphorous: 95% Nitrogen: 65%, Organic carbon: 50%	0.226 KWh/m ³	Page et al., 2020; 2021
DAF	N/A	50 m ³ /h	Turbidity: 80% Chlorophyll a concentration: 71% TP: 72%	N/A	Tian et al., 2018

emptied for six months annually, decentralized algae removal might be one of the options to address the challenges. This study has focused on exploring the latest decentralized laboratory and pilot-scale algae removal technologies. The main goal is to identify cost-effective, feasible, and deployable technologies to remove filamentous microalgae effectively at the early stages of algae growth.

During the literature review, it became evident that a significant portion of the research has concentrated on addressing harmful algal blooms rather than filamentous algae. Many research studies rely on chlorophyll a concentration measurement to gauge the efficiency of diverse technologies in mitigating harmful algal blooms. This indicates that technologies proven effective against harmful algal blooms may also be successful in removing filamentous algae, as the chlorophyll a concentration consistently proves to be a reliable indicator for the removal of filamentous algae as well. However, a research gap exists in the field of freshwater filamentous algae removal, emphasizing the need for future studies. This study reveals promising options for algae removal, including suspended air flotation (SAF), dissolved air flotation (DAF), hydrodynamic cavitation, spiral blade centrifuge, and coagulation. SAF is considered the most suitable choice, while DAF and hydrodynamic cavitation offer eco-friendly advantages. Further research and pilot testing are needed to determine the optimal decentralized algae removal technology for the Lake Diefenbaker Irrigation Canals.

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References

- Albariño, R., Venturino, A., Montagna, C.M. and de D'Angelo, A.M.P. (2007). Environmental effect assessment of Magnacide® H herbicide at Río Colorado irrigation channels (Argentina). Tier 4: In situ survey on benthic invertebrates. *Environ. Toxicol. Chem.*, 26(1), 183-189. <https://doi.org/10.1897/06-086R.1>
- Berkman, J.A.H. and Canova, M.G. (2007). *Algal biomass indicators: Techniques of Water-Resources Investigations*. U.S. Geological Survey, Chapter A7, Section 7.4. <https://doi.org/10.3133/twri09A7.4>
- Bürger, R., Diehl, S., Martí, M. and Vasquez, Y. (2020). Simulation and control of dissolved air flotation and column froth flotation with simultaneous sedimentation. *Water Sci. Technol.*, 81(8), 1723-1732. <https://doi.org/10.2166/wst.2020.258>
- Clemson University (2021). Filamentous algae conditions and control options. <https://www.clemson.edu/extension/water/stormwater-ponds/problem-solving/aquatic-weeds/algae-filamentous/index.html> (accessed January 4, 2024).
- Cota-Sánchez, J.H. and Remarchuk, K. (2007). An inventory of the aquatic and subaquatic plants in SASKWater canals in central Saskatchewan, Canada, before and after the application of the herbicide magnacide. *Can. Field-Nat.*, 121(2), 164-167. <https://doi.org/10.22621/cfn.v121i2.441>
- Diaz, D., Church, J., Young, M., Kim, K.T., Park, J., Hwang, Y.B., Santra, S. and Lee, W.H. (2019). Silica-quaternary ammonium "Fixed-Quat" nanofilm coated fiberglass mesh for water disinfection and harmful algal blooms control. *J. Environ. Sci.*, 82, 213-224. <https://doi.org/https://doi.org/10.1016/j.jes.2019.03.011>
- Ecologix Environmental Systems (2022). Enhanced dissolved air flotation (E-DAF) system. <https://www.ecologixsystems.com/dissolved-air-flotation-e-series/> (accessed February 3, 2022).
- Eliasson, E., Haglund, O., Hozouri, D. and Wahrén, H. (2020). *Design of a Toxic Algae Harvester*. Bachelor's Thesis, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden.
- Gallardo, J.J., Astuya, A., Llanos, A., Avello, V. and Ulloa, V. (2017). A critical review on control methods for harmful algal blooms. *Rev. Aquac.*, 11(3), 661-684. <https://doi.org/10.1111/raq.12251>
- Ge, S.J., Madill, M. and Champagne, P. (2018). Use of freshwater macroalgae *Spirogyra sp.* for the treatment of municipal wastewaters and biomass production for biofuel applications. *Biomass Bioenerg.*, 111, 213-223. <https://doi.org/10.1016/j.biombioe.2017.03.014>
- Gebreselassie, S.T. (2023). *Algal Control and Prevention Technologies for Lake Diefenbaker Irrigation Canals*. Master of Applied Science. Environmental Systems Engineering, University of Regina, Regina, Saskatchewan, Canada.
- Government of Saskatchewan (2014). \$10 million rehabilitation of M1 Canal underway. <https://www.Saskatchewan.ca/Government/News-and-Media/2014/November/26/M1-Canal-Rehab>. (accessed November 26, 2014).
- Government of Saskatchewan (2021). Lake Diefenbaker irrigation projects. <https://Diefenbakerirrigation.ca/Our-Projects/> (accessed September 13, 2021).
- Grima, E.M., Fernández, F.G.A. and Medina, A.R. (2003). Downstream processing of cell-mass and products. *Handbook of Microalgal Culture: Biotechnology and Applied Phycology*. Blackwell Publishing, pp. 215-252. <https://doi.org/10.1002/9780470995280.ch10>
- Hairom, N.H.H., Soon, C.F., Mohamed, R.M.S.R., Morsin, M., Zainal, N., Nayan, N., Zulkifli, C.Z. and Harun, N.H. (2021). A review of nanotechnological applications to detect and control surface water pollution. *Environ. Technol. Innov.*, 24, 102032. <https://doi.org/10.1016/j.eti.2021.102032>
- Hariz, H.B., Lawton, R.J. and Craggs, R.J. (2023). Novel assay for attached filamentous algae productivity and nutrient removal. *J. Appl. Phycol.*, 35(1), 251-264. <https://doi.org/10.1007/s10811-022-02857-11>
- Heron Innovators (2022). *Suspended Air® Flotation a New Environmental Remediation Tool*, Heron Innovators, Inc., Rocklin, CA, USA.
- Heron Innovators (2019). *Case Study: Anaerobic Digestate; Heron SAF®, DeLaval Waste Water Program Saves Brewery Money and Ensures Compliance*. DeLaval Cleaning Solutions, Kansas City, MO, USA.
- Huang, H., Wu, G., Sheng, C., Jiannan, W., Li, D. and Wang, H. (2020). Improved cyanobacteria removal from harmful algae blooms by two-cycle, low-frequency, low-density, and short-duration ultrasonic radiation. *Water*, 12, 2431. <https://doi.org/10.3390/w12092431>
- Huang, Z.Q., Cheng, C., Liu, Z.W., Luo, W.H., Zhong, H., He, G.C., Liang, C.L., Li, L.Q., Deng, L.Q. and Fu, W. (2019). Gemini surfactant: A novel flotation collector for harvesting of microalgae by froth flotation. *Bioresour. Technol.*, 275, 421-424. <https://doi.org/10.1016/j.biortech.2018.12.106>
- Jančula, D., Mikula, P., Maršálek, B., Rudolf, P. and Pochylý, F. (2014). Selective method for cyanobacterial bloom removal: Hydraulic jet cavitation experience. *Aquac. Int.*, 22(2), 509-521. <https://doi.org/10.1007/s10499-013-9660-7>
- Jiang, S.H., Xiao, S.Z., Chu, H.Q., Zhao, F.C., Yu, Z.J., Zhou, X.F. and Zhang, Y.L. (2020). Intelligent mitigation of fouling by means of membrane vibration for algae separation: Dynamics model, comprehensive evaluation, and critical vibration frequency. *Water Res.*, 182, 115972. <https://doi.org/10.1016/j.watres.2020.115972>
- John, D.M. and Rindi, F. (2015). Filamentous (non-conjugating) and plantlike green algae. *Freshwater Algae of North America* (Second Edition). Academic Press, pp 375-427. <https://doi.org/10.1016/B978-0-12-385876-4.00008-6>
- Jung, S., Cho, H., Kim, D., Kim, K., Han, J.I. and Myung, H. (2017).

- Development of algal bloom removal system using unmanned aerial vehicle and surface vehicle. *IEEE Access*, 5, 22166-22176. <https://doi.org/10.1109/ACCESS.2017.2764328>
- Kennedy, A., McQueen, A., Ballentine, M., Fernando, B., May, L., Boyda, J., Williams, C. and Bortner, M. (2022). *Sustainable Harmful Algal Bloom Mitigation by 3D Printed Photocatalytic Oxidation Devices (3D-PODs)*. Engineer Research and Development Center, USA. <https://doi.org/10.21079/11681/43980>
- Khatib, T., Qalalweh, S., Ameerah, R. and Warad, I. (2019). An efficient method for water treatment of artificial ponds in Jordan valley based on photovoltaic pumping system. *Agriculture*, 9(7), 151. <https://doi.org/10.3390/agriculture9070151>
- Kim, M.S. and Kwak, D.H. (2014). Evaluation of initial collision-attachment efficiency between carbon dioxide bubbles and algae particles for separation and harvesting. *Water Sci. Technol.*, 69(12), 2482-2491. <https://doi.org/10.2166/wst.2014.171>
- Kumar, N., Banerjee, C., Negi, S. and Shukla, P. (2023). Microalgae harvesting techniques: Updates and recent technological interventions. *Crit. Rev. Biotechnol.*, 43(3), 342-368. <https://doi.org/10.1080/07388551.2022.2031089>
- Kwak, D.H. (2015). Flotation of algae for water reuse and biomass production: role of zeta potential and surfactant to separate algal particles. *Water Sci. Technol.*, 72(5), 762-769. <https://doi.org/10.2166/wst.2015.265>
- Laamanen, C.A., Ross, G.M. and Scott, J.A. (2016). Flotation harvesting of microalgae. *Renew. Sust. Energ. Rev.*, 58, 75-86. <https://doi.org/10.1016/j.rser.2015.12.293>
- Liu, P.R., Yang, Z.Y., Hong, Y. and Hou, Y.L. (2018). An in situ method for synthesis of magnetic nanomaterials and efficient harvesting for oleaginous microalgae in algal culture. *Algal Res.*, 31, 173-182. <https://doi.org/https://doi.org/10.1016/j.algal.2018.02.013>
- Liu, Z.Y., Hao, N.H., Hou, Y.Y., Wang, Q., Liu, Q.L., Yan, S.H., Chen, F.J. and Zhao, L. (2023). Technologies for harvesting the microalgae for industrial applications: Current trends and perspectives. *Bioresour. Technol.*, 387, 129631. <https://doi.org/10.1016/j.biortech.2023.129631>
- Morgan, A.M., Royer, T.V., David, M.B. and Gentry, L.E. (2006). Relationships among nutrients, chlorophyll-a, and dissolved oxygen in agricultural streams in Illinois. *J. Environ. Qual.*, 35(4), 1110-1117. <https://doi.org/10.2134/jeq2005.0433>
- Najjar, Y.S.H. and Abu-Shamleh, A. (2020). Harvesting of microalgae by centrifugation for biodiesel production: A review. *Algal Res.*, 51, 102046. <https://doi.org/10.1016/j.algal.2020.102046>
- North, R.L., Davies, J.M., Doig, L.E., Lindenschmidt, K.E. and Hudson, J.J. (2015). Lake Diefenbaker: The prairie jewel. *J. Gt. Lakes Res.*, 41, 1-7. <https://doi.org/10.1016/j.jglr.2015.10.003>
- Page, M.A., MacAllister, B.A., Campobasso, M.A., Urban, A.B., Thomas, C.C., Cender, C.J. and Lovins, W. (2021). *Optimizing the Harmful Algal Bloom Interception, Treatment, and Transformation System (HABITATS)*. Engineer Research and Development Center, USA. <https://doi.org/10.21079/11681/42223>
- Page, M.A., MacAllister, B.A., Urban, A., MacAllister, I.E., White, C.S., Pokrzywinski, K.L., Riley, J. and Schmidt, A. (2020). *Harmful Algal Bloom Interception, Treatment, and Transformation System, "HABITATS"*. Engineer Research and Development Center, USA. <https://doi.org/10.21079/11681/35214>
- Phoochinda, W. and White, D.A. (2003). Removal of algae using froth flotation. *Environ. Technol.*, 24(1), 87-96. <https://doi.org/10.1080/0959330309385539>
- Phoochinda, W., White, D.A. and Briscoe, B.J. (2005). Comparison between the removal of live and dead algae using froth flotation. *J. Water Supply Res. Technol. Aqua.*, 54(2), 115-125. <https://doi.org/10.2166/aqua.2005.0011>
- Ren, B., Weitzel, K.A., Duan, X., Nadagouda, M.N. and Dionysiou, D.D. (2022). A comprehensive review on algae removal and control by coagulation-based processes: Mechanism, material, and application. *Sep. Purif. Technol.*, 293, 121106. <https://doi.org/10.1016/j.seppur.2022.121106>
- Shokoohi, R., Rahmani, A., Asgari, G., Ashrafi, M. and Ghahramani, E. (2023). Removal of algae using hydrodynamic cavitation, ozonation and oxygen peroxide: Taguchi optimization (case study: raw water of Sanandaj water treatment plant). *Process Saf. Environ. Protect.*, 169, 896-908. <https://doi.org/10.1016/j.psep.2022.11.057>
- Smithheart, J.W. (2018). *Exploring Vertical Mixing and Other Controls on Cyanobacteria Blooms in Shallow Eutrophic Reservoirs*. Master of Science. Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA.
- Sun, R., Sun, P.F., Zhang, J.H., Esquivel-Elizondo, S. and Wu, Y.H. (2018). Microorganisms-based methods for harmful algal blooms control: A review. *Bioresour. Technol.*, 248, 12-20. <https://doi.org/10.1016/j.biortech.2017.07.175>
- Sun, X., Liu, J., Ji, L., Wang, G., Zhao, S., Yoon, J. Y. and Chen, S. (2020). A review on hydrodynamic cavitation disinfection: The current state of knowledge. *Sci. Total Environ.*, 737, 139606. <https://doi.org/10.1016/j.scitotenv.2020.139606>
- Tchobanoglous, G., Leverenz, H. and Zeller, D. (2022). Applying Aphron technology innovation in air flotation leads to solid alternative to a legacy process. *Water Environ. Technol.*, <https://heroninnovators.com/applying-aphron-technology>.
- Tian, Z., Wang, C. and Ji, M. (2018). Full-scale dissolved air flotation (DAF) equipment for emergency treatment of eutrophic water. *Water Sci. Technol.*, 77(7-8), 2018046. <https://doi.org/10.2166/wst.2018.046>
- Tse, S.P.K., Yung, K.F., Lo, P.Y., Lam, C.K., Chu, T.W., Wong, W.T. and Lo, S.C.L. (2022). Rapidly deployable algae cleaning system for applications in freshwater reservoirs and water bodies. *Phycology*, 2(1), 60-75. <https://doi.org/10.3390/phycolgy2010004>
- Venturino, A., Montagna, C.M. and de D'Angelo, A.M.P. (2007). Risk assessment of Magnacide® H herbicide at Río Colorado irrigation channels (Argentina). Tier 3: Studies on native species. *Environ. Toxicol. Chem.*, 26(1), 177-182. <https://doi.org/10.1897/06-085R.1>
- Waghmare, A., Nagula, K., Pandit, A. and Arya, S. (2019). Hydrodynamic cavitation for energy efficient and scalable process of microalgal cell disruption. *Algal Res.*, 40, 101496. <https://doi.org/10.1016/j.algal.2019.101496>
- Wiley, P.E., Brennenman, K.J. and Jacobson, A.E. (2009). Improved algal harvesting using suspended air flotation. *Water Environ. Res.*, 81(7), 702-708. <https://doi.org/10.2175/106143009X407474>
- Wurtsbaugh, W.A., Paerl, H.W. and Dodds, W.K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *Wiley Interdiscip. Rev. Water*, 6(5), e1373. <https://doi.org/10.1002/wat2.1373>
- Yang, S.S., Twiss, M.R., Fernando, S., Grimberg, S.J. and Yang, Y. (2022). Mitigation of cyanobacterial harmful algal blooms (cHABs) and cyanotoxins by electrochemical oxidation: From a bench-scale study to field application. *ACS EST Engg.*, 2(7), 1160-1168. <https://doi.org/10.1021/acsestengg.1c00344>
- Zhan, M.M., Liu, P.R., Liu, X.Y., Hong, Y. and Xie, X. (2021). Inactivation and removal technologies for algal-bloom control: Advances and challenges. *Curr. Pollut. Rep.*, 7(3), 392-406. <https://doi.org/10.1007/s40726-021-00190-8>
- Zhang, H.H., Yan, M.M., Huang, T.L., Huang, X., Yang, S.Y., Li, N. and Wang, N. (2020). Water-lifting aerator reduces algal growth in stratified drinking water reservoir: Novel insights into algal metabolic profiling and engineering applications. *Environ. Pollut.*, 266, 115384. <https://doi.org/10.1016/j.envpol.2020.115384>
- Zheng, H.X., Zheng, Y. and Zhu, J. (2022). Recent developments in hydrodynamic cavitation reactors: Cavitation mechanism, reactor design, and applications. *Eng.*, 19, 180-198. <https://doi.org/10.1016/j.eng.2022.04.027>