Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2023.29857

307 (2023) 222–231
September

On-site algae harvesting system using tailored bubble flotation

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Received 2 November 2020; Accepted 17 August 2023

ABSTRACT

This study investigated the efficacy of an algae harvesting system based on tailored bubble flotation in lakes prone to lake eutrophication. To improve algae removal, a bubble generator for adjusting the size and amount of bubble charge was applied to the customized algae removal system. A coagulant, polyaluminum hydroxy chloro sulfate, was optimized at 10 mg/L to maximize its efficacy in sludge recovery. Field tests demonstrated substantial reductions in total nitrogen (TN) and total phosphorus (TP) in sediments, with efficiencies exceeding 80% and 85%, respectively. The final TN and TP concentrations were 1.97 and 0.06 mg/L, respectively, showing overall improvement in the region where the algae harvesting system operated. In addition, suspended solids, Chl-a, and chemical oxygen demand concentrations decreased with algae removal, leading to improved water quality. Therefore, the tailored bubble flotation system presents a viable solution for efficient algae management and overall water quality improvement in lakes and reservoirs.

Keywords: Algal blooms; Water quality; Tailored bubble; Flotation

1. Introduction

Against the backdrop of climate change, the importance of effective water management, with appropriate management of lakes being crucial for securing our scarce water resources, has garnered increasing attention [1,2]. In particular, most of the reservoirs in Korea are artificial, and the lake is likely to be eutrophied owing to the construction of an irrigation reservoir [3,4]. Eutrophication, driven by nutrient pollution from both external and internal sources, leads to excessive growth of algae or cyanobacteria, a phenomenon that poses significant threats to aquatic ecosystems, water aesthetics, and human health [5,6]. This nutrient influx primarily comprises nitrogen and phosphorus from agricultural runoff, wastewater discharge, atmospheric deposition, and lakebed sediments [7–9].

Current methods for dealing with excessive algae growth due to eutrophication involve physical strategies, including aeration and flotation; chemical methods, such as algicides, red clay, and coagulation sedimentation; and biochemical methods using aquatic plants [10–14]. Filtration is a reliable method and reservoiricularly effective when combined with other water treatment processes. Its limitations include the difficulties in filtering out smaller, filamentous types of algae and potentially high costs, particularly in relatively large water bodies owing to the labor-intensive nature of the process and the need for periodic maintenance [15,16].

Flotation, while effective for certain algae types, relies heavily on several variable factors, such as the type and concentration of coagulant and algae, and the water quality parameters [11,12]. The requirement for close monitoring, the potential for water quality issues resulting from incorrect coagulant dosage, and the overall expense

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of coagulants contribute to the high cost of using this method [16].

Modified clay treatment effectively combats certain types of surface bloom-forming algae, but its effectiveness is subject to similar variables such as flotation. Additional drawbacks include increased turbidity, sediment accumulation, and the high cost of the clay materials and their application [9,17]. However, these traditional methods often offer temporary relief at best, and at worst, can trigger secondary pollution and further degrade water quality [14,18]. These limitations necessitate a relatively sustainable and efficient solution for managing lake eutrophication.

A common approach toward water quality improvement is the use of dissolved air flotation, which involves the use of a microbubble generator [18,19]. Recent advancements in technology and elucidation of aquatic ecosystems have facilitated the development of innovative, tailored solutions [20–22].

Comparatively, the proposed algae harvesting system using tailored bubble flotation has shown significant potential, demonstrating high removal efficiency without significantly impacting water quality parameters [23,24]. This system is field-deployable, meaning it can be easily moved to various locations, and it primarily involves the generation of microbubbles and the use of a small amount of coagulant, leading to potentially lower operational and maintenance costs. In contrast with certain methods, this system does not result in sediment accumulation or residual coagulant concentration [9,20,25].

To increase the efficiency of the existing algae removal method, the authors investigated the use of a bubble generator that can effectively control the bubble size by producing relatively small bubbles [19]. In addition, a previous study coupled this method with one that harnesses the charge of algae, reservoiricles, and bubbles in the water by introducing a coagulant that generates bubbles with a positive charge, thereby increasing collision and treatment efficiencies [19,22]. A tailored bubble generator, a bubble generator that can adjust the size and potential of bubbles to increase the efficiency of pollutant removal, was used for this study's algae harvesting system [19,20].

The purpose of this study was to verify the validity of the green algae removal method involving the use of Tailored bubbles. The algae harvesting system equipped with a tailored bubble generator was used to remove algae and clean the sedimentary sludge. The operation of this system was conducted on reservoirs used for irrigation, and the water quality of reservoirs that were not managed at all was regarded as the control group.

2. Materials and methods

2.1. Study area

This field study was performed in the Sungdong reservoir located in Jeon-Nam province, South Korea (34°98′58.57″N, 126°48′21.59″E). The reservoir was built to provide water supply for agricultural land in 1975. It is located close to agricultural lands and small towns, from which wastewater flows into the reservoir and causes eutrophication by algal blooming. It has a surface area of approximately 70,000 m^2 and an average depth of 5 m with a capacity of 270,930 tons (Fig. 1a).

2.2. Monitoring sites and period

To evaluate the efficiency of the algae harvesting system using tailored bubble, the water quality of the two regions was monitored, as shown in Fig. 1b: A (control) and B (application of the algae harvesting system using tailored bubble). The algae harvesting system was operated in region B of the reservoir, and the efficiency of algae harvesting was verified compared to region A, which constituted the control group. The operation of the algae harvesting system in region B was carried out for 6 months (May to September 2016). Sediment washing in region B using the tailored bubble generator was performed for 5 months (March to July 2016). To analyze the correlation between reservoir water quality, seasonal effects, and the topographical characteristics of the reservoir, sampling and water quality monitoring of regions A and B of the reservoir were conducted from March 2016 to February 2017 (Fig. 1b). The monitoring of sediment in region B of the reservoir was also carried out every month from March 2016 to February 2017.

2.3. Equipment and procedure

A ship-based algae harvesting system using tailored bubble flotation was used to remove algae in a reservoir. The algae harvesting ship was only operated in region B, where

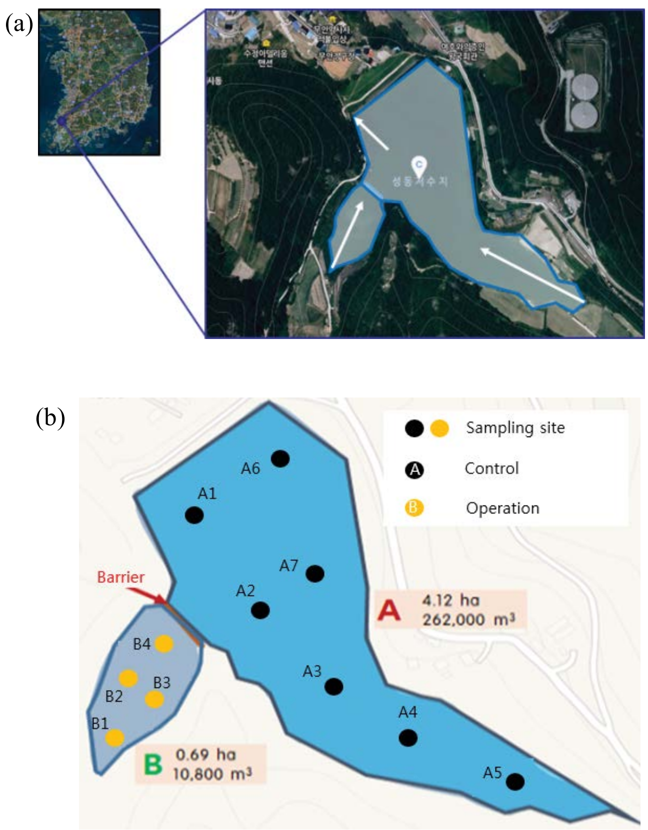

Fig. 1. Map of the study area (a) and sampling sites (b).

the effect of algae harvesting and sediment cleaning was analyzed. The ship consists of six main devices (Fig. 2): (1) the ship, (2) an auto fence to prevent spreading, (3) a bubble generator, (4) a sediment cleaner and algae harvesting equipment, (5) an auto-scraper, and (6) a dewatering system.

In the first step, the auto-fence, installed on the ship for algae harvesting, was submerged. In the second step, bubbles were applied 20 cm from the bottom of the reservoir. The coagulants used with the bubbles were polyaluminum hydroxy chloro sulfate (PAHCS, Al_2O_3 10%, Sam Gu Chemical Co., Korea), which showed optimum efficiency in the tailored bubble generator and added to the final concentration of 10 mg/L. In the third step, sediments and algae were floated as scum on the water surface and were collected by an auto scraper. Finally, the collected scum was dehydrated by a dehydrator. The picture and schematic graph are shown in Fig. 3. In addition, several preparation tests were performed for effective performance of the ship-based algae harvesting system with tailored bubble flotation. These included system stabilization for the algae harvesting system, and determination of optimal PAHCS concentration, pressure, bubble size, and number.

2.4. Bubble generator technology

The algae harvesting system was fitted with a tailored bubble generating device developed in previous studies. This splitter type bubble generator simultaneously intakes water and air using a centrifugal pump and sprays bubbles from a tank where the air and water mix [19–21]. The existing saturator-type bubble generator is composed of a high pressure recycle pump, an air compressor, and a saturator, which is complicated and difficult to operate. However, in this system, the air was introduced into the pump through the air intake valve, and the water was simultaneously sucked through the suction pipe to enter the splitting tank. The pressurized and decompressed water were then mixed again. The pressurized water in the gas–liquid mixed state was discharged to an atmospheric pressure state through the nozzle, and bubbles were generated due to pressure reduction and bubble collapse resulting from shear forces. The bubble generating apparatus may generate bubbles ranging in size from 20 to 30 μm; the operational conditions are shown in Table 1. PAHCS was used to control the zeta potential of the bubbles. Previous studies have provided reference for the generation of customized bubbles using PAHCS [20].

2.5. Sample analysis

Samples were taken every month from March 2016 to Feb 2017. Control region A and sediments in region B where the tailored bubble generator was applied were collected using a grab sampler. The collected sample was immediately transferred to the laboratory and dried; then visually distinguishable organic matter was removed and pulverized. The crushed sample was filtered through a 2 mm sieve (ASTM Standard No. 10) for the experiment. Total nitrogen (TN) and total phosphorus (TP) concentrations in the pretreated sediments were determined using the Kjeldahl method [26]. To evaluate the efficiency of the algae harvesting system, samples from region A (control) and region B were collected and analyzed using the water pollution process test method for suspended solids (SS), TN, TP, and chemical oxygen demand (COD). Temperature, dissolved oxygen (DO), and pH were measured directly in the field using a

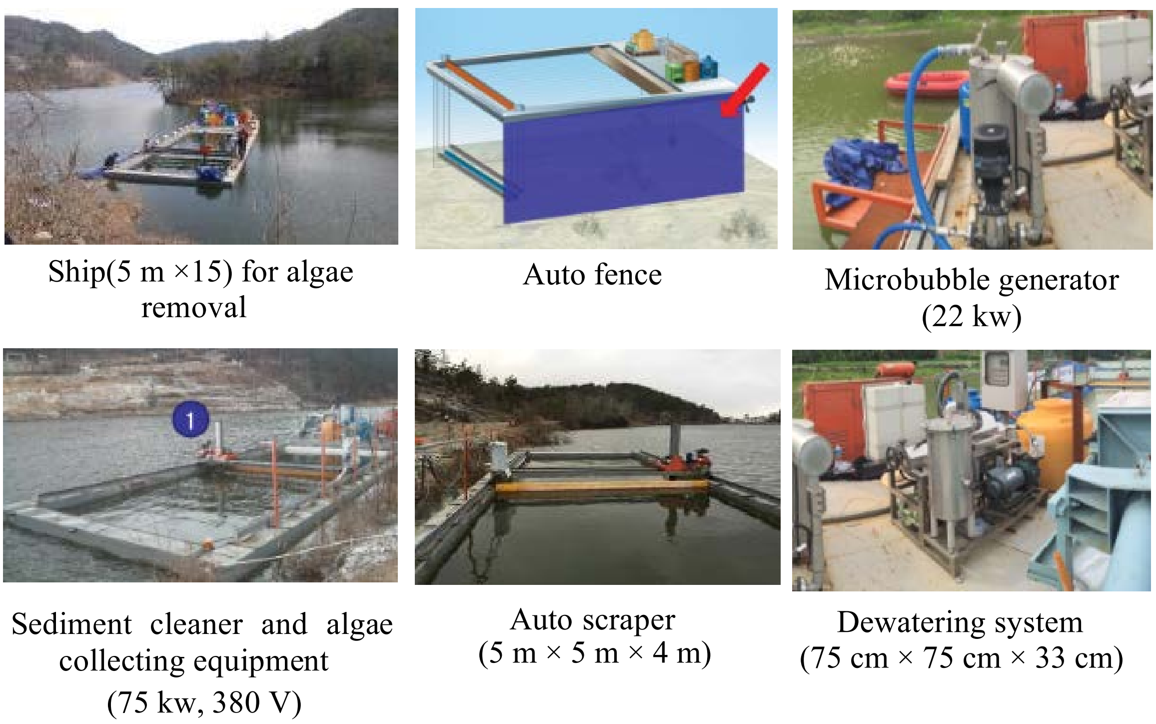

Fig. 2. Ship specifications including components for algae removal.

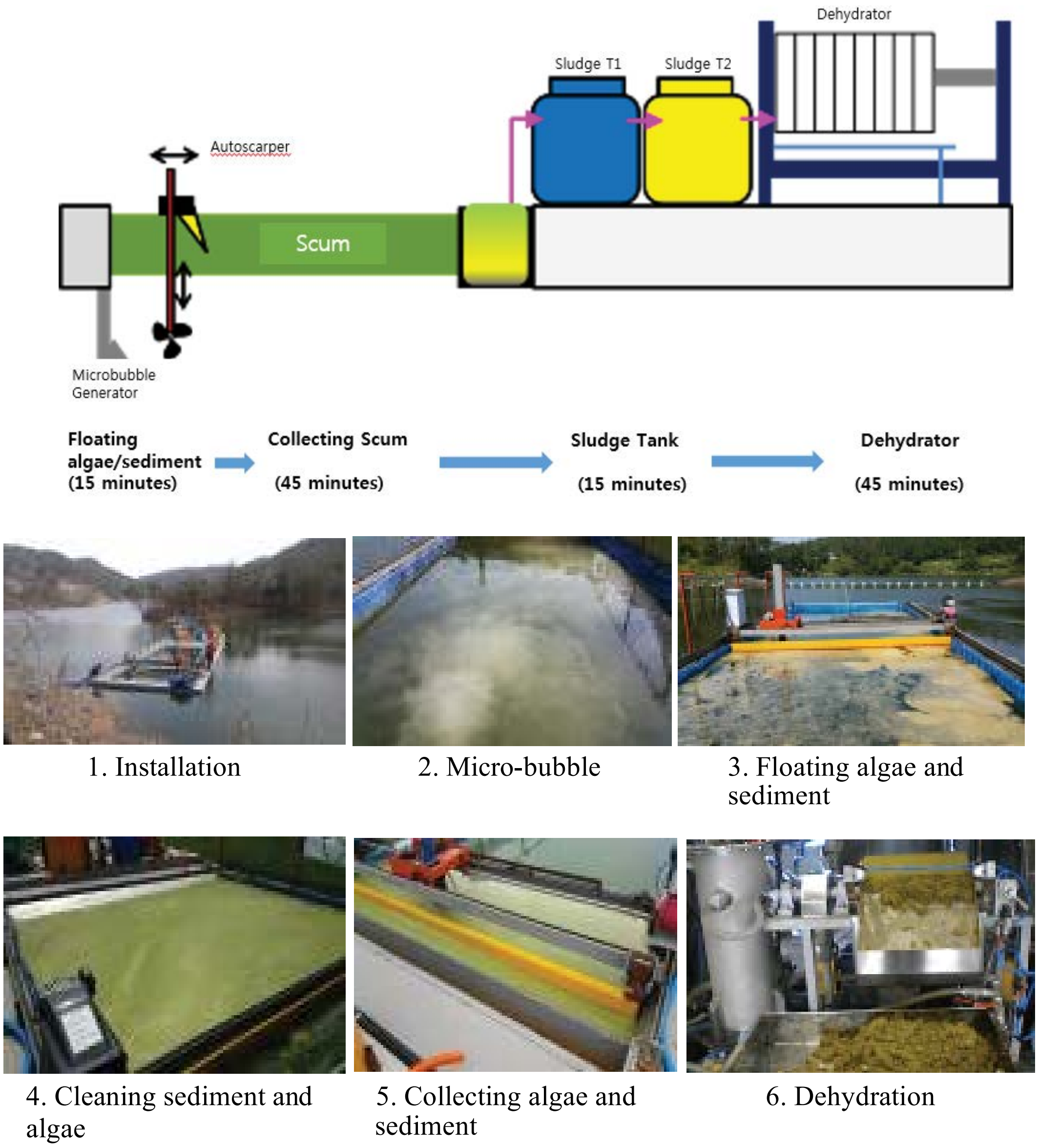

Fig. 3. Operational process of the algae removal treatment system.

water quality measuring instrument (Orion, YSI620). To analyze the dominant algae species, a sample was placed in a 500 mL sterilized polyethylene bottle and precipitated with lugol solution for 2 weeks. The supernatant was then concentrated. Algae cell counts were determined using a Palmer-Maloney counting chamber. Algae was identified using extracted 16S rDNA and the PCR technique by a genomic traction DNA kit. Table 2 shows a summary of the analytical parameters and methods for water and sediment analysis.

2.6. Statistical analysis

Correlation analysis was employed to determine the possible relationship between water quality and microbiological parameters. In addition, we performed a nonparametric Spearman's rank correlation to compare relevant parameters. Factor analysis was applied to reduce the number of parameters. Finally, the correlation value ranged from –1 to +1; any results with a correlation of ≤0.3 were excluded from this study.

3. Results and discussion

Conditions for the bubble generator (splitter type bubble generator), bubble size, and charge of bubbles formed in the algae harvesting system of this study were similar to those for previous studies [19–22].

3.1. Determination of PAHCS concentration

A PAHCS coagulant was used to make the bubble charge of the bubble generator a positive charge. In the lab test, the PAHCS concentration was adjusted to 0–20 mg/L based on the results of the previous study [20]. In the Sungdong

Table 1
Bubble generator specification and operational conditions

Bubble generator specification		
Air inhalation methods	Type (Size)	Ball valve/air-ejector (1.4-inch)
Pump	Type/capacity/max. pressure	High flow rate/1–3 HP/6 atm
Splitting tank	Material/shape/volume	SUS 304 L/cylinder/320 L
	Height/diameter No. inner tanks	400 mm/320 mm/7
Nozzle	Type/material	Nozzle/brass (4.5 atm)
Operational conditions		
Average velocity		0.008 knot (14.1 m/h)
Max. velocity		0.010 knot (14.1 m/h)
Operators		3 people
Operating distance		0.69 ha/h
Direction of operation		Outside > Center > Outside
Treatment period		3 d
Treatment capacity		580–4,533 m^3/d
Sediment treatment capacity		900 m^3/d
Elution treatment time		30 min
Fuel type		LNG & D.O
Microbubble size		Average 23 μm diameter

Table 2
Summary of analytical parameters and methods for (a) water and (b) sediment analysis

Parameters of water			
Parameter	Method	Preservation & pretreatment	Materials & analysis period (Mar. 2016–Feb. 2017)
Temperature	–	Direct measurement	YSI 620 (Field)
DO	–	Direct measurement	YSI 620 (Field)
pH	–	Direct measurement	YSI 620 (Field)
EC	–	Direct measurement	YSI 620 (Field)
Turbidity	–	Direct measurement	YSI 620 (Field)
COD	Acid digestion by $KMnO_4$	Add H_2SO_4 conc. (<pH 2) preserved at low temperature	–
SS	Filtering method of GF/C (APHA, 1994)	–	–
TN	UV Spectrophotometric method (APHA,1994)	Add H_2SO_4 conc. (<pH 2) preserved at low temperature	Spectrophotometer HP 8453
TP	Spectrophotometric method (Ascorbic acid) (APHA, 1994)	Add H_2SO_4 conc. (<pH 2) preserved at low temperature	Spectrophotometer HP 8453
Chl-a	Spectrophotometric Method (Acetone extraction) (APHA, 1994)	Extraction of filtered GF/C by acidified acetone	Spectrophotometer HP 8453
Parameters of sediment			
Parameter	Method	Analysis	Reference & analysis period
			(Mar. 2016–July 2016)
Loss of ignition (LOI)	Loss of ignition	Loss of ignition	Korea Standard Method for Marine Environment
TN	Kjeldahl	Kjeldahl	Korea Standard Method for Soil
TP	Perchloric acid, ascorbic acid (Molybdenum blue)	Perchloric acid, Ascorbic acid (Molybdenum blue)	Korea Standard Method for Soil

reservoir, PAHCS were used with the bubbles as a coagulant and a field test was performed for the optimal dose. The nozzle was located 20 cm from the bottom of the reservoir. As shown in Fig. 4, the dry weight of the recovered sludge was highest when 10 mg/L of the PAHCS agglomerating agent was injected, and tended to decrease when the injected PAHCS agglomerating agent was increased. The optimal injection concentration of PAHCS was 10 mg/L in the previous study where the lab test was performed. However, in the lab test, the amount of sludge recovered did not change even when the concentration of PAHCS exceeded 10 mg/L. This result is attributed to the variations in temperature and interfering substances in the field. Therefore, based on the results of the lab test and the field experiment, the concentration of PAHCS was adjusted to 10 mg/L during the operation of the algae harvesting system.

3.2. *Effect of the algae harvesting system with tailored bubble flotation*

3.2.1. *Sediment quality changes*

The algae harvesting system was applied in region B, leaving region A as the control. Fig. 5 shows the cleaning effect of sediment using the algae harvesting system with tailored bubble flotation. In regions A and B, initial average TN concentrations in the sediment were 2,383 and 2,753 mg/kg, respectively. Over time, the TN and TP concentrations in the sediment were significantly reduced. The efficiency of the algae harvesting system sharply increased during the ship operational period. Initial removal efficiencies were 32.7% for TN and 16% for TP in April and, after May, the removal efficiencies were more than 80% for TN and 85% for TP. Therefore, the major factors controlling the release of nitrogen and phosphorus from the sediment are thought to

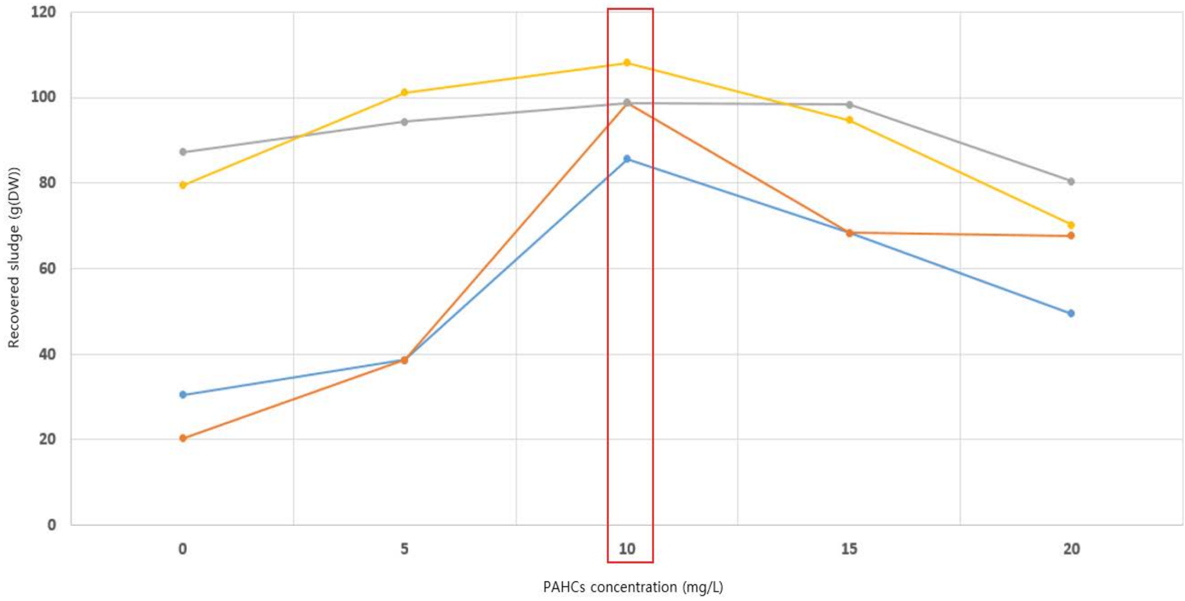

Fig. 4. Determination of optimal polyaluminum hydroxy chloro sulfate concentration.

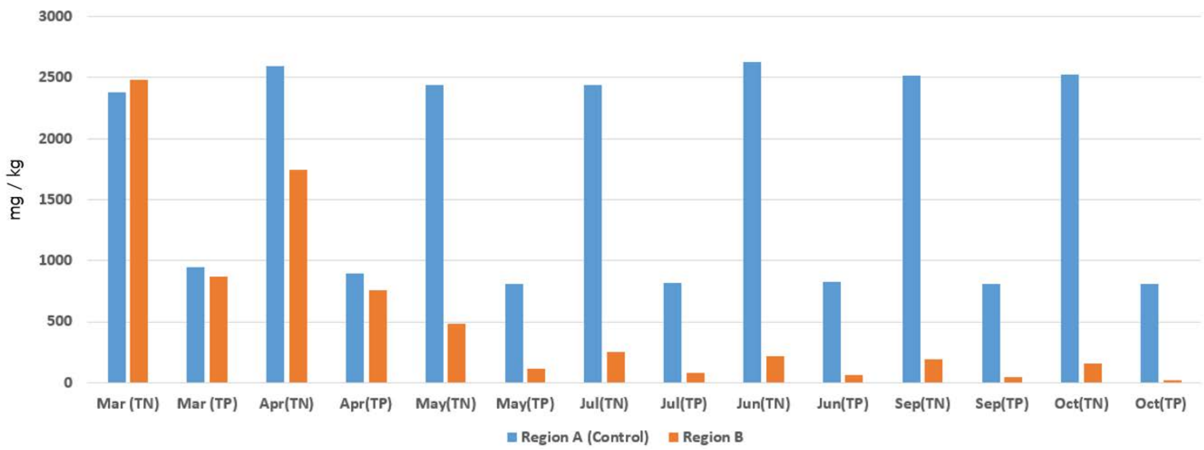

Fig. 5. Sediment cleaning effect following change in concentration after seven months of tailored bubble flotation.

be related to physical impacts rather than chemical effects [27]. The first physical mechanism for nitrogen and phosphorus release is bubble explosion. Second, the energy of bubble explosion increases as the bubble size decreases, and the explosion generates a shear force that increases energy release [27]. Third, smaller bubbles can reach the small pores of the sediments and enhance nitrogen and phosphorus release. Fourth, the increase in injection speed due to the increase in pressure enhances release efficiency by generating strong turbulence. This strong turbulence also increases the dissolution efficiency through active interactions and collisions between sediments [27].

3.2.2. Water quality changes

Field application experiments were conducted at Seongdong Reservoir to verify the effect of improving the water quality of the reservoir where the algae harvesting system was applied. Region A was not treated and was regarded as the control, and the water quality results levels monitored for 1 y are shown in Fig. 6. In region B, an algae harvesting system was operated for seven months. Sediment washing was carried out for five months (March to July 2016) and algae collection for six months (May to September 2016). Fig. 7 shows the water quality results monitored for 1 y from March 2016 to February 2017.

As shown in Fig. 6, for region A, SS 9 mg/L, COD 6 mg/L, and Chl-a 13 mg/L in March, and SS, COD, and Chl-a increased as the water temperature increased. In July, when the water temperature was highest, the values were SS 30 mg/L, COD 13 mg/L, and Chl-a 51 mg/L, and the water quality of the reservoir stabilized from September when the water temperature dropped. Conversely, for region B where the algae harvesting system was operated, the concentration of SS decreased as the experiment progressed, indicating that SS concentration decreases with algae removal, thereby improving the visible water quality, as shown in Fig. 6. In contrast with control A, which had the highest Chl-a concentration in July, SS was 13 mg/L, COD 6 mg/L, and Chl-a 9 mg/L in region B.

The TN concentration showed a similar pattern, except for an increase between August and September. However, in the case of TP, it decreased during the preparation test but then increased after July. These results are attributed to rising water temperatures in summer and heavy rainfall in July causing a lot of soil to flow into the reservoir. The final TN and TP concentrations of 1.97 and 0.06 mg/L, respectively, showed an overall improvement in region B. COD and Chl-a concentrations did not change significantly from May to August, but both decreased in September. Chl-a increased rapidly from 27.8 mg/m^3 in September to 82 mg/m^3 in October, then decreased gradually by 2.6 mg/m^3 in November.

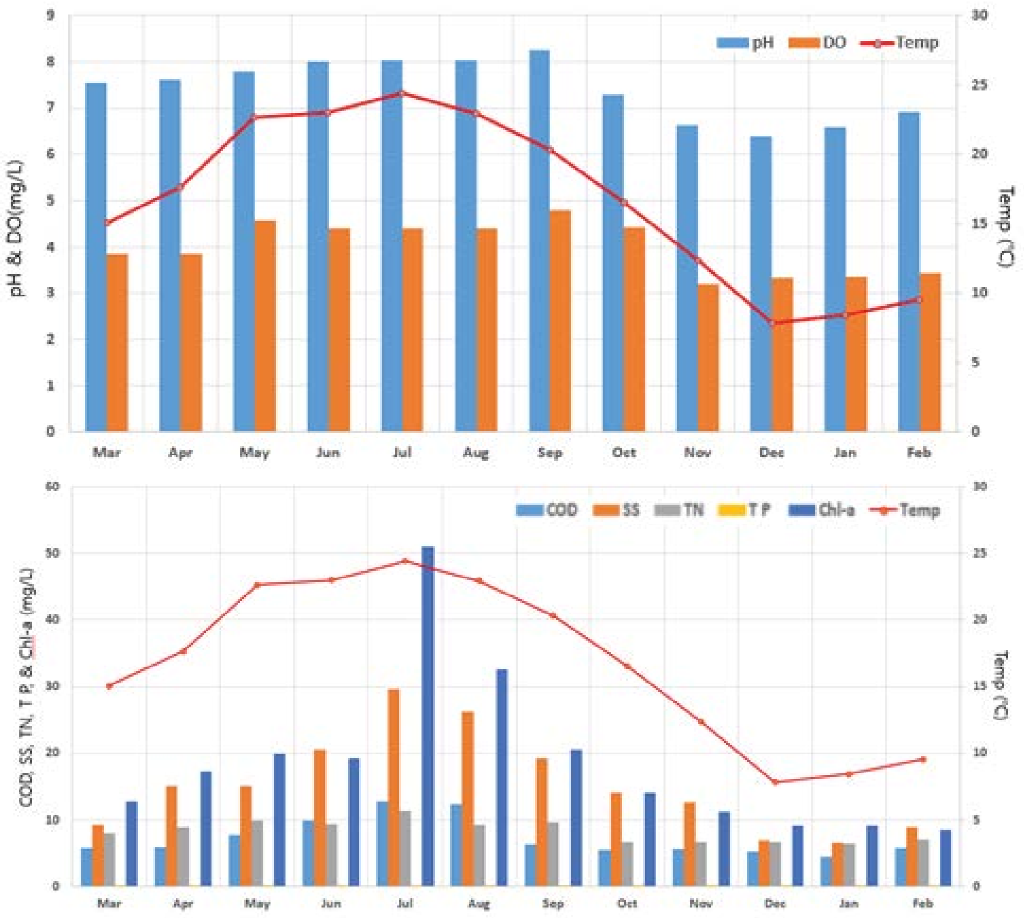

Fig. 6. Monthly average water quality of region A (control).

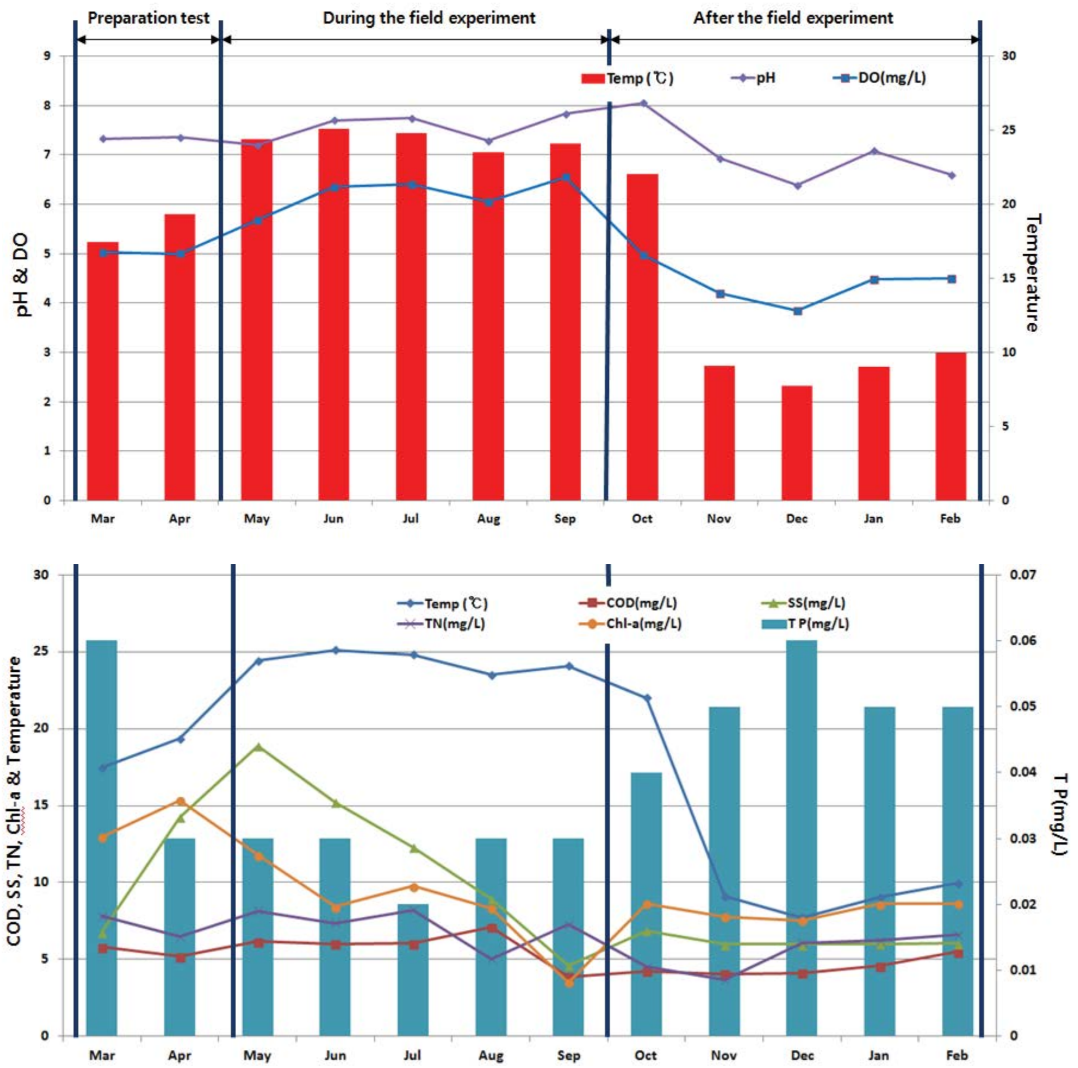

Fig. 7. Water quality change following treatment of region B.

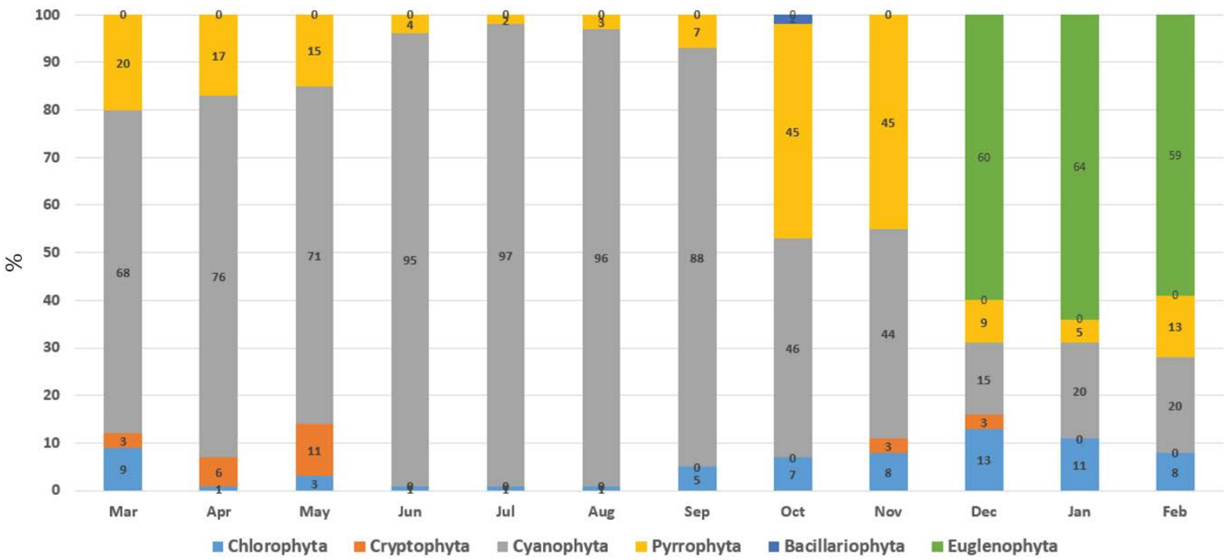

Fig. 8. Monthly distribution of dominant algal species.

Table 3
Correlation analysis of water quality and microbiological parameters

	pH	DO	Temp.	COD	SS	TN	TP	Chl-a	Pyrrophyta	Cyanophyta	Cryptophyta	Chlorophyta	Bacillariophyta	Euglenophyta
pH	1.00	0.80	0.90	0.90	0.90	0.90	–0.60	0.90	–0.50	0.90	–0.30	–0.60	–0.30	–0.70
DO		1.00	0.70	0.60	0.70	0.70	–0.30	0.70	–0.20	0.60	–0.20	–0.50	–0.20	–0.60
Temp			1.00	0.90	1.00	0.90	–0.70	0.90	–0.50	1.00	–0.20	–0.60	–0.20	–0.80
COD				1.00	0.90	0.90	–0.80	0.90	–0.50	0.90	–0.10	–0.60	–0.40	–0.60
SS					1.00	0.80	–0.60	0.90	–0.50	1.00	–0.20	–0.70	–0.10	–0.80
TN						1.00	–0.80	0.90	–0.50	0.80	0.00	–0.60	–0.50	–0.60
TP							1.00	–0.60	–0.20	–0.70	–0.20	0.40	0.40	0.60
Chl-a								1.00	–0.50	0.90	–0.10	–0.70	–0.20	–0.70
Pyrrophyta									1.00	–0.50	0.60	0.10	0.60	–0.20
Cyanophyta										1.00	–0.20	–0.60	–0.30	–0.70
Cryptophyta											1.00	–0.20	0.00	–0.20
Chlorophyta												1.00	0.00	0.50
Bacillariophyta													1.00	–0.30
Euglenophyta														1.00

As a result, when comparing the monitoring results of regions A and B, the water quality improvement effect of region B, where the algae harvesting system was operated, was clear.

3.3. Relationship between dominant algae species and water quality

The distribution of dominant algae species from A1 to A7 is shown in Fig. 8. From March to October, a period of 8 months, Cyanophyta was dominant in this reservoir, while Pyrrophyta was dominant in November and Euglenophyta was dominant for 3 months: December to February. To analyze the relationship between dominant algae species and water quality, the water quality data shown in Fig. 6 were analyzed, and the results are presented in Table 3. Regarding temperature, Cyanophyta and Euglenophyta have a strongly positive (+1.0) and a strongly negative (–0.8) relationship, respectively. Furthermore, Cyanophyta indicate a strongly positive (+0.8) relationship for TN concentration and a strongly negative (–0.7) relationship for TP. In addition, the Chl-a concentration is completely dependent on temperature, COD, SS, and TN.

4. Conclusions

The purpose of this study was to verify the feasibility of an algae removal system using Tailored bubbles applicable to the lake and reservoir. The optimal concentration of PAHCS coagulant, a key component of the bubble generator, was determined to be 10 mg/L. This concentration yielded to the highest dry weight of recovered sludge in the field tests, despite variances in temperature and interfering substances.

The application of the algae harvesting system drastically reduced the TN and TP concentrations in the sediment over time, with removal efficiencies exceeding 80% and 85%, respectively, after the operational period of the ship. These findings were attributed to physical effects, including bubble explosion and increased pressure, rather than chemical effects.

Improvements in water quality were also evident, particularly in the region where the algae harvesting system was operational. Reduced concentrations of SS were indicative of improved visible water quality. Meanwhile COD and Chl-a concentrations exhibited an overall decline. Notably, a sharp increase in Chl-a in October suggested that more frequent monitoring and adaptive management could enhance the effectiveness of the algae harvesting system.

The relationship between dominant algae species and water quality was also investigated. Temperature, COD, SS, and TN were found to significantly influence the concentration of Chl-a. For instance, Cyanophyta was positively correlated with temperature and TN concentration, but negatively correlated with TP. Euglenophyta showed a strong negative relationship with temperature.

Based on the study findings, the on-site algae harvesting system using tailored bubble flotation is a promising solution for algae management by reducing the presence of algae and improving the overall water quality. Future research should focus on refining the system's performance under varying conditions and its interaction with different dominant algae species.

Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF-2020R1I1A1A01070853).

This research was supported by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forest (IPET) and Korea Smart Farm R&D Foundation (KosFarm) through Smart Farm Technology Development Program, funded by Ministry of Agriculture, Food and Rural Affair (MAFRA) and Ministry of Science and ICT(MSIT), Rural Development Administration (RDA) (Project No. 421006-03-3-KIST), and by an intramural grant (2Z06831) from the Korea Institute of Science and Technology, South Korea.

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