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THEMATIC ISSUE

Spatial optimization of operating microalgae bioreactor for nitrogen removal and electricity saving

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Abstract

Various biological nitrogen removal processes have been developed for energy saving in the municipal wastewater treatment plant (MWTP). Recently, a nitrogen removal method using microalgae is emerging as an innovative method. This study has addressed how much of nitrogen was removed by microalgae and how much of electric energy was saved at the same time. For the verification purpose, a long term operation was carried out in a round shape reactor to identify an optimum condition of the highest energy saving rate along with the highest nitrogen removal rate, determined by adjusting time using a light emitting diode (LED) to activate photosynthesis reaction of microalgae and aeration time in a laboratory scale. As a result, it was found that 6.6% or up to 23.8% of energy was saved with biological reaction of microalgae, compared with the traditional nitrogen removal process based on nitrification–denitrification. This indicated that the operation can be flexibly conducted according to the specific operating conditions from each MWTP and its own target energy independence rate, and the findings can be used as a base data for applying such methods using microalgae to the actual treatment plant.

Keywords Optimization · BNR · Microalgae · Photosynthesis · Energy saving

Introduction

In the future, renewable energy is expected to attract a great deal of attention because of oil depletion and environmental problems (Sebastian et al. 2017). For this reason, the paradigm of "energy," associated with a municipal wastewater treatment plant (MWTP) has changed from energy consumption to energy production for the last 10 years (Gonzalez et al. 2014; Guven et al. 2019). In accordance with such paradigm shift, various methods and processes have been developed to lower the energy costs required for MWTP operation. Particularly, BNR (biological nitrogen removal) process has been widely used because of advantages of not only the environment but also economic and operational aspects. However, the BNR process is also not free from oxygen demand, because it requires oxygenation for nitrification with the use of electric power. In Korea, it was known that the power for oxygen demand for nitrification was approximately 40% of the total power consumption of the MWTP (Park 2008). Therefore, most previous studies have mainly focused on decreasing the amount of oxygen required for nitrification.

Among many methods to reduce energy associated with oxygen, wastewater treatment using microalgae has been studied (Kim et al. 2013, 2014), The nitrogen removal method using microalgae is relatively different from the previous oxygen saving methods because the oxygen required for nitrification is replaced by photosynthesis of microalgae and energy is produced autonomously by microalgae. However, it has the limitations. First of all, microalgae absorb light within 50 cm of the surface (Weinberger et al. 2011; Lee et al. 2015), when the water depth is enough, the photosynthesis of the algae is not so sufficient at the point where the transparency of sunlight is low as the amount of oxygen generated is quite low for nitrification to occur. In other words, such limitation requires a larger footprint for a nitrogen removal. As a result, the method of using microalgae seemed inappropriate for some countries with small

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Table 1 Characteristics of influent wastewater

	COD_{mn} (mg/L)	BOD (mg/L)	TN (mg/L)	NH_4^+–N (mg/L)	TP (mg/L)
Minimum	62.2	98.7	37.5	27.5	3.16
Maximum	135.3	245.9	40.6	31.2	6.16
Median	104.5	145.8	39.2	28.8	4.42

land. The second limitation is an availability of sunlight. To take advantage of algae photosynthesis, sunlight is always needed. It is quite difficult to cultivate microalgae in countries with large seasonal variations (Min and Hur 2015).

To overcome such limitations, the use of LED is providing a solution with more stable light than sunlight, while using a circular reactor type which is mainly used in existing MWTPs (Kim 2013). Additionally, to prevent the decrease of the nitrogen removal efficiency caused by insufficient light transmittance, the oxygen blower was used, which turned out to be effective from learning of experimental conditions. Ultimately, this article aims to find out how much energy can be saved, when using microalgae with some aeration, compared with the conventional nitrogen removal method only using an oxygen blower.

Materials and methods

Materials

Characteristics of influent wastewater

The influent wastewater used was sewage obtained from a domestic MWTP in Korea. Table 1 shows the basic properties of the influent wastewater. When the ammonia nitrogen was removed, the required alkalinity was about 7.14 (Bagchi et al. 2012). In this study, the concentration range of ammonia nitrogen was 27.5–31.2 mg/L. The alkalinity of the influent wastewater was adjusted to be higher than 230 mg/L. In addition, the optimum range of pH for the environment of nitrifying microorganisms, was maintained at pH of 7.5–8.5 (Im et al. 2014; Im and Gil 2015). Water quality analysis was conducted using standard methods (APHA (American Public Health Association) 2012).

Microalgae species

Chlorella vulgaris species, single-celled algae belonging to the order Chlorococcales, was used for this study. They are a spherical or elliptical shape with a small diameter of 2–10 µm and grow rapidly. They are known to contain chlorophyll-a and chlorophyll-b of photosynthetic pigments and reproduce asexually using spores (Marcin et al. 2016). In addition, the content of protein reaches 50% of the dry weight and the theoretical photosynthetic efficiency is as high as 8%, so they are expected to have a high value as food and energy sources (Chia et al. 2013).

Biological reactor

Figure 1 shows a schematic of the biological reactor. The laboratory scale reactor was made out of an acrylic cylinder with a volume of 3 L. The reactor before the two reactors was used for denitrification to happen by maintaining an anoxic state. The latter reactor was for nitrification with oxygen generated from photosynthesis of microalgae as well as from the oxygen blower.

In this study, the attached growth method was applied using media which are two types. One is K-3 (Kaldnes), which takes the shape of a toothed wheel and is mostly used for the cultivation of algae. The other is a media made of polyurethane for nitrifier. The reason for using the attached growth method is to prevent both bacteria loss caused by a short HRT and the light blocking phenomenon typically occurred by increased mixed liquor suspended solids (MLSS).

The LED is one of the reactor's important components that can help the photosynthesis of microalgae. Literature found that photosynthetic reactions of microalgae were more active at mixed wavelengths than at single wavelengths (Kaneko et al. 2006), meaning that nitrification proceeded more successfully at the mixed wavelength because of sufficient oxygen provided. An experiment was preliminarily carried out, testing different combinations of red (530–550 nm), blue (450–460 nm), and white wavelength (400–700 nm) (Kang 2016). As a result of the previous testing, when the red and blue wavelengths were combined, more oxygen was generated from the photosynthesis of microalgae. Hence, the combination of red and blue was found more effective and used in this study. A power meter was installed in each device using power to check the power in real time. It was installed in the locations where the stirring motor, the oxygen supplier, the pump, and the LED are placed. Table 2 exhibits characteristics of reactor components.

Methods

Photosynthesis of microalgae

Photosynthesis is the process by which green plants and algae synthesize organic matter from carbon dioxide and

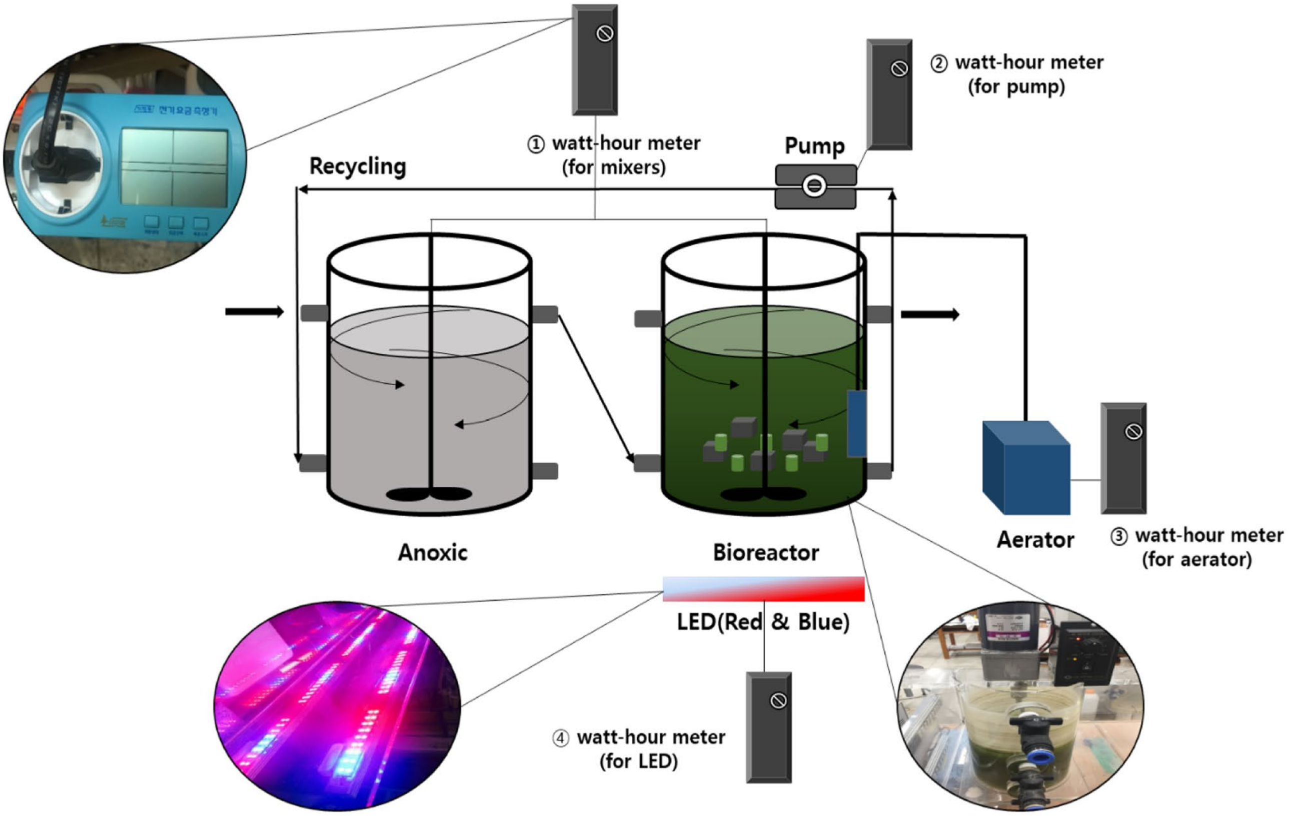

Fig. 1 Schematic diagram and figure of laboratory scale reactors

Table 2 Characteristics of reactor components

	Characteristics	
Microbial growth method	Attached growth	
Used media	K-3	Polyurethane
	Specific gravity: 0.95 Shape (size): gear wheel (radius 12–14 mm) Specific surface area: 500 m^2/m^3	Specific gravity: 0.07 Shape (size): Cube (15*15*15 mm) Specific surface area: 2000 m^2/m^3
LED	PPFD (photosynthetic photon flux density): 195–390 $\mu mol/m^2 \cdot s$	
Watt–hour-meter	Range: 0.1–3520 W	

water using energy from the sun. The photosynthetic reaction proceeds in the chloroplast, the light reaction takes place in the thylakoid membrane, and the dark reaction occurs in the stroma (Kang 2016). In the photosynthesis of microalgae, carbon dioxide, nutrients, and vitamins are converted to glucose, oxygen, nicotinamide adenine dinucleotide phosphate (NADPH), adenosine triphosphate (ATP), energy with the help of light (Eq. 1):

$$6CO_2 + 12H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O. \tag{1}$$

Analysis of algae biomass using chlorophyll-a

It is difficult to independently quantify the amount of microalgae because there are various organisms including microalgae, nitrifying bacteria, other bacteria in the reactor. Therefore, a proportion method was proposed. For example, the microalgae biomass concentration can be estimated by measuring the number of chlorophyll-a, which is present in all photosynthesizing organisms except bacteria as well as in the phytoplankton of water bodies. Raschke (1993) estimated that the number of chlorophyll-a accounts for about 1–2% of the dry weight of organic

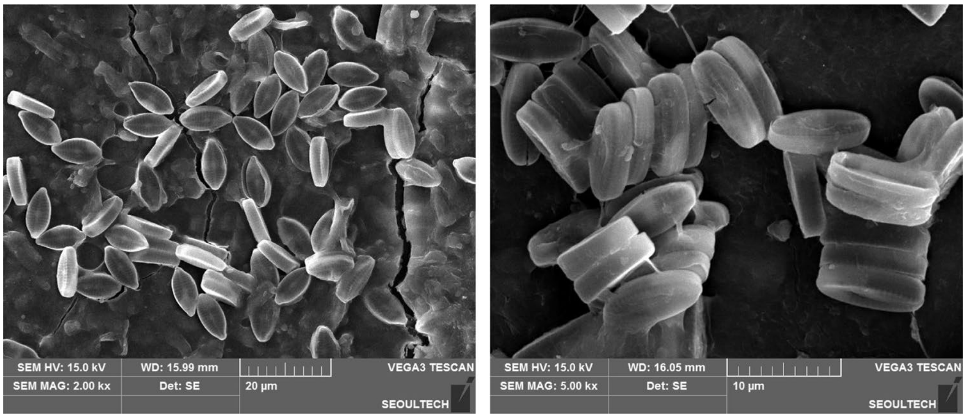

Fig. 2 SEM image of microalgae

Table 3 Operating conditions and nitrogen concentrations in each operating section

	Microalgae biomass (media)	Nitrifier (media)	HRT (SRT)	Infl_NH_4^+	Eff_NH_4^+	Eff_NO_2^-	Eff_NO_3^-
				Median (mg/L)			
A	0	2500–3000 mg/L (Polyurethane)	24 h (20 days)	30.1	5.2	1.2	22.2
B	380–400 mg/L (K-3)			29.3	7.9	1.1	12.4
C				29.1	9.3	1.0	11.2
D				29.2	12.9	0.8	8.2

algal matter. To derive the concentration of microalgae, the following equation was proposed by Raschke (Eq. 2):

$$\text{Algae biomass (mg/L)} = 100 \div 1.5 \times \text{ chlorophyll} - \text{a (mg/L)}. \tag{2}$$

Chlorophyll-a was measured according to the standard methods (2012). First, the samples were filtered with glass microfiber filter (GF: Whatman?)/C,[1] crushed using acetone (9 + 1), then stored in a cold dark place at 4 ℃ for 24 h. After centrifugation (500*g* for 20 min), the amount of chlorophyll-a in supernatant was measured based on it proportional absorbance at wavelengths of 663, 645, and 630 nm. The chlorophyll-a concentration was obtained using the following formula (Eq. 3):

$$\text{Chlorophyll} - \text{a (mg/ml)} = 11.64\ X_1 - 2.16X_2 + 0.10X_3. \tag{3}$$

($X_1 = OD_{663} - OD_{750}$, $X_2 = OD_{645} - OD_{750}$, $X_3 = OD_{630} - OD_{750}$).

OD: optical density.

Results and discussion

The findings of this paper were analyzed stage by stage. The first stage is to investigate the whether nitrification could proceed when the oxygen produced by the photosynthesis of microalgae can be viable for the nitrogen removal. The second stage is to optimize the nitrogen removal efficiency when the photosynthesis time fluctuates. The final step is to quantify how much energy is saved using microalgae, compared to the conventional method. The microalgae species used in this study were Chlorella vulgaris, an enlarged view of microalgae obtained by scanning electron microscope (SEM) in Fig. 2.

Applicability of microalgae to nitrification

The experiments including sections A through D were conducted for 200 days with 24 h of hydraulic retention time (HRT) and 20 days of solid retention time (SRT). In Table 3, the main operating conditions and nitrogen concentrations applied to each section are presented in this study, and Fig. 3 graphically illustrates the changes of nitrogen and alkalinity in each section.

In section A, the influent concentration of ammonia nitrogen was 30.1 mg/L and the effluent concentration was 5.2 mg/L. In section B, ammonia nitrogen flowed in with a concentration of 29.3 mg/L and was released at

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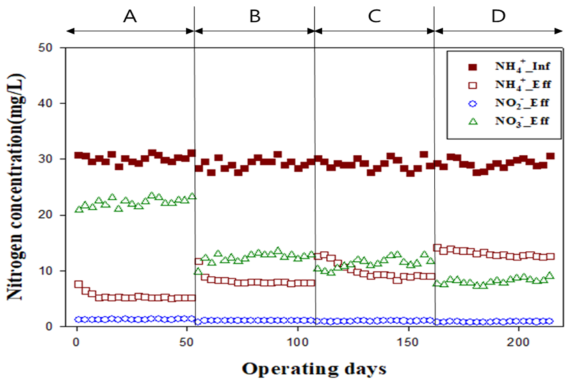
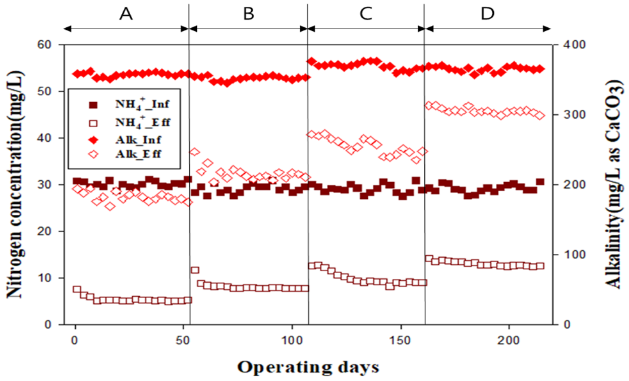
[1] Glass microfiber filters please delete.



(a) Nitrogen concentration variation



(b) Alkalinity variation

Fig. 3 Variations of nitrogen concentrations and alkalinity in each section

Table 4 Summary of results according to photoperiod

	Time ratio (hour) LED: aeration	Ammonium nitrogen removal efficiency (%)	TN removal efficiency (%)
A	0:24	82.8	77.8
B	6:18	72.7	66.1
C	12:12	67.5	60.7
D	24:0	55.0	52.3

a concentration of 7.9 mg/L. In section C, the influent concentration of ammonia nitrogen was 29.1 mg/L and the effluent concentration was 9.3 mg/L. In section D, the ammonia nitrogen with a concentration of 29.2 mg/L was introduced, and the effluent concentration was 12.9 mg/L. As shown in Fig. 3, it was confirmed as the concentration of ammonia nitrogen decreased, the concentration of nitrate nitrogen became increased while the alkalinity was consumed. This indicated that a stable nitrification proceeded with oxygen generated by the photosynthesis of microalgae.

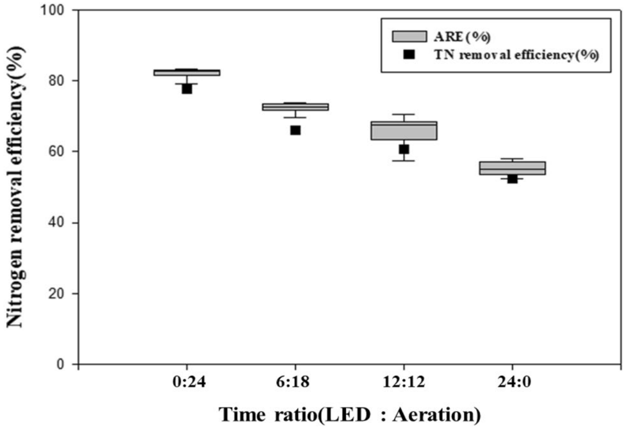


Fig. 4 Ammonium nitrogen and TN removal efficiency according to photoperiod

Analysis of nitrogen removal efficiency for photosynthesis time change

Table 4 summarizes the photoperiod condition, ammonia nitrogen removal efficiency, and TN (total nitrogen) removal efficiency for each operating section as median values. A section was operated for 24 h using only the oxygen supplier as similar as in a conventional MWTP system. In section B, for 6th hour out of 24 h, the LED was turned on to allow operation with oxygen generated by the photosynthesis of the microalgae. During the remaining 18 h the LED was turned off and bioreactor was operated with the oxygen supplier alone. In section C, the LED was used for 12 h of microalgae's activity time and was turned off for the rest 12 h of oxygen supplier time. In section D, the LED was turned on throughout 24 h, which meant that it was operated using only the photosynthesis of microalgae. Figure 4 shows the ammonia nitrogen removal efficiencies according to the photoperiod. The ammonia removal efficiency (ARE) was 82.8% and the TN removal efficiency was 77.8% in section A, which was operated using only the oxygen supplier for 24 h. In section B, the ARE was 72.7% and the TN removal efficiency was 66.1%. In section C, the ARE was 67.5% and the TN removal efficiency was 60.7%. Finally, in section D, which was operated by oxygen generated only by the photosynthesis of microalgae, the ARE was 55.0% and the efficiency of TN removal was 52.3%, the lowest nitrogen removal efficiency among all the sections. It is difficult to obtain a high nitrogen removal efficiency with only photosynthetic oxygen of microalgae based on HRT for 1 day, but it is possible to secure a considerable nitrogen removal efficiency when the photoperiod is appropriately controlled and the oxygen blower is used at the same time.

Table 5 Energy usage and saving rate according to LEUR

	Time ratio (hour) LED:aeration	LEUR (%)	Light energy Usage (kwh)	Aeration energy Usage (kwh)	Energy saving rate (%)
A	0:24	0	0	0.187	0
B	6:18	25	0.024	0.140	5.9
C	12:12	50	0.048	0.094	11.9
D	24:0	100	0.096	0	23.8

Energy savings

As a final step of this study, an evaluation was performed to determine the amount of energy that could be saved, when compared to conventional methods on the laboratory scale when nitrogen is removed by microalgae. Since the photoperiod can be expressed by whether the light energy is used or not, it can be represented by the ratio of the LED time to the total HRT, that is, the light energy use ratio (LEUR).

As seen in Table 5, the results of the analysis show that energy saving was achieved up to 23.8% when using only photosynthetic oxygen of microalgae, compared with the conventional method. However, when operated in this way, the nitrogen removal efficiency was only 52.3% of the total nitrogen, so that there is a possibility that the effluent water quality will deteriorate when applied to actual MWTPs. In other words, it is necessary to be balanced between "the nitrogen removal efficiency" and the "energy saving," depending on the influent characteristics of each MWTP.

For a better understanding, we have simulated how it can be applied to the Korean MWTPs. Figure 5 shows the average inflow, effluent TN concentration, and domestic effluent standards for ten representative MWTPs in Korea which applied the conventional nitrification–denitrification-based technology (Ministry of Environment 2017).

As shown in Fig. 5, the concentration of TN in the domestic effluent standard was 20 mg/L, but when the influent TN concentration was 35.5 mg/L on average, the average effluent concentration was 11.3 mg/L. 68% of the TN was removed. Assuming that such removal efficiency was applied to this study, a simple modeling could be run to find out how much nitrogen removal and energy reduction at the same time were obtained in Fig. 6. The *X*-axis shows energy savings, the *Y*-axis on the left shows the total nitrogen removal efficiency, and *Y*-axis on the right shows the LEUR. A regression graph was created based on the data obtained from experiments. When the average total nitrogen removal efficiency (68%) of MWTPs in Korea was assigned to the regression graph as "Case 1", about 6.6% was saved when compared with a classic BNR.

In the "Case 2" only the oxygen by the microalgae was used without any aeration from a blower, and the energy saving rate was maximized as 23.8%. At this time, TN removal efficiency was 52.3%, and when a domestic average influent TN of 35.5 mg/L was applied, the effluent concentration was 18.6 mg/L that could satisfy the effluent standard, 20 mg/L.

Finally, to find the highest balance between the TN removal efficiency and the LED usage rate, the intersection of the two graphs was prepared as "the Case 3". The TN removal rate was 60.7% and the energy saving rate was 11.9%. It can be induced that energy can be reduced by about 585, 494, 747 kw/h by converting the total annual electricity consumption (4, 920, 123, 924 kw/h) required by Korea's MWTPs in 2017. In addition, when 60.7% of 35.4 mg/L of TN was removed from the average TN influent concentration in a domestic MWTPs, the effluent concentration was about 13.9 mg/L.

The results of this study indicated that the energy independence rate can be maximized according to the target discharge water quality at each MWTP. However, because of the modeling results obtained through the experimental data set, the results on the full-scale are needed to be further studied.

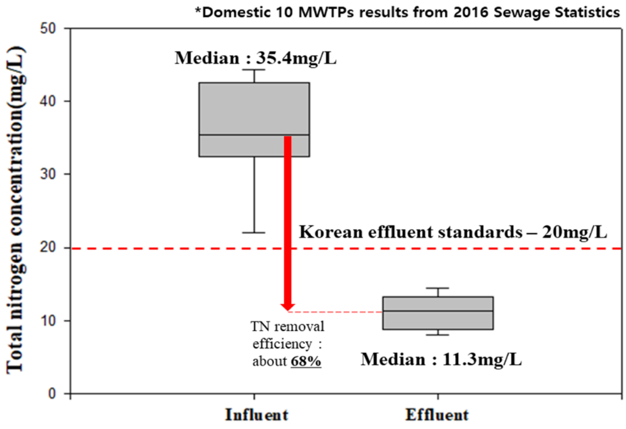
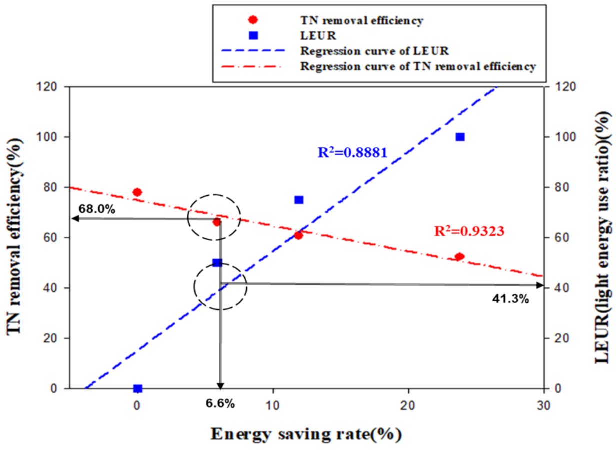
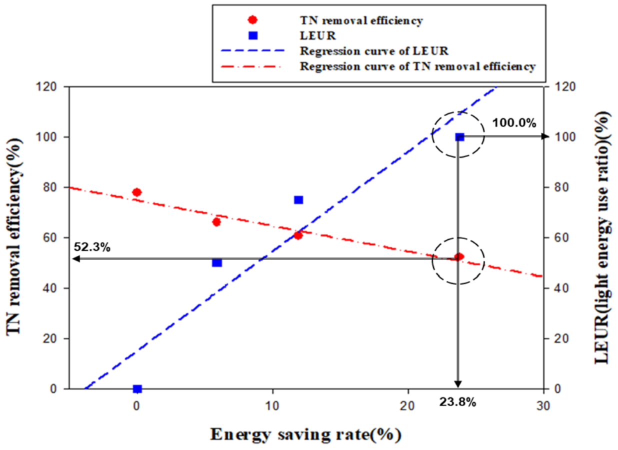


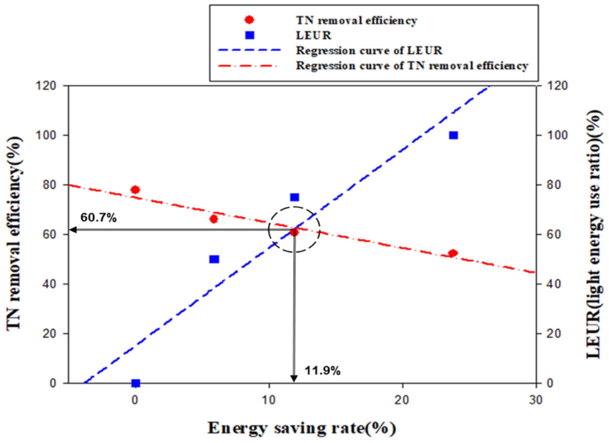
Fig. 5 TN median concentration of influent and effluent in Korean MWTPs



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 6 Energy saving modelling for optimizing

Conclusions

In this study, the operation of a wastewater treatment reactor was carried out by utilizing photosynthetic oxygen generated by microalgae for more than 200 days and optimal operating conditions for energy saving were determined. The results of this study are considered to be economic considerations when introducing microalgae into MWTP. If the proper agreement is found considering the removal efficiency and economic feasibility, it is possible to utilize the microalgae.

1. Nitrogen removal using microalgae was possible in the existing reactor of MWTPs, but the nitrogen removal efficiency was relatively low because of insufficient light transmission. So, it was compensated using the oxygen supplier together. Nitrogen removal efficiency and energy saving rate according to oxygen supply and the LED time were analyzed to determine a highest balance ratio.
2. By adjusting the oxygen utilization of microalgae associated with the LED usage time, electric energy can be saved from a minimum of 6.6% to a maximum of 23.3%.
3. The regression modeling was conducted with the average TN removal efficiency of 60.7%, treating the domestic sewage. As a result, electric energy can be saved by 11.9% while stably meeting the effluent standards. This suggests that the utilization of microalgae can be optimized depending on the environment of each MWTP and the quality of the effluent water.

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