Performance evaluation of novel attached-growth high rate algal pond system with additional artificial illumination for wastewater treatment and nutrient recovery

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ABSTRACT

Domestic wastewater containing a high proportion of organic matter and nutrients is a serious pollution problem in developing countries. This study aimed to evaluate the performance of a novel attached-growth high rate algal pond (AG-HRAP) employing attached-growth media and artificial light sources for treating domestic wastewater and enhancing nutrient recovery. Light intensities in the range of 40–180 μmol/m^2/s were used in the AG-HRAPs. The experimental results showed that the highest chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) removal efficiencies of 88, 62 and 69%, respectively, were found at the hydraulic retention time (HRT) of 15 days and the average light intensity of 180 μmol/m^2/s. Moreover, the effluent COD concentrations could meet Thailand's national discharge standard. The highest biomass and protein productivities of 54 ± 4 and 37 ± 8 g/m^2/d, respectively, were found in the AG-HRAPs, which were higher than in previous studies of HRAPs. The Stover-Kincannon kinetic values for COD, TN and TP removals of the AG-HRAPs ($R^2 = 0.9$) were higher than those of the conventional systems. Additionally, the novel AG-HRAP system could provide a highly cost-effective operation when compared to other microalgal systems.

Key words | artificial light sources, attached-growth high rate algal pond, biomass productivity, domestic wastewater, nutrient recovery

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HIGHLIGHTS

- The novel attached-growth high rate algal ponds (AG-HRAPs) equipped with artificial light sources and attached-growth media were effective for wastewater treatment and biomass production.
- Additional artificial light sources and attached-growth media could enhance biomass and protein productivities, and these could be reused as animal feed, fertilizers, and food additives.
- The novel AG-HRAP system could be highly cost effective in terms of both investment and operation.

LIST OF ABBREVIATIONS

AIT	Asian Institute of Technology	CO_2	carbon dioxide
AG-HRAP	attached-growth high rate algal pond	DO	dissolved oxygen
COD	chemical oxygen demand	HRAP	high rate algal pond

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HRT	hydraulic retention time
LED	light emitting diode
NH_3-N	ammonia nitrogen
NO_2-N	nitrite nitrogen
NO_3-N	nitrate nitrogen
NLR	nitrogen loading rate
OF	optical fiber
OLR	organic loading rate
O_2	oxygen
PLR	phosphorus loading rate
TKN	total Kjeldahl nitrogen
RAB	revolving algal biofilm
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids

INTRODUCTION

Domestic wastewater generated from households is a major problem cause of water pollution in developing counties. In particular, wastewater discharged from toilets contain high levels of organic matter and nutrients (Polprasert & Koottatep 2017). Direct discharging of untreated toilet wastewater leads to various adverse ecological effects and climate change issues, such as eutrophication, low DO levels in water bodies, changing growth rates of aquatic life and depreciation of water quality (Glibert 2017).

To overcome these issues, due to low investment, operation and maintenance costs compared with other treatment systems, the HRAP system, an algal-based wastewater treatment technology employing microalgal-bacterial symbiotic reactions, has been widely applied to reduce both organic matter and nutrients in wastewater. In addition, biomass is produced, which is a way of recovering valuable bio-products such as protein and nutrients (Polprasert & Koottatep 2017).

In the HRAP system, microalgae and bacteria contribute to the production of O_2 and CO_2, respectively. The O_2 produced from photosynthetic processes of microalgae promotes oxidation of organic matter and ammonia by heterotrophic and autotrophic bacteria (nitrifying bacteria), respectively. The CO_2 released from the bio-degradation of organic matter in wastewater is utilized by the microalgae (Chaiwong *et al.* 2018).

Recently, many types of HRAP have been used for both wastewater treatment and biomass production (Uggetti *et al.* 2018). However, HRAP systems have some limitations, such as a large land area requirement, instability of light illumination, low light distribution, low biomass and protein production (Chen *et al.* 2008; Doma *et al.* 2016). Therefore, to minimize those limitations, a novel AG-HRAP system was developed in this study by increasing pond depth, employing attached media and additional artificial light sources.

Hence, this study aimed to evaluate the performance of the novel AG-HRAP in various operating conditions to treat domestic wastewater and enhance nutrient recovery from microalgal biomass. Furthermore, observation of microalgal species in the AG-HRAP under the optimum conditions were undertaken in this study.

MATERIALS AND METHODS

Algal inoculum and wastewater source

In this study, microalgal inoculum (*Chlorella* sp.) was obtained from Chulalongkorn University, Bangkok, Thailand. Untreated domestic wastewater collected from an academic building in the AIT campus, Phathumtani, Thailand, was used as influent wastewater.

Experimental set-up

Three AG-HRAP units were made out of cement, each with a configuration of 0.46 × 0.92 × 1.00 m (width × length × depth) and a working volume of 400 L (Figure 1(a)). Each AG-HRAP was equipped with a baffle and paddle wheels to prevent short-circuiting and maintain mixing conditions, respectively (Figure 1(a)). Attached-growth media, made of nylon mesh with a surface area of 0.23 m^2/piece, were placed into each AG-HRAP, which had a specific surface area of 9.2 m^2/m^3 (Figure 1(b)). The outdoor AG-HRAPs were equipped with combined OF and red-blue LED lamps (Figure 1(c)) (Bogdan®, Bogdan LED – J&Y Trading, Thailand) to continuously illuminate the entire mixed liquor of the AG-HRAP units and therefore promote the photosynthetic reactions of the microalgae. The light intensities inside the AG-HRAPs were controlled with dimmer switches. In this study, the light intensities were measured as photosynthetic photon flux density (PPFD).

Wastewater characteristics

The untreated AIT domestic wastewater was prepared three times a week by mixing it with blackwater to give an N:P

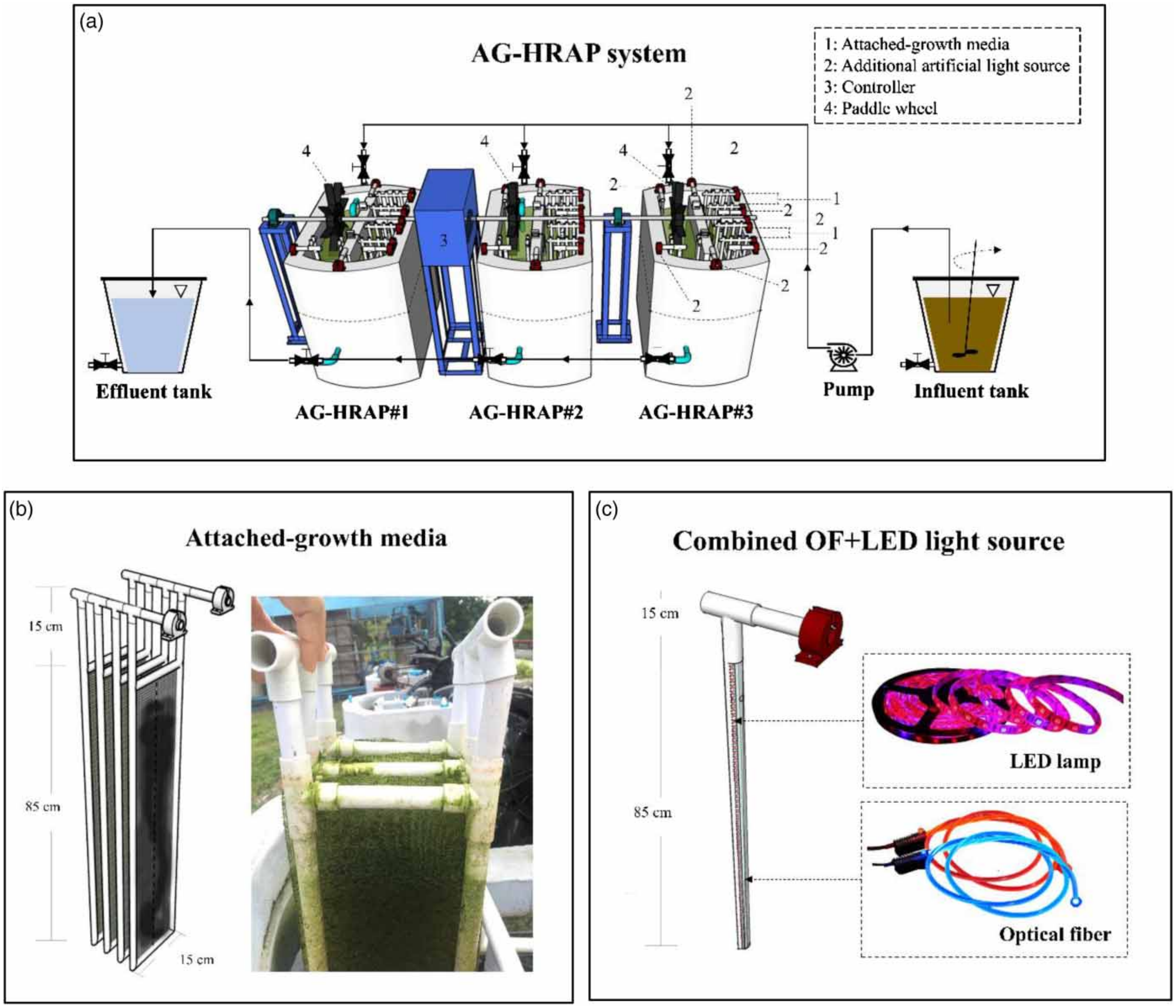

Figure 1 | Experimental set-up of the AG-HRAPs (a), attached-growth media (b), and combined OF and LED light source (c).

ratio of 7:1 and a COD concentration of about 800 mg/L, corresponding to high-strength domestic wastewater (Metcalf & Eddy *et al.* 2014). This was fed to the AG-HRAP units. The influent wastewater characteristics are shown in Table 1.

Cultivation of microalgal-bacterial growth

Microalgal-bacterial biofilm was cultured in the AG-HRAP units according to Chaiwong *et al.* (2018). The three AG-HRAP units were continuously illuminated with light intensities of 40 ± 18, 160 ± 18 and 180 ± 15 μmol/m^2/s, respectively, and under ambient temperature (~30 °C), for 14 days to allow microalgal growth (Lee *et al.* 2014). After that, the AG-HRAP units were continuously fed with the influent wastewater until steady conditions, based on relatively constant effluent COD concentrations, were obtained.

Table 1 | Characteristics of influent wastewater

Parameter	Unit	Influent
pH	–	7.6 ± 0.3
Temperature	°C	27 ± 2.0
DO	mg/L	0.1 ± 0.1
TSS	mg/L	380 ± 84
COD	mg/L	830 ± 140
TN	mg/L	91 ± 9
NH_3-N	mg/L	83 ± 13
TP	mg/L	14 ± 6

Operating conditions

The AG-HRAP units were continuously fed by a peristaltic pump at the average flow rates of 100, 50, and 27 L/d to achieve HRTs of 4, 8, and 15 days, respectively, corresponding to the OLRs, NLRs, and PLRs of 243, 90, and 55; 15, 12, and 5; and 3, 2, and 1 mg/L/d, respectively (Table 2). During the operating periods, the light intensities in the AG-HRAP units were maintained at 40, 160 and 180 μmol/m^2/s to promote growth of algae (Table 2). Furthermore, to prevent biomass settlement and promote better contact between the influent wastewater and the microalgal-bacterial biomass, the rotating speed of the paddle wheel in each AG-HRAP was maintained at 10 rpm, resulting in a mixing velocity of 15 cm/sec and homogeneous water content in the AG-HRAPs (Polprasert & Koottatep 2017).

Analytical methods

Wastewater analysis

Temperature, pH, DO and light intensity were measured on-site using a temperature/pH meter (Mettler Toledo AG 2009), DO probe (Mettler Toledo S4-Standard Kit Seven2Go), and quantum flux meter (Apogee MQ-200), respectively. Light intensity was measured at three points (0.05, 0.35 and 0.65 m) down the depth of the AG-HRAP.

Influent and effluent samples were collected twice a week for analysis of COD, TSS, TKN, NH_3-N, NO_2-N, NO_3-N and TP concentrations at AIT's Environmental Engineering and Management laboratory in accordance with the Standard Methods for Examination of Water and Wastewater (APHA 2012).

Biomass productivity and chlorophyll *a*

Both the attached-growth and suspended-growth biomass of the AG-HRAP units were measured three times a week as TSS. A sharp-edged tool was used to manually scrape the attached-growth biomass from the attached media with a certain scraped area (m^2) and then diluted in 50 mL deionized water. To sample the suspended biomass 50 mL was taken from three depths of the AG-HRAP units (0.05, 0.35 and 0.65 m from the surface). Both of attached-growth and suspended-growth biomass samples were filtered through glass microfiber filters (GF/C, Whatmann, 0.45 mm). The cells retained on the filter paper were dried at 105 °C for 4 hours (Lee *et al.* 2014).

Analysis of chlorophyll *a* concentration in the harvested biomass was done in accordance with the Standard Methods for Examination of Water and Wastewater (APHA 2012). About 25 mL of the harvested biomass was centrifuged at 5,000 rpm for 5 min. Chlorophyll *a* in the biomass was extracted with 90% aqueous acetone in a tissue grinder. The extracted samples were kept in the dark at 5 °C for 3 hours and then measured at three wavelengths: 664, 647, and 630 nm, using a spectrophotometer (UV-VIS Spectrophotometer, UV-1700 PharmaSpec, SHIMADZU, Japan). The results were used to determine chlorophyll *a* concentration (mg/L) according to the Standard Methods for Examination of Water and Wastewater (APHA 2012).

Table 2 | Operating conditions

			Loading (mg/L/d)		
AG-HRAP unit	Light intensity (μmol/m^2/s)^a	HRT (day)	OLR	NLR	PLR
AG-HRAP#1	40 ± 18	4	243 ± 40	15 ± 2	3 ± 1.3
		8	90 ± 15	12 ± 1	2 ± 0.8
		15	55 ± 9	5 ± 1	1 ± 0.4
AG-HRAP#2	160 ± 18	4	243 ± 40	15 ± 1	3 ± 1.3
		8	90 ± 15	12 ± 1	2 ± 0.8
		15	55 ± 9	5 ± 1	1 ± 0.4
AG-HRAP#3	180 ± 15	4	243 ± 40	15 ± 1	3 ± 1.3
		8	90 ± 15	12 ± 1	2 ± 0.8
		15	55 ± 9	5 ± 1	1 ± 0.4

Note: [a]Continuous lighting for 24 hours.

Algal species

Algal species of the attached-growth and suspended-growth biomass samples were identified by using the microscopic method (APHA 2012) at AIT's Environmental Engineering and Management laboratory.

Protein productivity

The attached-growth and suspended-growth biomass samples were measured for TKN concentration, which were converted to crude protein concentration according to Equation (1) (Bleakley & Hayes 2017):

$$\text{Crude protein (mg/L)} = 6.25 \times \text{TKN (mg/L)} \quad (1)$$

Kinetic model

The Stover-Kincannon model was applied to determine kinetic constants for COD, TN and TP removals in the AG-HRAP units (Chen et al. 2008) as expressed in Equation (2). These kinetic constants can be used for the design and operation of the AG-HRAP units to achieve the desired performance.

$$\frac{V}{Q \times (S_0 - S)} = \frac{K_B}{U_{max}} \frac{V}{Q \times S_0} + \frac{1}{U_{max}} \quad (2)$$

where K_B is a constant of saturation value (mg/L/d), U_{max} is a constant of maximum substrate utilization rate (mg/L/d), S_0 is initial concentration in the influent (mg/L) and S is concentration remaining in the effluent (mg/L).

Statistical analysis

The experimental data of this study were tested for their statistical significance by using analysis of variance (ANOVA, SPSS (V.23.0)).

RESULTS AND DISCUSSION

DO, pH and temperature in the AG-HRAP units

At the steady-state condition in AG-HRAP#1, AG-HRAP#2 and AG-HRAP#3, the pH values were 7.4 ± 0.5, 7.8 ± 0.5, and 8.2 ± 0.6, respectively, the temperatures were 31 ± 2, 32 ± 2, and 32 ± 2 °C, respectively, and the DO concentrations were 4 ± 1, 6 ± 1, and 7 ± 1 mg/L, respectively.

Light penetration down the water column of the AG-HRAP units

Light was considered to be a main factor influencing microalgal growth and enhancing biomass production. Light penetration in the AG-HRAP units was measured to express the advantages of using additional artificial illumination to enhance biomass productivity. Due to a combination of sunlight and the artificial light source, and because sunlight could not penetrate below 0.30 m in most raceway ponds (Chisti 2007; Lee et al. 2014), the light intensities of the top layer (water depth 0.05 m) of the AG-HRAPs were observed to be highest (Table 3). The light intensities of the middle and bottom layers (water depth 0.35 and 0.65 m, respectively) of the ponds were lower than those of the top layer. Sforza et al. (2012) reported that a high microalgal growth rate was obtained with light intensities greater than 120 μmol/m^2/s. The attached-growth system improved light penetration and promoted microalgal growth at the bottom of the AG-HRAP units. Table 3 shows the average light intensities of AG-HRAP#1, AG-HRAP#2 and AG-HRAP#3 to be 40 ± 18, 160 ± 18 and 180 ± 15 μmol/m^2/s, respectively, corresponding to the results of biomass productivity in the AG-HRAP units. The additional artificial light illumination increased light penetration and allowed sufficient light intensity for microalgal cultivation at greater water depths.

Treatment performance of the AG-HRAP units

The experimental results of COD, TN and TP removal efficiencies, shown in Figure 2, were found to increase

Table 3 | Light penetration down the water column in the AG-HRAP units

Units	Water depth (m)	Light intensity (μmol/m^2/s)	Average light intensity (μmol/m^2/s)
AG-HRAP#1	0.05	105 ± 36	40 ± 18
	0.35	32 ± 19	
	0.65	20 ± 10	
AG-HRAP#2	0.05	251 ± 26	160 ± 18
	0.35	164 ± 38	
	0.65	69 ± 14	
AG-HRAP#3	0.05	242 ± 23	180 ± 15
	0.35	171 ± 19	
	0.65	86 ± 25	

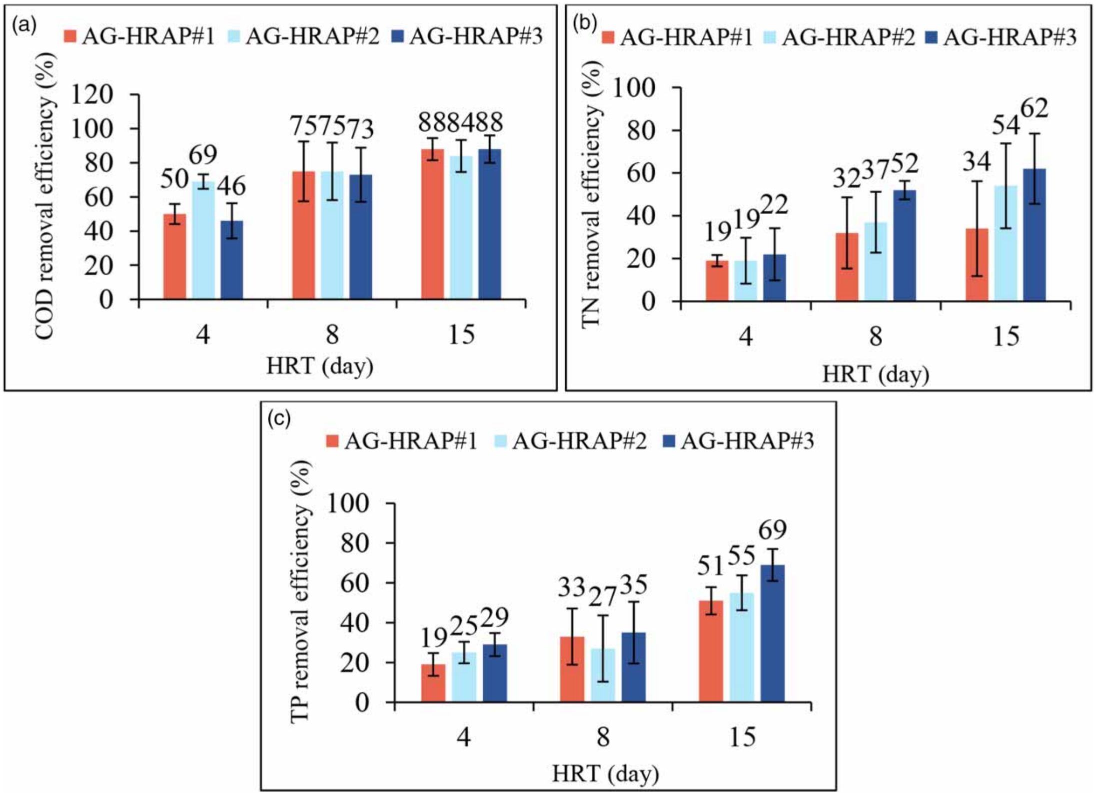

Figure 2 | Removal efficiencies of COD (a) TN (b) and TP (c).

with increasing HRT. The highest COD removal of 88 ± 8% (Figure 2(a)) occurred at the HRT of 15 days, resulting in the effluent COD concentration of less than 100 mg/L, meeting Thailand's national discharge standard (PCD 2010). The TN removal efficiencies of 22 ± 12, 52 ± 2 and 62 ± 9% were found in the AG-HRAP#3 at the HRTs of 4, 8, and 15 days, respectively, which were higher than those of AG-HRAP#1 and AG-HRAP#2 (Figure 2(b)). Similarly, the highest TP removal efficiency of 69 ± 8% was found in AG-HRAP#3 at the HRT of 15 days, higher than those of AG-HRAP#1 and AG-HRAP#2 (Figure 2(c)). Due to the relatively neutral pH found in the AG-HRAP units, it could be anticipated that the TN and TP concentrations in the influent were mainly removed via algal-bacterial biomass assimilation and nitrification/denitrification reactions, rather than ammonia volatilization and phosphorus precipitation, respectively (Sawyer *et al.* 2003), but further studies in this aspect are strongly recommended.

Because lighting conditions could affect algal growth in AG-HRAP units, AG-HRAP#3, using the highest light intensity of 180 μmol/m^2/s, gave higher TN and TP removal efficiencies than AG-HRAP#1 and AG-HRAP#2 (Figure 2(b) and 2(c)), corresponding to the results of biomass productivities and abundance of algal species among the AG-HRAP units (Figures 3 and 4, respectively). The data of Figure 2 were used to determine kinetic constants for design and operation of the AG-HRAP system.

Biomass productivity

The highest biomass and protein productivities of 54 ± 4 and 37 ± 8 g/m^2/d, respectively, were found in the AG-HRAP#3, which were higher than those of the other two units (Figure 3), corresponding to the results of the TN and TP removal efficiencies shown in Figure 2(b) and 2(c), respectively. Moreover, the highest attached biomass productivity of this study (54 ± 4 g/m^2/d) was higher than those of previous studies, which were 5–41 g/m^2/d (Table 4) (Shelef. 1982; Wood *et al.* 1988; Gross & Wen. 2014; Lee *et al.* 2014). Therefore, applying additional artificial light illumination in the AG-HRAP system was beneficial for enhancing microalgal growth and biomass productivity. Correspondingly, the highest chlorophyll *a* concentration of 13 mg/L

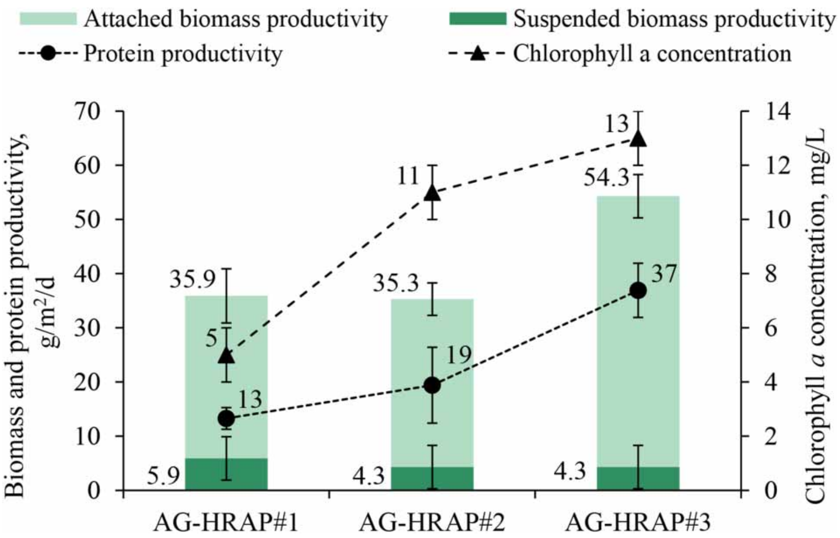

Figure 3 | Biomass and protein productivities and chlorophyll *a* concentrations in the AG-HRAP units.

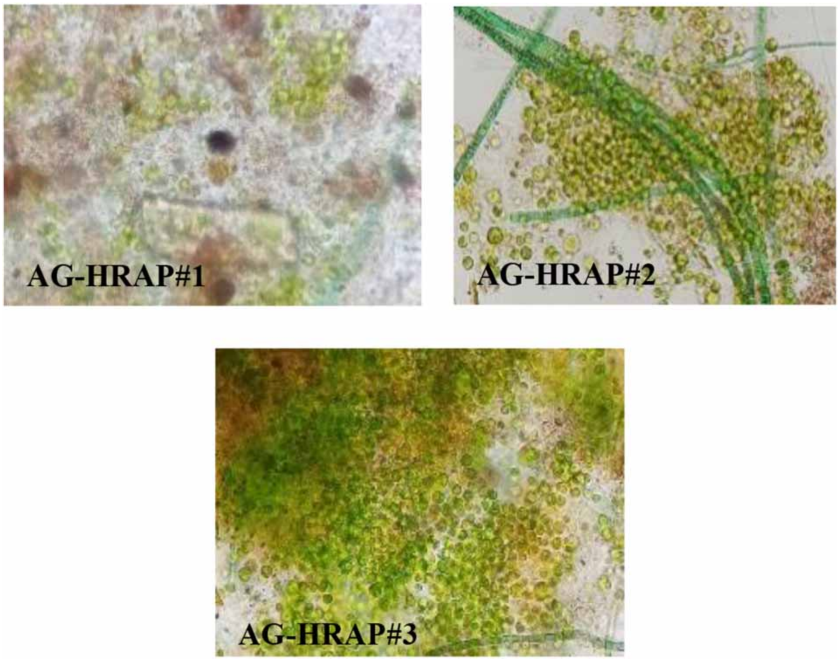

Figure 4 | Algal species in the AG-HRAP units.

were found in AG-HRAP#3. The suspended biomass productivities were found to be only about 8% of the total biomass in the three AG-HRAP units (Figure 3). Hence, these results suggest the potential benefits of the novel AG-HRAP in wastewater treatment and biomass and protein productivities. The latter could be reused in animal feeds, fertilizers or some food additives, etc.

Algal species in the AG-HRAP units

Algal species

The major algal species in all AG-HRAP units was found to be *Chlorella* sp., the same as the inoculum (Figure 4). Due to the raw wastewater used as the influent, other contaminant algal species i.e. *Scenedesmus* sp. and *Oscillatoria* sp. could also be

Table 4 | Comparisons of average biomass and protein productivities of the novel AG-HRAP units and other studies

Units	Total biomass productivity ($g/m^2/d$)	Chlorophyll *a* concentration (mg/L)	Protein content (%)	Total protein productivity ($g/m^2/d$)	References
AG-HRAP#1	35.9 ± 11	5 ± 1	37 ± 3	13 ± 2	This study
AG-HRAP#3	35.3 ± 9	11 ± 1[a]	55 ± 13	19 ± 7	
AG-HRAP#3	54.3 ± 4	13 ± 2	68 ± 14	37 ± 5	
AG-HRAP	9	NA	NA	NA	Lee *et al.* (2014)
Triangular RAB retrofit raceway	5	NA	41	2	Gross & Wen (2014)
Vertical RAB retrofit raceway	11	NA	40	4	
Conventional HRAP	41	NA	45–50	19–21	Shelef (1982)
Conventional HRAP	14	NA	42	6	Wood *et al.* (1988)

Note: [a]NA, not available.

observed in the systems (Polprasert & Koottatep 2017). There were no substantial differences in the algal species among the three AG-HRAP units. The presence of these algal species suggests the applicability of the novel AG-HRAP system for producing useful algal species to perform photosynthesis which produces O_2 for the heterotrophic bacteria to biodegrade organic matter, and the algal biomass could be further reused.

Application of kinetic model and cost effectiveness of the AG-HRAP system

The Stover-Kincannon kinetic model was applied in this study to determine kinetic constants for COD, TN, and TP removal in the AG-HRAP units (Table 5). In this study, the kinetic constants of U_{max} and K_B for COD removal in the AG-HRAP were found to be 121, 107; 222, 232 and 74, 52 mg/L/d in AG-HRAP#1, AG-HRAP#2 and AG-HRAP#3 ($R^2 = 0.99$), respectively, which were higher than the U_{max} and K_B for COD removal of 19.74–34.68 and 22.4–27.9 mg/L/d, respectively, of the conventional waste stabilization pond (Gratziou & Chalatsi 2016). Probably because COD removals in the AG-HARPs were achieved by biological degradation of the heterotrophic bacteria (Chaiwong *et al.* 2018), the obtained results of the COD removal constants (Table 5) were not affected by the applied light intensities and the observed biomass productivity in the systems. Additionally, the highest U_{max} and K_B constants for TN and TP removals of 9, 16 and 1.8, 2.7 mg/L/d were found in AG-HRAP#3, with an R^2 of more than 0.9 (Table 5). Because there was not only biomass assimilation but also TP removal by other processes, i.e. precipitation or sedimentation (Chaiwong *et al.* 2018), there were no significant differences among the TP removal constants of the AG-HRAP units. Consequently, the calculated kinetic constants for COD, TN and TP removals could be applicable for the design of AG-HRAPs to achieve desired effluent standards.

The results for energy consumption and cost effectiveness of the AG-HRAP systems are shown in Table 6. The land area requirement for wastewater treatment (m^2/m^3)

Table 5 | Stover-Kincannon model for COD, TN and TP removals in the AG-HRAP units

	COD removal constant			TN removal constant			TP removal constant		
Unit	U_{max} (mg/L/d)	K_B	R^2	U_{max} (mg/L/d)	K_B	R^2	U_{max} (mg/L/d)	K_B	R^2
AG-HRAP#1	121	107	0.99	5	3	0.63	1.4	2.8	0.95
AG-HRAP#2	222	232	0.99	8	11	0.90	1.5	2.7	0.99
AG-HRAP#3	74	52	0.99	9	16	0.90	1.8	2.7	0.99

Table 6 | Energy consumption and cost effectiveness for operation of the novel AG-HRAP systems

		Energy consumption		**Cost[a]**				
Unit	**Land area requirement for wastewater treatment (m^2/m^3)**	**Wastewater treatment kWh/m³/d**	**Biomass production kWh/kg/d**	**Wastewater treatment USD/m³/d**	**Biomass production USD/kg/d**	**Revenue from dry biomass[b] USD/kg/d**	**Benefit/ cost ratio**	**References**
AG-HRAP#1	1	0.18 ± 0.11	0.51 ± 0.32	0.14 ± 0.01	0.39 ± 0.03	7.03 ± 0.22	14 ± 0.6	This study
AG-HRAP#2		7.78 ± 4.81	22.78 ± 14.09	0.71 ± 0.36	2.07 ± 0.82	6.83 ± 1.32	3 ± 0.6	
AG-HRAP#3		3.98 ± 2.46	7.71 ± 4.77	0.42 ± 0.18	0.81 ± 0.38	10.32 ± 1.82	11 ± 2.3	
Conventional HRAP	5	NA[c]	NA[c]	NA[c]	8.11	0.02	0.002	Chauton *et al.* (2015)
Flat panels	17	NA[c]	NA[c]	NA[c]	4.43	0.07	0.02	
Tubular system	22	NA[c]	NA[c]	NA[c]	6.23	0.01	0.002	
Open raceway pond	1.6	NA[c]	NA[c]	NA[c]	3.80	2.34	0.62	Chisti (2016)
Closed photobioreactors (PBR)	36	NA[c]	NA[c]	NA[c]	2.95	30.7	10.4	Asiedu *et al.* (2018)

Notes: [a] Including investment cost for the artificial light sources and operational costs. The investment costs were calculated according to Blanken *et al.* (2013). Electrical cost is 0.074 USD per kWh (Provincial Electricity Authority of Thailand; PEA 2015)

[b] Price of dry biomass is 50 USD per kg biomass (Voort *et al.* 2015)

[c] NA = not available.

of each AG-HRAP unit was 1 m^2/m^3, which was lower than those of other microalgal systems (1.6–36 m^2/m^3) (Chauton *et al.* 2015; Chisti 2016; Asiedu *et al.* 2018). Additionally, the energy consumption for biomass production of AG-HRAP#1, AG-HRAP#2 and AG-HRAP#3 were found to be 0.51 ± 0.32, 22.78 ± 14.09 and 7.71 ± 4.77 kWh/kg/d, corresponding to the biomass production costs of 0.39 ± 0.03, 2.07 ± 0.82 and 0.81 ± 0.38 USD/kg/d, respectively. The revenues for the produced biomass of AG-HRAP#1, AG-HRAP#2 and AG-HRAP#3 were estimated to be 7.03 ± 0.22, 6.83 ± 1.32 and 10.32 ± 1.82 USD/kg/d, respectively, resulting in the benefit/cost ratios of 14 ± 0.6, 3 ± 0.6 and 11 ± 2.3, respectively. These benefit/cost ratios of the AG-HRAP systems were significantly higher than those of other microalgal systems, which were 0.002–10.04 (Chauton *et al.* 2015; Chisti 2016; Asiedu *et al.* 2018). Therefore, it could be suggested that the AG-HRAP system is of value for treating wastewater while simultaneously being highly cost effective in terms of system operation.

CONCLUSIONS

The novel AG-HRAP units were found to be effective for wastewater treatment: the treated effluent could meet Thailand's national discharge standards when operated at an HRT of 15 days. Enhanced biomass and protein productivities were achieved in the AG-HRAP units equipped with the additional artificial light sources, and these could be further reused as animal feed, fertilizers, and food additives. The Stover-Kincannon model was found to be applicable for determining the kinetic constants for COD, TN and TP removals, which can be used for the design of the AG-HRAP system treating wastewater. The major algal species in all AG-HRAP units were found to be *Chlorella* sp., *Scenedesmus* sp. and *Oscillatoria* sp., suggesting the applicability of the novel AG-HRAP system in wastewater treatment and biomass production. The operation of the novel AG-HRAP system could be very cost effective when compared to other microalgal systems.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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