Control of algal production in a high rate algal pond: investigation through batch and continuous experiments

H. Derabe Maobe, M. Onodera, M. Takahashi, H. Satoh and T. Fukazawa

ABSTRACT

For decades, arid and semi-arid regions in Africa have faced issues related to water availability for drinking, irrigation and livestock purposes. To tackle these issues, a laboratory scale greywater treatment system based on high rate algal pond (HRAP) technology was investigated in order to guide the operation of the pilot plant implemented in the 2iE campus in Ouagadougou (Burkina Faso). Because of the high suspended solids concentration generally found in effluents of this system, the aim of this study is to improve the performance of HRAPs in term of algal productivity and removal. To determine the selection mechanism of self-flocculated algae, three sets of sequencing batch reactors (SBRs) and three sets of continuous flow reactors (CFRs) were operated. Despite operation with the same solids retention time and the similarity of the algal growth rate found in these reactors, the algal productivity was higher in the SBRs owing to the short hydraulic retention time of 10 days in these reactors. By using a volume of CFR with twice the volume of our experimental CFRs, the algal concentration can be controlled during operation under similar physical conditions in both reactors.

Key words | algal biomass, continuous flow reactor, greywater treatment, growth rate, high rate algal ponds, sequencing batch reactor

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INTRODUCTION

In Africa, the variability of the rainfall results in areas of severe aridity with limited freshwater resources and an equatorial region with abundant freshwater resources. In regions characterized by water stress and water scarcity (1,000–1,700 m^3 per capita/year according to Arthurton *et al.* (2006)), the water demand is more critical than in other areas and outstrips available resources. For instance, in Burkina Faso, owing to the limited water resources, a large part of the population do not have access to drinking water and irrigation is restricted (MAHRH 2003). Moreover, in the urban and peri-urban areas of this country, the access to water and sanitation services is unequal. The existing centralized sewerage connection serves only the administrative, university and industrial areas, and about 5% of the population use improved latrines or septic tanks (Vezina 2002). As a result, the greywater from their kitchen, showers and washing facilities is poured onto streets or into inadequate pits that often overflow. To solve this problem associated with urban water and improve public health and environmental conditions, Morel & Diener (2006) and Katuzika *et al.* (2012) recommended that the greywater in urban areas of developing countries should be considered as a valuable resource to cover different water needs. In fact, there is an opportunity to recover treated water, nitrogen and phosphorus from the treatment of greywater, all of which can be used to ensure the growth and survival of plants.

In this study, since greywater has the nutrients required for the growth of algae, attention has been focused on the use of high rate algal ponds (HRAPs) for greywater treatment under arid and semi-arid conditions. As confirmed by Chen *et al.* (2003) the HRAP technology, involving the use of microalgae, provides an appropriate means of domestic wastewater treatment. According to the same author, high nitrogen and phosphorus removal efficiency, low investment cost and simple management are the main benefits of such treatment. However, the main disadvantage concerns the washout of algae from ponds, which increases the total suspended solids (TSS) concentration in the effluent (Mara *et al.* 1992; Shelef & Kanarek 1995).

To produce high-quality treated effluent, many harvesting methods including centrifugation, flocculation, filtration and

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screening, gravity sedimentation, flotation and electrophoresis techniques have been investigated (Uduman et al. 2010; Pragya et al. 2013). Because of its low energy consumption and low cost (capital, chemicals, operating cost), the present study focuses on the harvesting of algae through the gravity sedimentation process. We discuss the selection mechanisms and the efficiency of algae separation by varying the hydraulic retention time (HRT) and solids retention time (SRT) in replications of batch and continuous experiments. The experiments described in this paper were carried out to investigate the algal productivity and nutrient removal efficiency.

MATERIALS AND METHODS

All experiments were carried out on a laboratory scale and the collected data will be used for the operation of the pilot scale implemented in the 2iE campus in Ouagadougou (Burkina Faso). The systems operated in the laboratory scale consisted of a series of sequencing batch reactors (SBRs) and continuous flow reactors (CFRs).

Reactor setup and operation

Figure 1 illustrates the operation of SBRs and CFRs. To ensure the reliability and validity of the results, the SBR and CFR configurations consisted of an experimental system including three replications of SBR and three others for the CFRs. The CFRs and SBRs were constructed from PVC, had a cylindrical shape, a capacity of 11.5 L and a depth of 0.4 m.

In both reactors, the temperature was continuously maintained at $30 \pm 2\,^{\circ}$C (the expected temperature in tropical countries), and the water was mixed using mixers (AS ONE and EYELA MDC-NC) to avoid algal sedimentation and to enhance light penetration (Paterson & Curtis 2010). The irradiance light in the reactors was supplied by conventional white light emitting diode (LED) lamps (Toshiba LDR9L-W). A 12 h light–12 h dark cycle was employed and the LED lamps provided a photosynthetic photon density of 430–550 μmol $m^{-2}\,s^{-1}$ at the surface of the pond. The wavelength of the photoluminescence spectrum emitted by these LEDs ranged between 400 and 800 nm and exhibited a peak at 465 nm.

The three SBRs were operated with a HRT of 10 days and a SRT of 20 days. The SRT was controlled by withdrawing a designated amount of the mixture in the reactor calculated from Equation (1). During each day, the reaction (feeding and mixing), settling and discharging (idle) times were 17.5, 6 and 0.5 h, respectively.

SRT in reactors:

$$SRT = \frac{(V_R \times TSS_{SBR})}{(x \times TSS_{SBR}) + (\text{Effluent}_{\text{flowrate}} \times TSS_{E\_SBR})} o \qquad (1)$$

V_R: Reactor volume (L), SRT: Solids retention time (d), TSS_{SBR}: TSS concentration in SBR (mg/L), $\text{Effluent}_{\text{flowrate}}$: Effluent flow rate (L/d), TSS_{E_SBR}: TSS concentration in effluent from SBR (mg/L), x: Withdrawal volume (L/d).

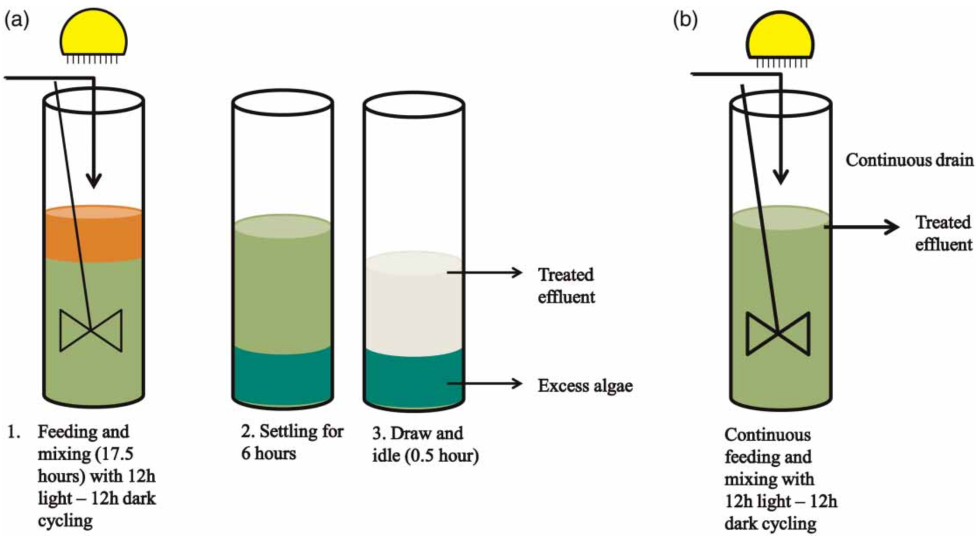

Figure 1 | Daily operations of reactors. (a) SBR. (b) CFR.

The three CFRs were continuously fed with synthetic greywater. Experiments were carried out using the same HRT and SRT of 20 days, and supernatants (E_CFRs) were withdrawn continuously (Figure 1(b)). The configuration of the CFRs, such as the location of the outlet, was the same as that of the SBRs to equalize the hydraulic conditions.

For both reactors, the HRT used for the operation corresponded to that in previous studies (Oswald 1986; Garcia *et al.* 2000) and the expected value in practical operation.

The attached biomass in all the reactors was removed by cleaning the reactor's walls before collecting each sample. Furthermore, protozoa grazers were removed by transferring the mixed liquor to a supersonic disruptor to break down the protozoa bodies. This operation was carried out approximately every 2 months because of the proliferation of grazers.

The algal culture originated from pond water sediment collected from the wastewater treatment plant in 2iE campus (International Institute for Water and Environmental Engineering) in Ouagadougou (Burkina Faso). 0.5 L of the sediment was first grown at room temperature and under illumination in an Erlenmeyer flask containing 0.5 L of synthetic greywater. Cultures were renewed weekly and both reactors were inoculated with 0.5 L of the grown cultures after 2 weeks.

Synthetic greywater composition

Synthetic greywater was used throughout the experiments. Both reactors were fed with a similar feed of synthetic greywater (Figure 1) with a composition similar to that used in Raude *et al.* (2009) and that was obtained from greywater in peri-urban areas of Nakuru (Kenya). Using a dilution ratio of 400, the synthetic solution was prepared by dissolving the following compounds in one litre of pure water: dextrin hydrate (3.68 g), bacteriological peptone (8 g), fish meal (2.69 g), yeast extract powder (8 g), KCl (1.6 g), NaCl (0.8 g), $MgSO_4 \cdot 7H_2O$ (1 g), KH_2PO_4 (8.72 g), NH_4Cl (11.18 g), KNO_3 (5.68 g) and Fe-citric acid (2.4 g). The chemical characteristics of the synthetic greywater with their average values ±SD are given in Table 1.

Table 1 | Main characteristics of the synthetic greywater (mean ± SD)

Characteristic	Mean ± SD
pH	6.76 ± 0.45
TN (mg/L)	12.41 ± 3.00
TP (mg/L)	5.26 ± 0.40
TOC	21.83

Analytical methods

Samples withdrawn from the influent tanks, SBRs, CFRs and corresponding effluent tanks were immediately analyzed. The temperature and pH were always measured at the moment of collection using a pH meter (Horiba, D-52). The photosynthetic photon flux was measured at the centre of the reactor and at the top of the liquid surface with a photosynthetically active radiation meter (Apogee SE-MQ200). The total amount of suspended solids was determined in accordance with APHA (2005) using glass fibre filters (Advantec GS-25, 47 mm). Settleable algae were measured by the gravimetric method (APHA 2005) and the percentage of settable algae was calculated according to Equation (2). Before nutrient analysis, samples were filtered with membrane filters (Advantec GF-45, 0.45 μm). NH_4^+-N, total nitrogen (TN) and total phosphorus (TP) were determined by Hach methods 8038, 10,071 and 8190, respectively. Nitrite, nitrate and soluble reactive phosphorus concentrations were also measured using Hach methods 10,019, 10,020 and 8114, respectively. The removal efficiency and total productivity of each reactor were calculated using Equations (3)–(6).

Percentage of settleable solids:

$$\text{Settleable solids (\%)} = \left(\frac{TSS_{\text{Reactor}} - \text{non-settleable solids}}{TSS_{\text{Reactor}}}\right) \times 100 \quad (2)$$

TSS_{Reactor}: TSS concentration of the reactor's mixtures (mg/L), non-settleable solids: TSS concentration of the supernatant after 1 h of sedimentation (mg/L).

TSS removal efficiency:

$$R_{\text{TSS}}\,(\%) = \frac{TSS_{\text{Reactor}} - TSS_{\text{effluent}}}{TSS_{\text{Reactor}}} \times 100 \quad (3)$$

R_{TSS}: TSS removal efficiency (%), TSS_{effluent}: Effluent TSS concentration (mg/L).

Nutrient removal efficiency:

$$R_{\text{nutrient}}\,(\%) = \frac{C_{\text{inf}} - C_{\text{eff}}}{C_{\text{inf}}} \times 100 \quad (4)$$

R_{nutrient}: Nutrient removal efficiency (%), C_{inf}: Influent concentration (mg/L), C_{eff}: Effluent concentration (mg/L).

Total algal productivity of SBRs:

$$P_{\text{SBR}}(mg/d) = X_{\text{Excess algae}} + X_{\text{E\_SBR}} + \Delta X_{\text{SBR}} \quad (5)$$

P_{SBR}: Total productivity of SBR (mg/d), $X_{Excess\,algae}$: Algal biomass withdrawn from the SBR (mg/d), X_{E_SBR}: Algal biomass in effluent from SBR (mg/d), ΔX_{SBR}: Variation of algal biomass in SBR (mg/d).

Total algal productivity of CFRs:

$$P_{CFR}(mg/d) = X_{E\_CFR} + \Delta X_{CFR} \tag{6}$$

P_{CFR}: Total productivity of CFR (mg/d), X_{E_CFR}: Algal biomass in effluent from CFR (mg/d), ΔX_{CFR}: Variation of algal biomass in CFR (mg/d).

The algal growth rate in the SBRs and CFRs was evaluated as follows.

Algal growth rate in SBRs:

$$\mu_{SBR} = \frac{\Delta X_{SBR} + X_{E\_SBR} + X_{excess\,algae}}{X_{SBR}} \tag{7}$$

μ_{SBR}: Algal growth rate in SBRs (d^{-1}).

Algal growth rate in CFRs:

$$\mu_{CFR} = \frac{\Delta X_{CFR} + X_{E\_CFR}}{X_{CFR}} \tag{8}$$

μ_{CFR}: Algal growth rate in CFRs (d^{-1}).

RESULTS

Algal biomass productivity in SBRs and CFRs

The total algal productivity in the SBRs represents the biomass productivities of the excess algae and the effluent. For the CFRs, it represents the biomass productivity of the effluents. The SRT was the same, i.e. 20 days for both reactors, and in the SBRs, the excess algae corresponded to the amount of the mixture withdrawn and was evaluated by using Equation (1). In the CFRs, the HRT of 20 days enabled the self-control of the SRT at 20 days, and the mixture was continuously withdrawn.

As given in Table 2, during the steady-state region in Figure 2 (Day 33 to Day 44), the mean total areal productivity of the algae in the SBRs was three times higher than that in the CFRs (3.6 g/m^2/day in the SBRs and 1.2 g/m^2/day in the CFRs). Then, the TSS concentrations and the growth rate of the mixture in each reactor were estimated to clarify the reason for the difference in the observed algal productivity.

Algal concentrations and algal settleability

The algal productivity was affected by the algal concentration which was determined in terms of TSS concentration (Table 2). The mean algal concentration was determined during the steady-state period, and the results in Figure 2 confirmed that the algal concentration was higher in the SBRs (190 mg/L) than in the CFRs (130 mg/L). After the steady state period in the SBRs, a decrease in TSS concentration was observed. This might be due to the effect of the photoinhibition occurring at a shallow depth, leading to a decrease in the number of large algae flocs.

Table 2 | Average algal production in SBRs and CFRs

Averages	Effluent (mg/d)	Excess algae (mg/d)	Total productivity (mg/d)	Total areal productivity (g/m^2/d)
SBRs	3.4 ± 3.6	104.5 ± 17.6	108	3.60
CFRs	35.7 ± 12.3	–	36	1.20

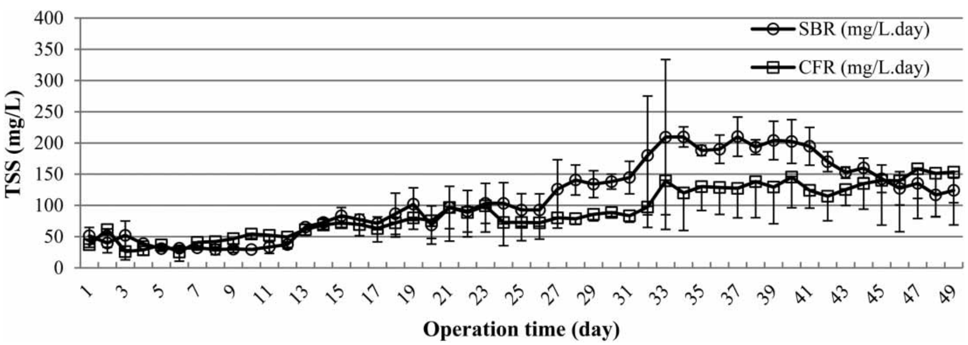

Figure 2 | Average algal concentration in the mixture in each reactor.

Experiments determining the percentage of settleable solids revealed that the percentage of settleable algae was significantly higher in SBRs (97 ± 2%) than in CFRs (83 ± 14%).

Algal growth rates

The mean algal growth rates in the SBRs and CFRs were obtained using Equations (7) and (8), respectively. The results are shown in Figure 3, which reveals that the algal culture had similar growth rates under batch and continuous operations. The operation of the SBRs and CFRs with the same SRT may explain this similarity of the algal growth rate.

Nutrient removal

The concentrations of nitrogen and phosphorus before and after the treatment are given in Table 3.

Larger amounts of NH_4^+-N and TN were removed from the SBRs, than from the CFRs during the entire experimental period. The nitrogen from the reactors was not eliminated in the form of oxidized N. In fact, the nitrate concentrations throughout the steady-state period of the cells were insignificant (average values of 0.33 ± 0.08 mg/L and 1.08 ± 0.43 mg/L in effluents from SBRs and CFRs respectively). The pH was measured in the SBRs and CFRs and the corresponding average did not exceed 8.5.

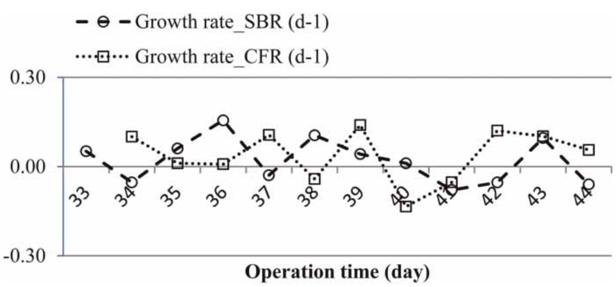

Figure 3 | Mean algal growth rates in SBRs and CFRs.

In all reactors, more nitrogen than phosphorus was removed and the concentrations of dissolved phosphorus in the effluents from the SBRs were lower than those in the effluents from the CFRs.

Total organic carbon (TOC) removal in HRAP has been investigated in previous studies of our research group. The results have shown that the TOC removal efficiency was around 61%.

DISCUSSION

Algal biomass productivity in SBRs and CFRs

The SBR simulates an HRAP with algal recirculation and the CFR simulates a conventional HRAP without algal recirculation in our experiment.

In SBRs and CFRs where the percentages of settleable algae were higher than 80%, the bioflocculation of algal biomass occurred naturally. On the other hand, by introducing algal sedimentation in SBRs, the selection of settleable algae was efficient, thus increasing the percentage of settleable algae in SBRs. In CFRs, where continuous operations were conducted, a low percentage of settleable algae was observed probably due to the absence of algal sedimentation.

As shown in the results section, the growth rates of the SBRs and CFRs were similar. However, the areal algal productivity and algal concentration were higher in the SBRs than CFRs in spite of the same SRT, as shown in Table 4.

Why have the differences in the areal algal production occurred?

Investigations on algal growth and TSS concentrations in both reactors were conducted to find the reason.

- The apparent algal growth rate was controlled by the physical and chemical growth conditions, such as light intensity, nutrient concentration, and the SRT, but it was not affected by the HRT or reactor volume. This is because, as shown in Equations (7) and (8), the apparent

Table 3 | Nutrient concentrations (mean ± sd) in influent and effluent for each reactor

	Influent	E-SBR	E-CFR	% removal SBR	% removal CFR
TN	14.12 ± 2.23	5.41 ± 0.93	8.59 ± 1.36	58.77 ± 7.02	37.74 ± 9.49
NH_4-N	7.16 ± 0.97	3.29 ± 0.39	5.57 ± 0.38	53.39 ± 5.15	20.07 ± 5.40
TP	5.03 ± 0.63	3.51 ± 0.15	4.52 ± 0.20	30.19 ± 3.23	8.02 ± 3.97
PO_4-P	4.24 ± 0.45	2.69 ± 2.69	4.16 ± 0.17	33.36 ± 6.82	1.14 ± 4.17

E-SBR: effluent from SBR; E-CFR: effluent from CFR

Table 4 | Average algal productivity, TSS concentration and growth rate of SBRs and CFRs

	Areal productivity (g/m^2/d)	Algal concentration in reactors (mg/L)	Algal growth rate (d^{-1})	Algal productivity (L^{-1} of influent)
SBR	3.60	190	0.02	93.9
CFR	1.20	130	0.04	62.6

growth rate is not a function of HRT or reactor volume. When the physical and chemical growth conditions and the SRT are the same, and consequently the apparent growth rate is the same, the algal masses of the SBR and CFR should be the same under the steady state.

- Interestingly our present study shows a significant difference in algal concentration and algal production rates. This result might be attributed to the different HRT operation among the reactors due to the availability of sufficient nutrients. The daily flow rate of greywater in SBRs was twice as much as that of CFRs. Obviously this has affected the TSS concentrations in both reactors: the algal concentration in SBRs (HRT = 10 days) was higher than that in CFRs (HRT = 20 days). A similar observation was made for the algal productivity per litre of influent (Table 4).

Further, due to the high algal concentration found in SBRs and due to the daily withdrawal of excess algae from these reactors, the algal productivity became two to three times higher (Table 4) than that of CFRs. In contrast the lack of excess algae removal in CFRs may result in lower algal production rates. In both reactors the limitation of algal growth due to insufficient nutrients was avoided.

Results from our present study imply that operating a CFR with a volume two times larger than that of a SBR and with a similar influent flow rate as a SBR would result in the production of half the algal biomass amount produced in a SBR. Additionally, by simulating the HRAP under continuous operation or batch operation with algal recirculation, control of the algal productivity could be achieved.

Nutrient removal

The negligible nitrate concentrations and low pH observed in both reactors confirm that nitrification and ammonia volatilization were not the major processes responsible for nitrogen removal. The short HRT and the effect of sedimentation applied in the SBRs resulted in a higher algal concentration (Figure 2) and thus promoted nitrogen removal by assimilation into the algal biomass and the sedimentation process, similar to that observed in the HRAP. In contrast to SBRs, low NH_4^+-N uptake has occurred in CFRs where the algal concentration was lower (Figure 2). As a result, a higher NH_4^+-N concentration was found in E-CFRs (Table 3).

Since the greywater did not contain enough cations (Fe^{2+}, Al^{3+}, Ca^{2+}, Mg^{2+}, …), inorganic phosphate might not be removed by the precipitation and adsorption processes in both reactors (Diaz *et al.* 1994; Nurdogan & Oswald 1995). In these reactors, phosphorus might have been removed through assimilation/sedimentation or through a combination of growth and the uptake of phosphorus (Powell 2009). By comparing N and P elimination, much less phosphorus than nitrogen was removed from the reactors during the monitored experimental period. The N:P ratio of algae was 15:1 (Redfield 1934) and consequently, the greywater with a N:P ratio of 4:1 did not contain sufficient nitrogen to enable the complete removal of phosphorus by the assimilation process (Nurdogan & Oswald 1995; Craggs 2010).

CONCLUSIONS

In this study, a series of batch experiments were carried out to simulate the high rate algal pond (HRAP) with algae recirculation, and a series of continuous experiments reproduced the operation of usual HRAP without algal recirculation.

- In contrast to CFR, the operation of HRAP under batch mode has enhanced the selection of settleable algae through the sedimentation process.
- In SBRs and CFRs, because of the same SRT of 20 days, the algal growth rate was similar. However, the high algal productivity observed in the SBRs was attributed to the short HRT.
- The nutrient removal efficiency was higher in the SBRs than in the CFRs, and biomass uptake was the main mechanism responsible for the nutrient removal.
- By simulating the HRAP under continuous operation or batch operation with algal recirculation, the control of the algal productivity and the independent control of HRT and SRT were achieved.

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