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ORIGINAL ARTICLE

Removal of Organic Pollutants from Municipal Wastewater by Applying High-Rate Algal Pond in Addis Ababa, Ethiopia

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Abstract

The discharge of inadequately treated municipal wastewater has aggravated the pollution load in developing countries including Ethiopia. Conventional wastewater treatment methods that require high capital and operational costs are not affordable for many developing nations, including Ethiopia. This study aimed to investigate the performance of two high-rate algal ponds (HRAPs) in organic pollutant removal from primary settled municipal wastewater under highland tropical climate conditions in Addis Ababa. The experiment was done for 2 months at hydraulic retention times (HRTs) ranging from 2 to 8 days using an organic loading rates ranging 333–65 kg BOD_5/ha/day using two HRAPs, 250 and 300 mm deep, respectively. In this experiment, *Chlorella* sp., *Chlamydomonas* sp., and *Scenedesmus* sp., the class of Chlorophyceae, were identified as the dominant species. Chlorophyll-a production was higher in the shallower ponds (250 mm) throughout the course of the study, whereas the deeper HRAP (300 mm) showed better dissolved oxygen production. The maximum COD and BOD_5 removal of 78.03 and 81.8% was achieved at a 6-day HRT operation in the 250-mm-deep HRAP. Therefore, the 300-mm-deep HRAP is promising for scaling up organic pollutant removal from municipal wastewater at a daily average organic loading rate of 109.3 kg BOD_5/ha/day and a 6-day HRT. We conclude that the removal of organic pollutants in HRAP can be controlled by pond depth, organic loading rate, and HRT.

Keywords High-rate algal ponds · Organic removal · Municipal wastewater · Water depth · HRT

1 Introduction

The degree of ecosystem degradation due to environmental pollution has increased over the last century (Murray et al. 2009). Continuing population growth and economic growth has greatly increased freshwater consumption and, in turn, the generation of ever increasing volumes of wastewater (Cai et al. 2013). In addition, the uncontrolled discharge of inadequately treated municipal and industrial wastewater has aggravated the pollution load in the ecosystem (Renuka et al. 2013). Untreated wastewater contains high levels of easily biodegradable organic pollutants, and its discharge can increase the pollution load such as total suspended solids (TSS), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD). These pollutants can degrade the water quality by reducing the oxygen level and by changing the composition of existing physico-chemical constituents, thereby damaging the aquatic ecosystem (Chan et al. 2009).

Sewage water treatment is often a challenge in developing country due to the disparity between the inadequacy of sanitation facilities and the quantity of wastewater produced (Wang et al. 2014). In Ethiopia, the level of wastewater management is low, even by sub-Saharan standards, due to a general lack of sanitation infrastructure, skill, and knowledge of wastewater treatment (Troyer et al. 2016). As a result, large volumes of untreated wastewater are discharged to the environment everyday. A survey by the Ministry of Water Irrigation and Energy (MoWIE) showed that only 7.3% of all sewage generated in Addis Ababa is treated at the secondary level (MoWIE 2015). Apart from lack of effective treatment

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systems, the release of untreated waste into the ecosystem is an emerging threat for the country due to the fact that most of the population depends on freshwater resources for livelihood (Renuka et al. 2015). Furthermore, indiscriminate sewage water discharge constitutes a considerable threat to surface water quality by providing a breeding ground for many disease-causing organisms.

The conventional wastewater treatment technology which is commonly employed for organic waste removal is often not affordable in developing nations (Olukanni and Ducoste 2011; Wang et al. 2014). Factors that negatively impact the application of this system include high capital cost, high energy demand, and lack of technical expertise, which is often a challenge in these nations (Renuka et al. 2013). Even after these technologies are built and put into operation, the concentration of nutrients, particularly N and P in the effluent, is very high, which requires costly chemical treatment methods to prevent eutrophication (Pittman et al. 2011). Furthermore, the disposal of large volumes of sludge produced as a by-product during chemical treatment requires a costly dewatering and disposal process (Olguín 2012). Therefore, identifying mitigation methods, which can facilitate cost-effective treatment in an environmental-friendly way and permit operation of treatment plants under minimal supervision, is increasingly being considered as a possible approach in developing countries. One potential treatment option is the use of algal-based wastewater treatment process that can reduce capital cost and technological inputs compared to conventional treatment methods (Pittman et al. 2011).

The most common use of microalgae in wastewater treatment is in waste stabilization pond (WSP) (Kaya et al. 2007; Olukanni and Ducoste 2011). Compared to the conventional wastewater treatment methods, WSP has numerous advantages, including pathogenic organism reduction by natural disinfection, low sensitivity to hydraulic and organic shock load, and minimum need for mechanical equipment and external sources of energy for their operation (Mayo and Hanai 2014). However, the slow reaction rate during the treatment process, the need for large areas of land for their construction, and high algal seston concentration in the effluent are often problematic (Mayo and Hanai 2014). These limitations of WSP may be attributed to design features such as high organic loading rates, great operational depth, and absence of a mixing system, which are not optimal for intense algal growth since algae photosynthetic oxygen production derives organic matter oxidation by bacteria (Olguın 2003). The limitations may be minimized by reducing the land requirement and increasing the reaction rate and treatment efficiency (Mayo and Hanai 2014).

High HRAPs designed in shallow depth (0.2–0.5 m) algal cells kept in suspension by a paddle wheel mixing system improved the removal of COD, suspended solids, and pathogens (Craggs et al. 2012). HRAPs have also been claimed as the most efficient reactor system for maximum utilization of solar energy, were cost-effective for commercial biomass production using wastewater resources (Olguín 2012) and their use has increased during the last decades (Nurdogan and Oswald 1995; Sutherland et al. 2014c). As in other pond systems, organic matter removal in HRAP wastewater treatment system is the result of algae–bacteria symbiotic processes. Algae photosynthetic activity supplies oxygen for organic matter oxidation by bacteria while algae in turn utilize CO_2 produced by bacterial respiration for growth (Mun and Guieysse 2006). Hence, the algae–bacteria mutual relationship may represent an alternative free aeration in situ which could probably save 45–75% of the total energy cost required for aeration during the activated sludge wastewater treatment process (Razzak et al. 2013). Moreover, HRAPs are easier to operate, more economical and offset more greenhouse gas emissions than mechanical treatment systems (Craggs et al. 2014; Rawat et al. 2011).

The performance of biological wastewater treatment is usually controlled by different design and operational factors, including environmental, operational, and biological factors that can affect the system performance (Grobbelaar 2010; Larsdotter 2006). These factors need to be optimized; otherwise, they can alter physical, chemical, and biological processes in the system, and in turn, can compromise the development of microorganisms involved in pollutant removal and thus ultimately affect treatment efficiency (Assemany et al. 2015). However, negative influences of many physical/chemical factors can be minimized through the modification of HRAP operational features such as organic loading rate, pond depth, and hydraulic retention time (Sutherland et al. 2015). Pond depth influences the physical, biological, and hydrodynamic aspect of ponds. According to Sutherland et al. (Sutherland et al. 2014a, b, c), the volume of wastewater treated and the amount of light a microalgae receives are largely determined by pond depth. Other factors, such as biomass concentration and mixing regime, influence light intensity in HRAP. The depth of ponds can also affect the treatment efficiency by altering the synergetic balance between heterotrophic bacteria and autotrophic microalgae through organic carbon and oxygen exchanges (Lundquist et al. 2010).

Pond hydraulic retention time (HRT) is also an important parameter in the proper design of HRAP and ultimately affects effluent quality and algae biomass productions (Faleschini et al. 2012). Various suggestions of operational depth and HRT for HRAPs have been made (Rawat et al. 2016). However, according to the recommendations of several studies, HRT falls in the range of 3–10 days and the operational depth of HRAPs varies from 15 to 100 cm in different seasons and climatic conditions (Mehrabadi et al. 2015; Nurdogan and Oswald 1995; Olguın 2003). Depth, HRT, and climate conditions also affect organic loading rate, as the loading rate is directly related to the ability of ponds to remain aerobic (Butler et al. 2017). According to USEPA (2011), HRT between 120 and 180 days was required for the BOD loading rate between 11 and 22 kg/ha/day, respectively, in winter at temperatures below 0 °C to achieve 95% BOD_5 removal efficiency. This shows that many of the factors affecting the performance of HRAP are interrelated, suggesting that optimizing these parameters is critically important.

Various studies have tested HRAPs for the treatment of municipal, industrial, and agricultural wastes (Park et al. 2011). Some studies have been carried out to optimize HRAP performance for wastewater treatment, focusing on single operational features such as depth, HRT, mixing system, and organic loading rate (Garcia 2000; Sutherland et al. 2014a, b, c; Cromar and Fallowfield 1997). These studies examined operational and environmental conditions for maximum algal growth and productivity, which are fundamental to the successful application of HRAP for both wastewater treatment and biomass production for economic use. Other factors in algal growth and productivity in HRAPs include HRT, organic loading rate, and others, all of which are affected by weather condition. This study aimed to determine the performance of HRAPs for organic (COD and BOD) removal from primary settled municipal wastewater using two pond depths with different HRTs and organic loading rates in the tropical highland climate of Addis Ababa, Ethiopia.

2 Materials and Methods

2.1 Experimental Site and Wastewater Characteristics

Primary settled wastewater was used in the experiment. The wastewater was primary sedimentation chamber wastewater from a waste stabilization pond (WSP) located in Akaki-Kaliti wastewater treatment station in the southern part of Addis Ababa, Ethiopia. The city is located at 2400–2500 m altitude and has a temperate humid tropical highland climate. The Akaki-Kaliti treatment system consists of two series of ponds, each consisting of one facultative pond, one maturation pond, and two polishing ponds. The treatment plant receives daily about 7600 m^3/day sewage water, which it discharges into the Little Akaki River after approximately 30-day HRT. The physico-chemical quality of the wastewater after primary sedimentation used in this study is shown in Table 1. In terms of organic content, the influent can be grouped into weak, medium, and strong wastewater (Metcalf-eddy 2003).

Table 1 Physico-chemical characteristics of wastewater used in testing

Parameter (mg/l)	*N*	Average	Range	Standard deviation
pH	24	7.26	6.63–8.06	0.45
TDS	24	398.32	340–422	20.43
TSS	24	260.65	128–312	23.36
BOD_5	24	266.49	246–285	11.55
COD	24	355.55	335–378	12.31

2.2 Experimental Setup

Two pilot HRAPs were constructed externally from wooded (timbered) and internally laminated by PVC (polyvinyl chloride) materials with the following dimensions: width 0.6 m, length 1.8 m, and illuminated surface area 2.0826 m^2. Two three-paddle wheels, each 0.28 m in diameter and made from stainless steel, were locally constructed for mixing the wastewater and mounted to one 4-m-long metal shaft. The two HRAPs were placed parallel to each other in a way that was suitable for the movement of the water in the two ponds with the metal shaft at the same rotational speed (Fig. 1).

The shaft was driven by a 0.1 kW electrical motor with a speed control to provide 0.2 m s^{-1} horizontal water velocity. The pond bottom was lined with plastic geomembrane to prevent infiltration of wastewater.

2.3 Experimental HRAP Operation

To assess the treatment performance of the pilot HRAPs as a function of depth and HRT, two identical HRAPs but with two different water depths (250 and 300 mm) and corresponding working volume of 0.43 and 0.52 m^3 were constructed. The two HRAPs were operated under four different HRTs (2, 4, 6, and 8 days). The range of the depth and HRT operational parameters was chosen based on the recommendation by various studies of HRAP reactors (Mehrabadi et al. 2015; Nurdogan and Oswald 1995; Olguín 2012; Olguın 2003). Although these studies stated HRT in the range of 4–10 days, operating HRAPs at longer HRT require large land area and lower inorganic carbon content in the pond, which in turn negatively affect the economic viability and treatment efficiency of the system (Sutherland et al. 2014a, b, c). Hence, considering the practicability of the system, the maximum HRT for two HRAPs was set to 8 days in this study. Initially, both HRAPs were operated in batch mode for 10 days to allow stabilization of algae in the ponds as described by (Kim et al. 2014), and then switched to semi-continuous mode. The daily influent flow rate to maintain semi-continuous mode was calculated using working volume and HRT. Accordingly, 215, 108, 72, and 54 l in 250-mm-deep HRAP, and 258.4, 130, 86, and 65 l in

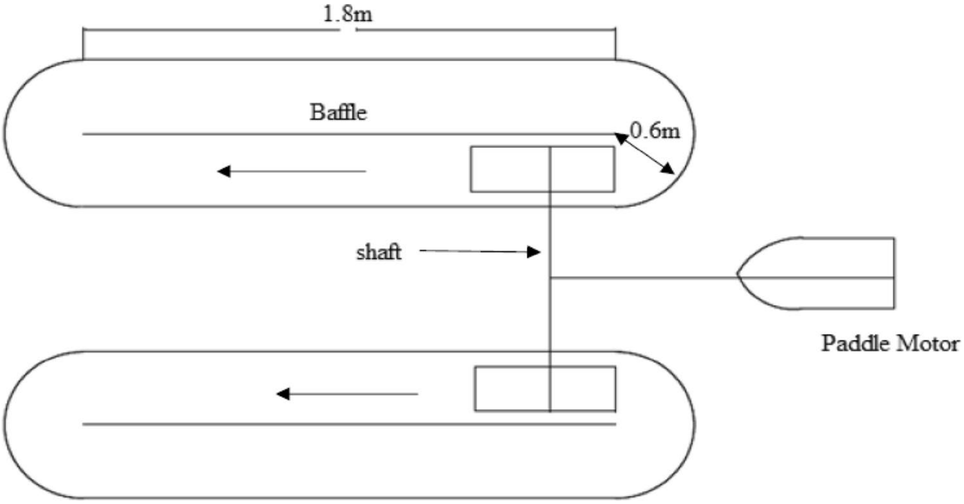


Fig. 1 Layout of the two pilot-scale experimental HRAPs

the 300-mm-deep HRAP were exchanged daily with algal culture during HRTs of 2, 4, 6, and 8 days, respectively.

Fresh wastewater in the primary sedimentation chamber was pumped after sedimentation to a 500 l tank installed near the experimental facility. After taking 250 ml using a clean plastic bottle for laboratory analysis, respective prescribed volumes of wastewater were measured and exchanged with equal volumes of culture during the semi-continuous operation between 10:00 a.m. and 10:30 a.m. everyday. The experiment was run for 2 months from March to April, 2016, approximately for 15 days under each HRT. Before starting the semi-continuous experiment, both HRAPs were pre-cultured with 10 l of indigenous wastewater containing the algae consortia *Chlorella* sp., *Chlamydomonas* sp., and *Scenedesmus* sp. These consortia were obtained from the effluent of a maturation pond and allowed to operate in batch mode for 10 days to allow the stabilization of algae in the pond. On the tenth day, the concentration of algae biomass exceeded 1 g/l, which according to Kim et al. (2014) can be acclimatized to the organic and nutrient loading rate during continuous process treatment.

2.4 Experimental Control and Organic Matter Measurement

Grab samples from each HRAP effluent were collected every 2 days for laboratory analysis of COD, BOD_5, TSS, and nutrients using 250 ml sampling between 10:00 a.m. and 10:30 a.m. throughout the course of the experiment. The analytical method used for these parameters follows standard procedures outlined by the APHA (2005). Other physical parameters measured daily on site throughout the experimental period were pH by HI 9024 microcomputer pH meter (HANNA instruments), TDS conductivity and salinity by SX713 Cond/TDS/Sal/Res meter (HANNA instruments), and dissolved oxygen by an oxygen meter (Co-411 ELMEIRON).

2.5 Species and Chlorophyll Analysis

Three major algal species resident in the experimental ponds were identified at the genius level with the help of an inverted microscope (Leica model) equipped with a Leica microscopic camera at a magnification of 400× using various identification keys as outlined by APHA (2005). Chlorophyll-a was determined spectrophotometrically according to the monochromatic method of Lorenzen (APHA 2005). Then, 150 ml of samples was filtered through Whatman GF/F filters for the determination of total chlorophyll-a. Pigments of cells retained on the filter papers were extracted in 90% acetone for 24 h in the dark at 4 °C after homogenization. Chlorophyll-a concentration was determined using the following formula by Lorenzen (Lorenzen 1966):

$$\text{Ch-a}\left(\text{mg/m}^3\right) = \left[26.7\left(E_{665b} - E_{750b}\right) - \left(E_{665a} - E_{750a}\right)\right]\frac{V_e}{L \times V},$$

where V_e = volume of extract in milliliters, V = filtered volume in liter, L = cuvette light path in centimeter, E_{665b} = optical density before acidification, E_{665a} = optical density after acidification, E_{750b} = optical density for light scattering before acidification, and E_{750a} = optical density for light scattering after acidification.

Finally, each analysis was made in triplicate and all data points represent the mean of replicate measurements except were noted. Finally, the percentage reduction is calculated following the equation below:

$$\text{Removal efficieny} = \left(\frac{\text{Influent concentration} - \text{effluent concentration}}{\text{influent concentration}}\right) \times 100.$$

2.6 Weather Conditions

Daily solar irradiation was obtained from CAMS McLean v2.7 Satellite model at 8.77565 N and 38.85 E in Addis Ababa, Ethiopia (http://www.soda-pro.com/web-services/radiation/cams-mcclear). Daily temperature data were provided from the National Metrological Station in Akaki-Kaliti. Minimum and maximum daily solar irradiation values from March to April were 7.46 and 8.35 kW/m^2/day, respectively. The minimum and maximum daily air temperatures were 23 °C and 31 °C between March and April. March to May are the driest months (spring season) in Addis Ababa. Review of the metrological record shows that the maximum solar irradiation and temperatures occured during spring. The temperature and irradiance data recorded during the experimental period fall in the favorable range for most microalgal species (Mun and Guieysse 2006).

2.7 Data Analysis

The software package, SPSS Statistics 21, was used to perform the statistical analysis. One-way analysis of variance (ANOVA) was used in the case of replicate measurements. Paired *t* test was used to evaluate the difference in mean organic removal between the two treatments at the 5 and 1% significant levels. Pearson's correlation was used to evaluate the relationship between variables. Microcal origin (8.0) was used for data plotting and graphs.

3 Result and Discussion

3.1 Environmental Variables and Chlorophyll-a Production

Culture pH, DO, and chlorophyll-a production were positively correlated with HRT in both HRAPs. The pH value increased to 9.02 and 8.97 from the average initial pH value of 6.73 in the 250- and 300-mm-deep HRAPs during the 9-day batch treatment period, respectively. The maximum pH values tested were 9.34 and 9.16 during 4-day HRT operation in the 250- and 300-mm-deep HRAPs, respectively. Maximum DO production of 10.08 mg/l recorded in the 250-mm-deep HRAP was during 6-day HRT operation and of 12.01 mg/l in the 300-mm-deep HRAP was during 4-day HRT operation. Maximum chlorophyll-a production in 250- and 300-mm-deep HRAPs was 2.91 and 2.76 mg/l during 6-day HRT operation, respectively.

While culture pH and DO were positively correlated to HRT in both HRAPs, a different trend was recorded between pH and DO with respect to the operational water depth. Higher DO production was recorded in the 300-mm-deep HRAP than in the 250-mm-deep HRAP, whereas higher pH value was recorded in the 250-mm-deep HRAP than in the 300-mm-deep HRAP. These differences can be explained in terms of carbon requirement, biomass concentration, and pond depth. Marginally, higher chlorophyll-a concentration was observed in the 250-mm-deep HRAP, indicating higher carbon requirements. However, considering the absence of external carbon addition, the available inorganic carbon from wastewater and paddling was apparently over consumed in shallow HRAP. Furthermore, higher chlorophyll concentration coupled with carbon limitation can reduce photosynthetic efficiency at least during part of the day and resulted in less cumulative DO production in the shallower pond (Sutherland et al. 2014a, b, c). Thus, deeper ponds are more favorable to keep the pH at moderate values, indicated in our study by the relatively low pH values in the deeper HRAP.

Areal biomass productivity increased with increasing pond depth. Increased areal productivity with pond depth suggests that algae growth in 300-mm-deep HRAPs was less affected by inorganic carbon limitation due to pond depth, while algae growth in the shallower HRAP was more constrained in spite of favorable mixing and light exposure (Sutherland et al. 2014a, b, c). Inorganic carbon concentration from wastewater was higher in the 300-mm-deep HRAP, directly linked to the influent flow rate. Chlorophyll-a biomass of 2.6 mg/l in HRAP wastewater treatment was reported by Cromar and Fallowfield (1997), comparable to the result of our study. However, they recorded chlorophyll-a biomass of 3.49 mg/l by operating the same HRAP with higher carbon loading than in the present study. As discussed above, maintaining the availability of excess inorganic carbon is often a challenge in municipal wastewater algae cultivation as this limits algae photosynthetic efficiency via chlorophyll productivity and nutrient removal.

3.2 COD and BOD Removal

The average influent and removal efficiency in both HRAPs at each HRT are shown in Table 2. A maximum of 81.86 and 79.94% BOD$_5$ was removed from 250- and 300-mm-deep HRAPs during 8-day HRT operation, respectively. Conversely, higher percentage reduction of COD was achieved in the 250-mm-deep HRAP (78.03%) than in the 300-mm-deep HRAP (76.79% during 6-day HRT operation. The removal of COD and BOD$_5$ was positively correlated with HRT in both HRAPs throughout the experimental period. However, the concentration of COD increased in both HRAPs when the system switched to 8-day HRT.

At longer HRTs (> 2 days), inorganic carbon from the wastewater can be exhausted and algal growth is influenced by the available CO$_2$ through paddle rotation (Kim et al. 2014), probably accounting for the high COD concentration during 8-day HRT operation in both HRAPs (Fig. 2). Algae can also release some organic carbon back to the solution,

Table 2 Average influent (mg/l) and removal efficiencies (%) of COD and BOD_5 in the 250- and 300-mm-deep HRAPs

Parameter	Depth	250-mm-deep HRAP				300-mm-deep HRAP			
	HRT	2	4	6	8	2	4	6	8
BOD_5	Influent	266.59	263.37	264.53	264.79	266.59	263.37	264.53	264.79
	Rem. eff.	58.37	67.77	74.86	81.86	54.96	64.15	70.11	79.94
COD	Influent	356.67	356.93	358.47	349.91	356.67	356.93	358.47	349.91
	Rem. eff.	54.48	63.22	78.03	75.59	57.18	64.19	76.79	74.92

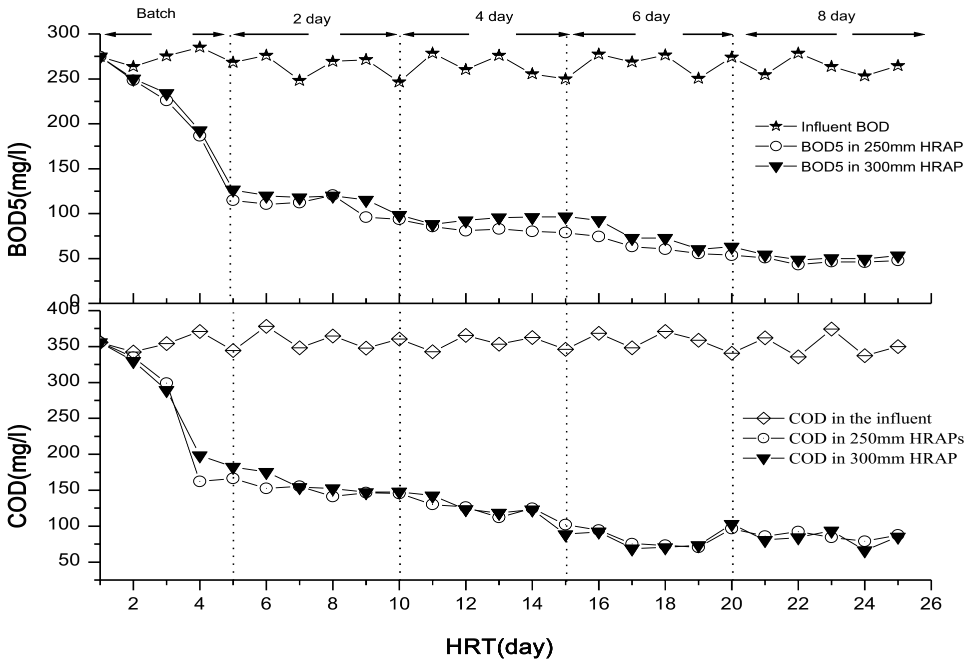


Fig. 2 BOD and COD reduction at 2-, 4-, 6-, and 8-day HRTs

especially during the stationary period in autotrophic growth (Wang et al. 2010). Increased COD after 7 days was also reported by He et al. (2013) in *Chlorella vulgaris* cultivated using municipal wastewater for 18 days. However, the removal efficiency of BOD_5 continued to increase with increased HRT.

The mean of BOD_5 removal between the two HRAPs varied significantly ($P < 0.05$) during 2-, 4-, and 6-day HRT operations. The mean removal of BOD_5 was high in the 250-mm-deep HRAP, while significant correlation ($P < 0.01$) between BOD_5 removal and DO production was observed only in the 300-mm-deep HRAP ($r = 0.566^{**}$). On the other hand, chlorophyll-a biomass and DO production were significantly correlated with both the 250- and 300-mm-deep HRAPs ($r = 0.809^{**}$). This result is surprising because the removal of organic matter in an aerobic reactor has a direct relationship with that of oxygen concentration. A possible explanation may be the observed comparable ratio between daily volumetric DO productions to volumetric BOD_5 rate loading rate (g/m^3/day) in both HRAPs during the 2-month study. The ratio between autotrophic (chlorophyll-a) to heterotrophic (VSS) biomass was slightly higher in the 300-mm-deep HRAP, suggesting that there was a greater proportion of heterotrophic/non-algal biomass in the 250-mm-deep HRAP.

Although pond depth may impact organic removal through modification of light distribution underwater by affecting photosynthetic oxygen production for organic matter oxidation by bacteria, the mean BOD_5 removal difference observed for 50-mm-deep difference in this study is not expected in large-scale application for wastewater treatment. This is due to surface water waves by wind that can increase the rate of oxygen transfer from the air coupled with paddle wheel algal cell vertical mixing (Boelee et al. 2014). The removal of COD did not show significant differences between the two HRAPs, while the production of chlorophyll-a was different in the two ponds. Based on this result, the 300-mm-deep HRAP offers an advantage in that it can reduce land area requirement for the same volume of wastewater treated. Furthermore, pond hydraulic retention time and pond depth may be used to control the organic matter removal in large-scale wastewater treatment application.

Several studies of COD and BOD$_5$ removal reported similar and dissimilar results as the present study. COD removal of pilot HRAP operated under different HRTs using municipal wastewater tested by Kim et al. (2014) increased with increasing HRT under greenhouse condition. They reported 85.44% COD reduction using 2-day HRT; a higher removal in spite of a shorter HRT than in our study, which may be explained by environmental conditions. According to Craggs et al. (2012), high-rate algal ponds at a large-scale municipal wastewater treatment plant also significantly reduced organic pollutants (BOD$_5$ reduction of 82–91%). Hoffmann (1998) reported 80% COD reduction using an algae–bacteria consortium obtained from municipal wastewater. The organic matter removal rates reported above are similar to those in our study. A similar study of pilot HRAPs under ambient environmental condition demonstrated that the algae–bacteria systems are capable of attaining up to 78.6% COD reduction from animal wastewater (Cromar and Fallowfield 1997).

3.3 Organic Loading Rate and HRAP Performance

Many HRAP performance indicators and organic loads are interrelated. The average daily organic loading rates estimated for the present study based on BOD$_5$ tests in the influent during 2-, 4-, 6-, and 8-day HRT operations were 275.3, 136.3, 91.5, and 68.7 kg/ha/day in the 250-mm-deep HRAP and 335.3, 164.4, 109.3, and 82.7 kg/ha/day in the 300-mm-deep HRAP, respectively. The relationship between BOD$_5$ loading rate and BOD$_5$ removal in the two HRAPs is shown in Fig. 3. Significant inverse relationships were observed for the 250-mm-deep HRAP ($r = -0.881^{**}$) and the 300-mm-deep HRAP ($r = -0.855^{**}$) at $p = 0.01$.

Similarly, strong negative correlation was observed for chlorophyll-a production in the 250-mm-deep HARP ($r = -0.895^{**}$) and 300-mm-deep HARP ($r = -0.953^{**}$) at $p = 0.01$ (Fig. 4). Decreased loading rates increased organic removal and algal biomass production.

Areal organic loading rate is one of the pond design factors that can affect large-scale HRAP performance for wastewater treatment and biomass production. Craggs et al. (2007)

Fig. 3 Influence of organic loading rates on HRAP performances in the 250- and 300-mm-deep HARPs

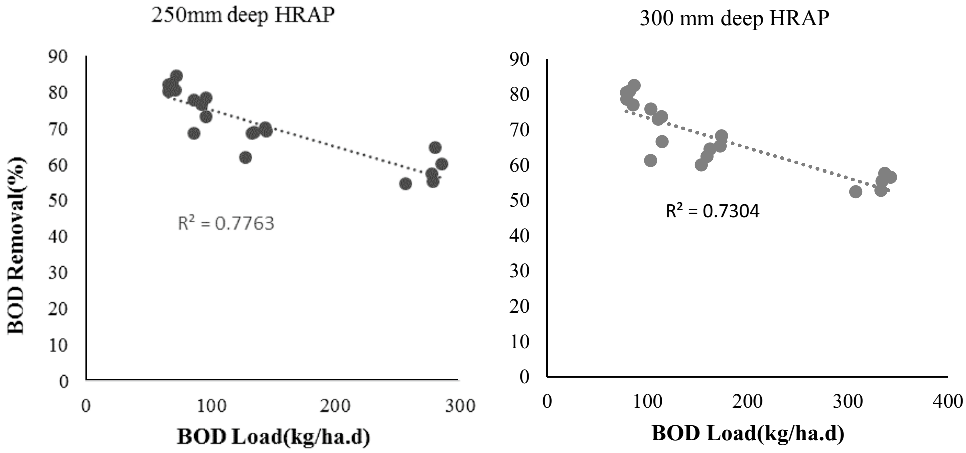
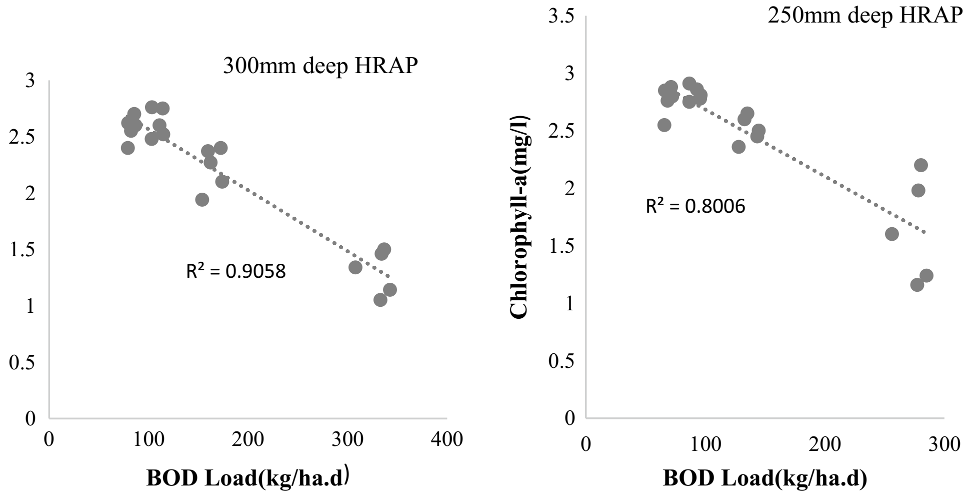


Fig. 4 Organic loading and chlorophyll-a biomass production in the 250- and 300-mm-deep HARPs



recommended organic loading rates in the range of 100–150 BOD_5 kg/ha/day for such kind of system, in agreement with values observed in our 300-mm-deep HRAP during 6-day HRT operation. On the other hand, chlorophyll-a production increased continuously during 2-, 4-, and 6-day HRT operations, decreasing only during 8-day HRT operation in both HRAPs. Factors such as nutrient limitation, low availability of light due to self-shading, and inorganic carbon in the absence of external aeration are probably responsible for the reduction of chlorophyll-a production during 8-day HRT.

Table 3 shows the average influent and effluent concentrations of TN, TP, NH_4–N, and dissolved reactive phosphorous (DRP) at each HRT operation. Although the removal of nitrogen and phosphorous increased with increasing HRT, the concentration of ammonium was reduced during 4-day HRT and remained low during 6- and 8-day HRT operations in both HRAPs (Table 3). It was also observed that the deeper pond found to perform better in nutrient removal, which can be explained partly by high photosynthetic rate in the shallow pond, raised pH and DO value possibly resulted in dissolved inorganic carbon depletion at early HRT in this system. For such condition, Lundquist et al. (2010) suggested that higher depth have an advantage in nutrient removal because it can hold CO_2 underwater relatively for long HRT before outgassing to the atmosphere.

The organic loading rate at 6-day HRT can support maximum DO and chlorophyll-a production (Fig. 5). However, BOD_5 and COD removal observed in 250- and 300-mm-deep HRAPs at 6-day HRT were 40 and 55% higher than the values stipulated in Ethiopia (EEPA 2003). This may be attributed due to raw wastewater strength in the influent feed to the HRAP. At high organic level, the pond may be converted into an anaerobic system that can suppress algal activity and ultimately reduce oxygen availability for organic matter degradation by bacteria (Butler et al. 2017). On the other hand, nutrient concentrations such as TN, TP, NH_4–N, and DPR in the two HRAPs effluent were well below the values of influent discharge requirements in Ethiopia at 6-day

Table 3 Average nutrient concentration (mg/l) in the influent and effluent at each HRT operation

Parameter	Depth	250-mm-deep HRAP				300-mm-deep HRAP			
	HRT	2	4	6	8	2	4	6	8
TN	Influent	78.984	80.786	79.03	81.808	78.984	80.786	79.03	81.80
	Effluent	28.0	14.63	11.52	8.81	33.86	12.47	0.57	6.7
NH_4–N	Influent	36.96	39.27	40.29	34.56	36.96	39.27	40.29	34.56
	Effluent	2.47	1.24	ND	ND	4.46	1.23	ND	ND
TP	Influent	14.24	13.96	13.06	13.664	14.24	13.96	13.06	13.664
	Effluent		3.94	4.48	3.53	8.48	5.54	4.06	3.1
DRP	Influent	11.56	10.84	12.40	11.11	11.56	10.84	12.40	11.11
	Effluent	6.52	3.14	2.54	1.57	6.24	2.42	2.12	1.04

ND not detected

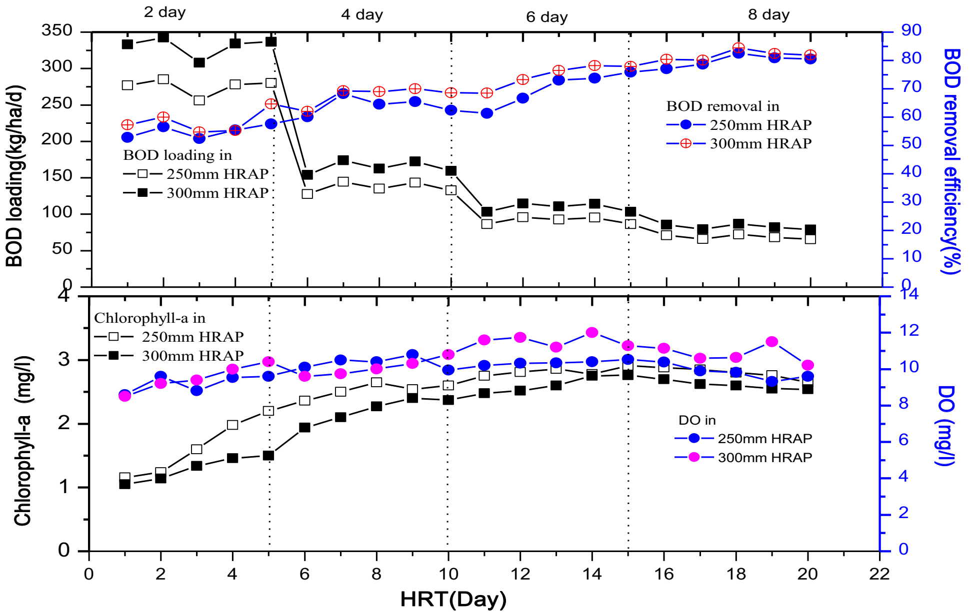


Fig. 5 Organic loading rate, BOD removal efficiency, and DO and chlorophyll production at 2-, 4-, 6-, and 8-day HRTs

HRT operation (EEPA 2003). These results may show that 250- and 300-mm-deep HRAPs can be designed for large-scale wastewater treatment at organic loading rates of 91.5 and 109.3 (BOD_5 kg/ha/day), respectively, and give similar results at 6-day HRT.

3.4 Algal Species Diversity in HRAPs

Hydraulic retention time, mode of operation, and treatment depth were presumed to cause changes in species diversity of algal assemblage in the treatment ponds. However, no shift in species dominance associated with changes in environmental variables of the experimental setting was observed. A group of Chlorophyceae algae consisting of the genera *Chlamydomonas*, *Chlorella*, and *Scenedesmus* was the dominant algal assemblage in both the pilot HRAPs throughout the course of the study. These algae genera are known to be among the ten most pollution tolerant microalgae (Godos et al. 2009).

Species dominance can be determined by different factors, including retention time, loading rate, and such environmental variables as incident surface radiation and temperature (Cromar and Fallowfield 1997). The shallow operational depth and short circulation times of wastewater in the pilot HRAP due to mixing of the water that kept the algae in suspension may have contributed to the observed algal assemblage. Keeping the algae cells in suspension plays a critical role in maintaining the dominance of a species in ponds (Reynolds 2012).

4 Conclusion

This study analyzed the performance of two pilot HRAPs with different depths and similar HRTs using primary settled municipal wastewater. The removal of COD and BOD_5 increased with increasing HRT regardless of depth. The BOD_5 removal achieved was statistically higher in the 250-mm-deep HRAP; this is not expected in large-scale applications in the presence of wind and a paddle wheel effect. The Chlorophyceae algae *Chlamydomonas*, *Chlorella*, and *Scenedesmus* dominated the algal assemblage in both pilot HRAPs. These species are known for their tolerance to high organic loading. Larger organic removal and larger volume of treated wastewater were achieved with the 300-mm-deep HRAP per land area than in the 250-mm-deep HRAP without compromising effluent quality. Further studies are required to examine the role of greater depth than 300 mm on discharge quality. Pilot studies may identify optimum HRAP designs for sewage and sewage application at a larger scale.

Furthermore, the results of the study presented here suggest that using indigenous algae–bacteria in HRAP is appropriate for the remediation and efficient reduction of COD and BOD_5 in municipal wastewater under tropical highland climate conditions. Moreover, the algal biomass from the final effluent should be harvested before discharge to the environment. Gravity settling is a low-cost biomass harvesting mechanism for further use and improving water quality.

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