Effects of organic loading rate in high-rate algal ponds: bioremediation potential, implications to design and operation

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Highlights:

- Three ponds were operated with increasing sewage flows to evaluate the effects of organic loading rates (kg BOD ha^{-1} day^{-1}).
- Hydraulic retention times of 5, 6.7, or 10 days did not differ significantly in treatment efficiency or biomass production.
- Further studies should investigate higher organic loads besides prioritizing HRAPs as tertiary treatment units.

Keywords: microalgae biomass; wastewater treatment; raceways; operational strategies.

INTRODUCTION

The Organic Loading Rate (expressed in kg BOD ha^{-1} day^{-1}) is one of the parameters used in the design of facultative ponds, with established removal coefficients for different operational ranges (Ho & Goethals, 2020). However, for High-Rate Algal Ponds (HRAPs), design methods lack standardization. Although studies have reported operational organic loading rates ranging between 100 and 150 kg BOD ha^{-1} day^{-1} (Craggs et al., 2014), the values for HRAP applications are not well defined in the literature. This type of system has been applied both as a secondary and tertiary treatment unit for domestic wastewater (DW) treatment with varying results. Despite the increasing adoption of HRAPs as an attractive alternative for decentralized treatment in small communities (Fallowfield et al., 2018), the establishment of reliable removal coefficients adjusted to variations in loading rates remains a substantial gap. Obtaining concrete data for removal coefficients under different operational scenarios is essential for formulating models and guidelines that provide accurate sizing and optimal performance. Thus, the aim of this study was to evaluate the operation, regarding treatment efficiency and biomass production, of HRAPs subjected to different organic loading rates.

METHODOLOGY

The experiment was conducted at the Laboratory of Sanitary and Environmental Engineering of the Federal University of Viçosa from August 2022 to February 2023. DW, collected after a septic tank, was used as the cultivation medium. Three HRAPs of 1m³ each were operated with different organic loading rates (measured in kg BOD ha^{-1} day^{-1}): 200 L/day (with a Hydraulic Retention Time - HRT = 5 days) for HRAP 1, 150 L/day (HRT = 6.7 days) for HRAP 2, and 100 L/day (HRT = 10 days) for HRAP

3. The DW had a mean biochemical oxygen demand (BOD) of 107.18 ± 50.45 mg/L, which resulted in organic loading rates of 64.96, 48.72, and 32.48 kg BOD ha^{-1} day^{-1} for HRAPs 1, 2, and 3, respectively. Environmental conditions and physical and chemical parameters of the DW and HRAPs were monitored weekly following APHA (2012) standards. The monitored variables included BOD, ammoniacal nitrogen ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), soluble phosphorus (Ps), soluble chemical oxygen demand (CODs), soluble total organic carbon (TOC), and volatile suspended solids (VSS). Chlorophyll-a (Chl-a) was extracted with 80% ethanol and measured by spectrophotometry; concentrations were determined using equations provided in the Dutch standard. Dissolved oxygen, pH, and temperature were measured with a Hach HQ40d probe. The phytoplankton community was analyzed for the inoculum and at the end of the operation for each HRAP, including organism identification, and density. The organic matter removal coefficients (k_{BOD}) were calculated for each treatment using von Sperling (2015) models based on BOD data for the complete mixing model (Bodenstein number of the HRAPs = 9.7). The results underwent normality tests followed by the Kruskal-Wallis test with a 5% probability, using PAST 4.03 software.

RESULTS AND CONCLUSIONS

The results for removal efficiencies and biomass production for each system are presented in Table 1.

Variable	Unit	DW	HRAP 1	Remov.	HRAP 2	Remov.	HRAP 3	Remov.	p*
Load	kg BOD/day /ha	-	64.96	-	48.72	-	32.48	-	X
BOD	mg/L	107.18 (50.45)	68.6 (21.13)	35.99%	80.24 (25.9)	25.13%	103.67 (34.69)	3.28%	0.1492
CODs	mg/L	164.75 (81.44)	129.5 (91.88)	21.40%	119.43 (31.44)	27.51%	98.92 (31.36)	12.72%	0.2195
pH	-	7.63 (0.22)	6.13 (1.19)	X	6.72 (1.24)	X	6.48 (1.09)	X	0.5738
DO	mg/L	0.79 (0.36)	10.66 (2.49)	X	10.61 (2.35)	X	10.61 (2.14)	X	0.9475
Temp.	ºC	23.65 (1.77)	23.08 (2.11)	X	23.38 (2.64)	X	22.78 (2.26)	X	X
$N\text{-}NH_4^+$	mg/L	96.12 (57.96)	23.23 (12.21)	75.83%	12.4 (11.02)	87.10%	19.03 (8.07)	80.20%	0.1339
$N\text{-}NO_3^-$	mg/L	11.38 (9.55)	43.56 (24.63)	-282.81%	60.91 (58.53)	-435.33%	58.29 (53.71)	-412.29%	0.9341
Ps	mg/L	10.51 (4.22)	8.88 (2.88)	15.46%	8.13 (3.01)	22.68%	9.62 (3.18)	8.47%	0.357
TOC	mg/L	34.89 (13.47)	36.73 (12.34)	39.77%	23.3 (8.6)	22.66%	20.49 (3.94)	36.45%	0.735
Chl-a	mg/L	-	1.35 (0.73)	X	1.75 (0.87)	X	1.61 (0.94)	X	0.6352
VSS	mg/L	-	100.75 (50.3)	X	157.54 (112.48)	X	119.57 (69.57)	X	0.7254

*p: p-value for the Kruskall-Wallis test.

Table 1. Treatment efficiencies and biomass production for each pond (average values and standard deviation between parenthesis).

In our preliminary analysis, no significant difference in treatment performance across different flow rates was found, indicating a lack of distinctive treatments. The average BOD removal efficiencies were 35.99%, 25.13%, and 3.28% for HRAPs 1, 2, and 3, respectively. Comparable results were observed by El Hafiane and Hamouri (2005) operating HRAPs with effluent from UASB with and without gravel filters. They applied a rate of 52 kg BOD/day/ha, achieving 22% BOD removal. Inlet BOD concentration was low at 45 mg/L after the gravel filter. Biomass production ranged from 131-185 mg VSS/L, with chl-a productivity averaging 0.05-0.08 g/m²/day, statistically equal among treatments.

Assis et al. (2017) achieved similar chl-a productivity (0.05 g/m²/day) with septic tank sewage. However, the total biomass productivity (3.68 g/m²/day) was lower than the range of the present study (4.44-5.67 g/m²/day). The primary domestic sewage used as a culture medium had a BOD concentration averaging 107.18 ± 50.45 mg/L, lower than typical values of 250-400 mg/L (Von Sperling, 2016), contributing to lower loading rates. Alemu et al. (2018) operated at higher rates but with higher influent BOD concentrations in the wastewater. The reduced BOD concentration may be due to dilution by rainwater, possibly due to deficiencies in the sewage collection network. Precipitation data support this hypothesis, which poses a challenge for treatment and biomass production in outdoor systems. Regarding phytoplankton community composition, significant differences were also not observed, with *Chlorella vulgaris* predominating, albeit at slightly different relative densities (3-15%). The k_{BOD} values for each system were 0.147 day^{-1} for HRAP 1, 0.049 day^{-1} for HRAP 2, and 0.024 day^{-1} for HRAP 3, with no statistically significant difference (p-value = 0.4452). While further studies operating at higher organic loads are necessary to compare performance, it can be concluded that HRAPs can effectively serve as tertiary treatment units, focusing on nutrient recovery to improve final effluent quality.

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REFERENCES

Alemu, K., Assefa, B., Kifle, D., & Kloos, H. (2018). Removal of Organic Pollutants from Municipal Wastewater by Applying High-Rate Algal Pond in Addis Ababa, Ethiopia. Earth Systems and Environment, 2(2), 377–386. https://doi.org/10.1007/s41748-018-0050-1

American Public Health Association (APHA), & Water Environment Federation. (2012). Standard methods for the examination of water and waste water.

Assis, L. R. de, Calijuri, M. L., do Couto, E. de A., & Assemany, P. P. (2017). Microalgal biomass production and nutrients removal from domestic sewage in a hybrid high-rate pond with biofilm reactor. Ecological Engineering, 106, 191–199. https://doi.org/10.1016/j.ecoleng.2017.05.040

Craggs, R., Park, J., Heubeck, S., & Sutherland, D. (2014). High rate algal pond systems for low-energy wastewater treatment, nutrient recovery and energy production. New Zealand Journal of Botany, 52(1), 60–73. https://doi.org/10.1080/0028825X.2013.861855

El Hafiane, F., & Hamouri, B. (2005). Anaerobic reactor/high rate pond combined technology for sewage treatment in the Mediterranean area. Water Science & Technology.

Fallowfield, H. J., Young, P., Taylor, M. J., Buchanan, N., Cromar, N., Keegan, A., & Monis, P. (2018). Independent validation and regulatory agency approval for high rate algal ponds to treat wastewater from rural communities. Environmental Science: Water Research & Technology, 4(2), 195–205. https://doi.org/10.1039/C7EW00228A

Ho, L., & Goethals, P. L. M. (2020). Municipal wastewater treatment with pond technology: Historical review and future outlook. Ecological Engineering, 148(February), 105791. https://doi.org/10.1016/j.ecoleng.2020.105791

Von Sperling, M. (2015). Wastewater Characteristics, Treatment and Disposal. Water Intelligence Online, 6(0), 9781780402086–9781780402086. https://doi.org/10.2166/9781780402086

Von Sperling, M. (2016). *Urban wastewater treatment in Brazil.*