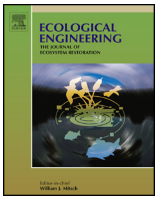
Ecological Engineering 98 (2017) 91–97

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Environmental and operational factors affecting carbon removal in model arctic waste stabilization ponds

Colin M. Ragush, Joanna M. Poltarowicz, Justine Lywood, Graham A. Gagnon, Lisbeth Truelstrup Hansen, Rob C. Jamieson*

Centre for Water Resources Studies, Dalhousie University, 1360 Barrington Street, Halifax, NS, Canada

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 29 July 2016
Accepted 5 October 2016
Available online 26 October 2016

Keywords:
Wastewater stabilization ponds
Municipal wastewater
Arctic
Biological treatment
Phytoplankton
Oxygen dynamics

ABSTRACT

Wastewater Stabilization Ponds (WSPs) are passive treatment systems influenced by both the ambient environment and the manner in which they are operated. Construction of wastewater treatment facilities is particularly challenging in the Canadian Arctic because of the remoteness of the communities and the extreme climate. Here, experimental bench scale WSPs were used to simulate single cell WSPs operating under summer treatment conditions in the Arctic. Experiments were performed to examine factors (temperature, irradiance, initial carbon concentrations, and organic loading rate) that may influence the oxygen state and carbon removal. All four factors were found to significantly ($p < 0.05$) affect oxygen state and carbon removal, but temperature (5 °C vs 15 °C) and initial carbon concentration (80 vs 240 mg/l) were found to be the most important factors. Final $CBOD_5$ concentrations in the experimental columns ranged from <10 to 150 mg/l, and only experimental columns operated at low temperature and high initial carbon concentrations had final $CBOD_5$ concentrations >30 mg/l. Phytoplankton growth and metabolism appears to have a prominent impact on $CBOD_5$ removal and the oxygen status of the experimental WSPs. The findings suggest that WSPs operating in cool arctic climates are more sensitive to perturbation by weather or operational changes than similar systems in warmer climates, and greater consideration for process resiliency needs to be incorporated into the design of arctic WSPs. This study provides further evidence that WSPs are an appropriate municipal wastewater technology for the Arctic and can achieve effluent $CBOD_5$ concentrations that meet secondary wastewater treatment standards, provided they are appropriately sized, designed, and operated for arctic conditions.

1. Introduction

Wastewater stabilization ponds (WSPs) are passive treatment systems that are strongly influenced by the ambient climate (Heinke et al., 1991). WSPs are a commonly used technology for treating agricultural, industrial and municipal wastewater, providing effective treatment of oxygen demanding substances, nutrients, suspended solids and pathogens (Shilton, 2005). WSPs are a popular technology for small remote communities as they are simple in design and operation, requiring minimal operator expertise, and are inexpensive in both capital and operational costs when compared to conventional mechanical treatment systems (Heinke et al., 1991; Mara et al., 1992).

Most communities in the Canadian northern territory of Nunavut utilize WSPs for municipal wastewater treatment. WSPs in Nunavut are typically designed as single cell storage WSPs with the capacity to store the volume of municipal wastewater generated over 11–12 months. These systems typically remain frozen for approximately 9–10 months of the year, with a short 2–3 month ice-free period during the arctic summer. Once a year, typically in late summer/early fall, WSPs are decanted over a 1–3 week period (depending on the size of the system) to provide capacity for the wastewater generated during the following year. Decant occurs in late summer because that is when the best effluent quality is assumed to occur. Elevated temperatures and solar irradiance experienced during the summer is presumed to facilitate biological treatment, and result in improved effluent quality by the time of fall decant.

Ragush et al. (2015) monitored four municipal WSPs in Nunavut during the summer treatment seasons of 2011–2014 to characterize pond conditions (chemical, biological and physical properties) and assess their performance in the context of the new Canadian Wastewater Systems Effluent Regulations. Ragush et al. (2015) identified that new design guidelines and strategies would need to

---

* Corresponding author.
E-mail address: jamiesrc@dal.ca (R.C. Jamieson).

http://dx.doi.org/10.1016/j.ecoleng.2016.10.031

Table 1
Factorial design – experimental factors and levels in the model waste stabilization ponds.

Factors	Levels	
Temperature	5 °C	15 °C
Irradiance	225 PAR (μe/m^2/s)	1050 PAR (μe/m^2/s)
Organic Loading Rate	3.8 kg CBOD$_5$/ha/d	15 kg CBOD$_5$/ha/d
Initial CBOD$_5$ Concentration	80 mg/l	240 mg/l

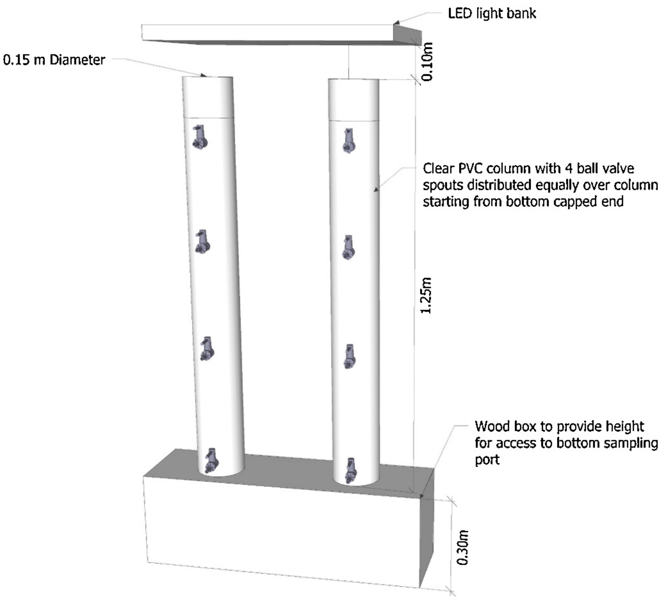


Fig. 1. Experimental setup for the model waste stabilization ponds.

be developed for arctic WSPs to meet the more stringent effluent quality criteria. The observation that systems designed to operate as facultative WSPs were generally anaerobic with limited phytoplankton populations, led us to hypothesize that the areal organic loading rates (OLRs) (kg CBOD$_5$/ha/day) might be too high. It is likely that anaerobic conditions in the WSPs negatively impacted the CBOD$_5$ removal (Mara et al., 1992; Shilton, 2005). The limited data available in the literature makes it difficult to predict the environmental and operational conditions that will lead to facultative conditions in arctic WSPs, but observations and literature suggest that water temperature (Lettinga et al., 2001), irradiance (Shilton, 2005), and OLR (US EPA, 1983) strongly influence WSP treatment performance and oxygen status.

Mara et al. (1992) state "(algal growth) is the whole basis of WSP treatment," and in typical WSP design guidelines at least one cell in the system is incorporated to promote prolific algal growth (Shilton, 2005). Algae provide a nutrient sink through nutrient assimilation (Middlebrooks et al., 1999), and an oxygen source for heterotrophic/aerobic bacteria (Shilton, 2005). Heterotrophic bacteria are more efficient at removing oxygen demanding material under aerobic conditions when compared to anaerobic conditions (Chan et al., 1999), and as a result, CBOD$_5$ removal efficiency is greatly enhanced by the presence of phytoplankton (Mara et al., 1992).

To better understand how environmental and operational factors influence phytoplankton dynamics and arctic WSP performance, a bench scale study of single cell WSPs operating under simulated arctic conditions was conducted. In the bench scale study, biological, chemical, and physical parameters were measured during 34–40 days simulations of arctic WSPs. The bench scale analysis of the arctic WSPs was used to assess the impact of irradiance, temperature, and organic loading conditions on: (i) oxygen status, and (ii) removal of carbonaceous oxygen demanding material.

2. Methods

2.1. Experimental design

Model WSPs were constructed out of transparent polyvinyl chloride (PVC) pipes (15.25 cm in diameter and 1.25 m in length) that were capped at one side, arranged vertically, and filled with synthetic wastewater (Fig. 1). The experiment was performed in a temperature-controlled chamber. A synthetic wastewater recipe (supplemental 1) was developed with comparable chemical, biological, and physical characteristics to wastewater contained in Pond Inlet, Nunavut's WSP (Ragush et al., 2015) at the start of the summer treatment season (late June/early July). The experiment was designed as a factorial design with 4 factors and 2 levels (Table 1) creating 16 unique conditions. Each set of unique conditions was tested in duplicate. A control column for phytoplankton growth, filled with Modified Bold 3N (University of Texas, 2015), and irradiated at 225 μe/m^2/s, was included within each trial. The low irradiance condition was used for the control column because the low light attenuation characteristics of the Modified Bold 3N, and phytoplankton experiencing conditions of high irradiance may exhibit inhibited growth (Dauta et al., 1990). Two initial carbon concentrations were simulated, because it was postulated that the initial carbon concentration of the WSP at the beginning of the biologically active summer period may impact treatment performance. A concentration of 240 mg/l represented the typical concentration of CBOD$_5$ in the Pond Inlet WSP at the start of the summer treatment season (Ragush et al., 2015). A lower concentration of 80 mg/l was included to assess how WSP systems would perform under a scenario in which a pre-treatment step (i.e. anaerobic cell) was included to reduce CBOD$_5$ before the facultative pond. Also, synthetic wastewater that was chemically comparable to raw untreated wastewater was added daily at two different rates to simulate an OLR comparable to that received by arctic WSPs (15 kg/ha/d) as well as a reduced rate to simulate how treatment performance may change under reduced loading conditions. Water lost due to evaporation and from sampling was replaced with distilled water daily to maintain a constant volume. Trials ran for 34–40 days, and samples were drawn every 5–7 days from the top sampling port, located approximately 20 cm below the water surface.

Temperatures of 5 °C and 15 °C were used as this range was representative of the observed surface water temperatures over the summer in arctic WSPs (Ragush et al., 2015). LED light banks were used to irradiate the columns and provide a light spectrum comparable to the solar spectrum. Two irradiance conditions were evaluated, with the high irradiance condition (1050 μe/m^2/s) being representative of a clear sky irradiance around solar noon. At the lower irradiance condition, 225 ue/m^2/s, roughly one quarter of the maximum incident irradiance, was used to represent the worst-case scenario in Pond Inlet where the observed average irradiance over the summers of 2012–2014 ranged from 292 to 355 ue/m^2/s.

2.2. Materials

2.2.1. Lights

Four Atlantik V1's LED light banks, designed to simulate the solar spectrum, from Orphek (Sao Paulo, Brazil) were installed 10 cm above the columns to provide irradiation. Each lighting unit had two columns situated under it (Fig. 1) that were strategically placed to provide equal amounts of irradiance upon each column. The irradiance was measured as Photosynthetic Active Radiation (PAR)