Journal of Environmental Chemical Engineering 4 (2016) 130–136

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

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

Simultaneous biological removal of nitrogen and phosphorus in a vertical bioreactor

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ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form 18 September 2015
Accepted 25 October 2015
Available online 30 October 2015

Keywords:
Simultaneous nitrification–denitrification
Biological phosphorus removal (BPR)
Biological nutrient removal (BNR)
Vertical tubular bioreactor

ABSTRACT

Nutrients pollution has become a global environmental threat. A large fraction of nutrient pollution is caused by point sources like the discharges of untreated domestic and industrial wastewater. As a result, there is a great demand to develop reliable, compact and efficient nutrient removal technologies. In the wastewater industry, most of the bioreactors have a large foot print with a plane configuration. Furthermore, the existing nutrient removal processes are based on well-known microbial species of genus *Nitrosomonas* and *Nitrobacter* involved in nitrification/denitrification and *Candidatus Accumulibater Phosphatis* responsible for biological phosphorous removal (BPR). The present work is unprecedented in two aspects: (1) The biological nitrogen and phosphorus removal from wastewater occurred in a multistage vertical, tubular bioreactor and (2) Two abundant microbial species were responsible for the simultaneous nitrification–denitrification–BPR in this vertical bioreactor. The abundant microbial populations included an unidentified bacteria of *Saprospiraceae* family and bacteria affiliated with the genus *Zoogloea*. The composition of the synthetic wastewater used in this study was: total phosphorous (TP) 32.6 ± 0.7 mg/L, total nitrogen (TN) 272 ± 7.5 in which 45 ± 1.8 mg/L was ammonia-nitrogen (NH_3-N). The bioreactor was continuously operated for over 350 days at constant flowrate, temperature and pH of 240 (L/day), 22–24 (°C) and 7–7.5. The results showed that simultaneous nitrification–denitrification–BPR was the dominant process by an, as yet not fully classified, microbial species. The effluent TP and TN concentrations were 2.7 ± 0.4 and 4.3 ± 1.2 mg/L respectively. Concentrations of NH_3-N, NO_2^- and NO_3-N in the effluent were 0.7 ± 0.1, 0.8 ± 0.5 and 0.3 ± 0.1. The simultaneous nitrification–denitrification–BPR was highly effective delivering above 90% TN and TP removal efficiency. The successful results presented in this paper have led to the construction of a 20,000 L/day demonstration plant in the City of Pickering, Ontario.

1. Introduction

Two design parameters are of paramount importance in the design of wastewater treatment plants. These are: (1) high standards of effluent quality and (2) low construction space or minimal foot print. For example, upgrade/expansion of plants in urban areas is limited by site constraints caused by demographic pressures and severe regulations. Thus, successful technologies in wastewater treatment must meet the above design criteria. Increasing chemical complexity in industrial and domestic wastewater, flow-rates variability, mixing, and emerging contaminants impose further difficulties in wastewater treatment and control. Among current environmental issues, nutrient pollution has become an overwhelming problem for many countries around the world. Excessive use of fertilizers in the agricultural sector and daily human activities are the main sources of nutrient pollution. This in turn causes extensive economic losses because of the degradation of fisheries, tourist facilities and coastal regions. This global problem can be mitigated with more stringent environmental regulations, and hence advanced bioreactors and processes.

1.1. Research objectives

In some wastewater treatment plants, nitrogen removal processes such as nitrification and denitrification are accompanied by biological phosphorus removal (BPR). However, due to hypersensitivity of the phosphorus removing organisms many plants adopt chemical treatments for phosphorus removal. Chemical treatment is both more expensive and less

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http://dx.doi.org/10.1016/j.jece.2015.10.035
2213-3437/

environmentally benign than biological treatment. Below is a list of the most common suspended growth processes which carry out both biological nitrogen and phosphorus removal [1]:

- 3 Stage pho-redox (A^2/O)
- 5 Stage bardenpho
- Modified University of Cape Town (modified UCT)
- Oxidation ditch
- Sequencing batch reactor (SBR)

The most appropriate reactor configuration for a biological nutrient removal (BNR) process depends on factors such as the target effluent quality, influent quality, process control, biological process complexity, and available foot print. Many of the existing BNR processes take place in plane, horizontal basins with large foot print. As pointed out before, construction space limitations is one of the problems facing municipal wastewater treatment facilities. The prime objective of the research presented herein was to design a pilot scale vertical bioreactor capable of achieving an effective biological nutrient removal process. The advantages of this reactor configuration were:

- Tubular geometry and vertical configuration provided construction flexibility and lower land requirements than comparable BNR bioreactors of the same flowrate. Since, tubular vertical reactors have lower foot print they can easily adapt to expansion and retrofits.
- The tubular geometry of this bioreactor provides superior mixing and mass transfer because they avoid the stagnancies which normally develop in rectangular bioreactors.
- The vertical configuration of this bioreactor provides smooth flow of water from one stage to the other without additional need for pumps.
- The configuration of the bioreactor permitted the creation of the environmental conditions leading to the formation of ecosystems that favor the growth of new microbial species as suggested by Littleton et al. [2]. The novel multistage, vertical bioreactor allows the nitrification, denitrification and BPR processes to integrate and operate simultaneously under the same environmental condition.
- As shown in our experimental results simultaneous nitrification–denitrification–BPR has lower organic carbon requirements than conventional BNR systems.

The multistage vertical bioreactor was designed, constructed and tested in the Water Technologies Laboratory at Ryerson University in Toronto.

1.2. Background

Nitrification is the oxidation of NH_4^+ to NO_3^- through a two-step process (Knapp) [3].

Step 1: ammonium oxidizing bacteria (AOBs) are responsible for the first process:

$$NH_4^+ + 3/2O_2 \rightarrow NO_2^- + 2H^+ + H_2O \quad (1.1)$$

Step 2: nitrite oxidizing bacteria (NOBs) complete the second step in nitrification:

$$NO_2^- + 1/2O_2 \rightarrow NO_3^- \quad (1.2)$$

Denitrification is very similar to the biological oxidation of organic matter except that it occurs in the absence of dissolved oxygen. Heterotrophic bacteria utilize NO_3^- for oxidation of organic compounds as shown below:

$$NO_3^- + \text{Organic Matter} \rightarrow N_2 + CO_2 + OH^- + H_2O \quad (1.3)$$

Biological phosphorus removal (BPR) process requires an anaerobic phase followed by an anoxic or aerobic phase. Under anaerobic condition, phosphorus accumulating organisms (PAOs) uptake volatile fatty acids (VFA) then produce and store intracellularly polyhydroxyalkanoates (PHAs). Under the aerobic or anoxic conditions, PAOs or denitrifying PAOs (DPAOs) break down their internal PHAs which release energy. This energy is immediately used by the PAOs to uptake dissolved phosphorus and produce and store polyphosphates. Haandel van and Lubbe van der [4] reported that PAOs can store polyphosphate up to 38% of their

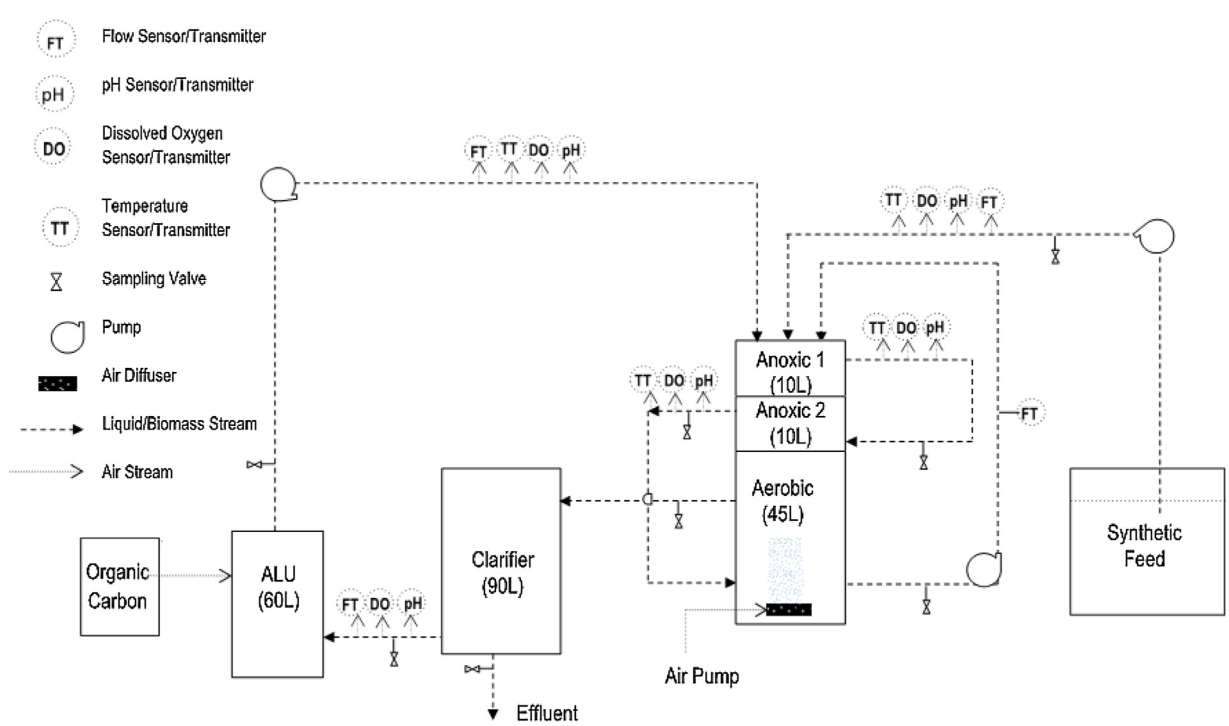

Fig. 1. Block diagram of the vertical bioreactor aligned with a clarifier and anaerobic lateral unit (ALU).