Bioresource Technology 102 (2011) 5645–5652

Contents lists available at ScienceDirect

Bioresource Technology

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

Performance evaluation and prediction for a pilot two-stage on-site constructed wetland system employing dewatered alum sludge as main substrate

A.O. Babatunde [1], Y.Q. Zhao *, R.J. Doyle, S.M. Rackard, J.L.G. Kumar, Y.S. Hu

Centre for Water Resources Research, School of Architecture, Landscape and Civil Engineering, University College Dublin, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 29 November 2010
Received in revised form 14 February 2011
Accepted 15 February 2011
Available online 19 February 2011

Keywords:
Alum sludge
Constructed wetland
Phosphorus
Water treatment residual
Multiple regression analysis

ABSTRACT

Dewatered alum sludge, a widely generated by-product of drinking water treatment plants using aluminium salts as coagulants was used as main substrate in a pilot on-site constructed wetland system treating agricultural wastewater for 11 months. Treatment performance was evaluated and spreadsheet analysis was used to establish correlations between water quality variables. Results showed that removal rates (in g/m^2 d) of 4.6–249.2 for 5 day biochemical oxygen demand (BOD_5), 35.6–502.0 for chemical oxygen demand (COD), 2.5–14.3 for total phosphorus (TP) and 2.7–14.6 for phosphate (PO_4—P) were achieved. Multiple regression analysis showed that effluent BOD_5 and COD can be predicted to a reasonable accuracy ($R^2 = 0.665$ and 0.588, respectively) by using input variables which can be easily monitored in real time as sole predictor variables. This could provide a rapid and cheap alternative to such laborious and time consuming analyses and also serve as management tools for day-to-day process control.

1. Introduction

Constructed wetland (CW) systems are becoming increasingly popular in response to increasing environmental issues and growing importance of natural and sustainable wastewater treatment systems. They are regarded as cost-effective and eco-friendly treatment systems with low maintenance and comparatively less energy consumption (Tomenko et al., 2007). They are also fast becoming the system of choice for wastewater treatment especially in rural or isolated areas where conventional systems are not as feasible because of cost effectiveness. It is well known that wastewater treatment in CW systems involve complex physical, chemical and biological processes.

Consequently, CW systems are often seen as complex "black box" systems and the processes within them are difficult to model due to the complexity of the relationships between most water quality variables (Gernaey et al., 2004; Lee and Scholz, 2006). On the other hand, the appropriate design, operation and evaluation of CW systems are crucial as well as contingent on a good understanding of the internal treatment processes and mechanisms. Regression analysis has been found to be useful for simplified description and analysis of CW systems performance as they provide a means of understanding their treatment process/mechanism (Tomenko et al., 2007; Murray-Gulde et al., 2008; Tang et al., 2009). Although, there are many more approaches with stronger capabilities that could be used to model CW systems performance such as artificial neural networks and multi-component reactive transport module (CW2D) (Langergraber, 2008; Akratos et al., 2009), the use of these complex approaches has been limited and yet to be proven.

The CW system described in the present study employs dewatered alum sludge as the main substrate in line with recent trends aimed at using natural and by-products as substrates in CW systems, e.g. limestone pellets (Tao and Wang, 2008) and filtralite (Albuquerque et al., 2009). Alum sludge is a by-product of drinking water treatment plants utilizing aluminum salts as coagulants. It is the most widely generated drinking water treatment residual and it is mostly landfilled, being perceived as a by-product of limited reuse value (Babatunde and Zhao, 2007). Therefore, the beneficial reuse of alum sludge in CW systems, hitherto considered as a waste by-product for wastewater treatment, may present an innovative approach of using waste for wastewater treatment. Extensive laboratory scale studies on the novel reuse of alum sludge in CW systems have been conducted in the authors research group (Zhao et al., 2009). Trials of several CW systems using the alum sludge as substrate are currently being conducted as pilot field-scale demonstrations to treat wastewater emanating from an animal research farm (Zhao et al., 2010). It is expected that these novel CW systems will offer a sustainable and cost-effective solution to the treatment of agricultural wastewaters, which is a wide-spread challenge particularly across the European Union. Until now, the prevalent practice on many farms is to store dirty water and spray it onto fields during the dry season and this has

* Corresponding author. Tel.: +353 1 7163215; fax: +353 1 7163297.
E-mail address: yaqian.zhao@ucd.ie (Y.Q. Zhao).
[1] Present address: Discipline of Civil Engineering, School of Computing, Science and Engineering, University of Salford, Salford, M5 4WT, Greater Manchester, U.K.

0960-8524/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biortech.2011.02.065

been found to cause degradation of surface and groundwaters (Wood et al., 2007). However, before the application of the novel CW systems on full scale, it is imperative to analyse their performance as a pilot field-scale model first. Therefore, this study presents performance analysis of a two-stage on-site CW system utilizing alum sludge as main substrate and explores the newly developed model for predicting final effluent concentrations. The key issues addressed are analysis of the CW system performance, identification of correlations among the water quality variables and the development of statistical models for predicting final effluent concentrations.

2. Methods

2.1. Design and operation of the system

The pilot field-scale CW system was constructed on an animal research farm in Newcastle, Co. Dublin, Ireland to treat wastewater (after settlement) emanating from the farm. The system consists of two stages operated with a hydraulic loading rate of 0.56 m^3/m^2 d and a hydraulic retention time of 4 h in each stage. The system is configured (from the top) with 20 mm gravel as distribution layer in the 0–10 cm depth range and this is followed 10–75 cm of dewatered alum sludge cakes as the main substrate layer and then 75–85 cm of 10 mm gravel as the support/drainage layer. The stages of the system, each with a total surface area of 1.17 m^2, were linked together using pipes connected to a submersible pump placed in each stage. The dewatered alum sludge cakes used were collected fresh from the industrial filter press of a drinking water treatment plant in Southwest Dublin, Ireland where aluminium sulphate is used as coagulant. The size/length (mean ± SD) of the alum sludge cakes used was 7.25 ± 1.48 cm. The characteristics of the alum sludge have been well investigated and reported elsewhere (Babatunde et al., 2009). Common reeds, *Phragmites australis*, were planted on top of each stage. The system was operated as a subsurface flow system using a tidal flow operation strategy, which allows the matrices of the system to be filled with wastewater, and then to be completely drained to enhance the aeration (Green et al., 1998). In this regards, the system was not designed to rely solely on *P. australis* for oxygen transfer into the system especially during the start up period. Wastewater from the farm activities was firstly collected from the holding tank on the farm and pumped into a 10 m^3 capacity tank. Appropriate dilution was then carried out to achieve desired concentration.

2.2. Data capture and analysis and model development

Water quality data were obtained by monitoring pollutant concentration in the influent and effluent samples of the system over a period of 11 months. Samples were analysed for COD (both total and soluble COD, (sCOD)), BOD_5 (Lovibond OxiDirect apparatus, Lennox, UK), TP (Ascorbic method, Clesceri et al., 1998), PO_4—P, total nitrogen (TN) (Persulfate method, Clesceri et al., 1998), ammonium nitrogen (NH_4—N), nitrate nitrogen (NO_3—N), nitrate nitrogen (NO_2—N), suspended solids (SS) and Turbidity (Hach turbidity meter 2100 N IS). Except where indicated, all the water quality parameters were analysed using a Hach DR/2400 spectrophotometer according to its standard operating procedures. From the water quality data, removal efficiencies and pollutant loading and removal rates were determined. Pollutant loading rate (g/m^2 d) was calculated by multiplying the hydraulic loading rate (m^3/m^2 d) by the influent pollutant concentration (mg/l) while pollutant removal rate (g/m^2 d) was defined as hydraulic loading rate multiplied by the difference in concentration between the influent and effluent. However, more emphasis was paid to the loading and removal rates. Metrological data was obtained from Irish Metrological service (www.met.i.e.) while real time measurements of oxidation–reduction potential (ORP), temperature and pH were obtained from an YSI multi-parameter probe inserted in the influent tank and in each stage of the CWs.

Correlations were sought between the different water quality variables and regression analysis and analysis of variance (ANOVA) were performed to determine if significant relationships existed between influent and effluent concentrations. By investigating correlations between the different variables, a deeper understanding of the relationship between the variables was obtained and this was used to develop models for the prediction of final effluent concentrations using multiple regression analyses (MRA). The models were tested for goodness of fit by using graphical analysis, the Student's *t* test and the F test. The *p* values were then considered for each model in order to determine which parameters were significant in forecasting the dependant variables. The MRA was particularly conducted to test the relationship between each of BOD_5, COD, sCOD and TP and other variables. The reason for these four variables being chosen as dependant variables are because firstly, BOD_5 analysis is crucial as it is widely applied to give a general indication of water quality status. Thus, it would be useful to be able to predict BOD_5 using other parameters that can be obtained in real time. Secondly, in the case of COD and sCOD, although they are relatively quick to analyse, they are very expensive and this can lead to substantial costs over a long period of testing. Finally TP was chosen because phosphorus (P) is a key factor in causing eutrophication and the analysis can also be time consuming.

After the models have been constructed, they were graphically analysed for goodness of fit by plotting the actual against the predicted results. The adjusted R^2 values were taken into account and the result of the F test was then observed for each model. These values were used in conjunction with the 95% confidence interval set during the regression. The significant *F* values had to be below 0.05 for there to be any significant statistical relationship present. The *p* values for each independent variable were also analysed to see how significant they were in predicting the dependant variable. This was done by setting thresholds of 0.05, 0.01 and 0.001. If $p < 0.05$, a parameter was deemed to be significant as the probability that the parameter influences the dependant variable was 95%. This variable then received an asterisk * according to the "Three Star" scale. If $p < 0.01$ it was then said to be highly significant and was denoted by two asterisks ** and if $p < 0.001$ it received three asterisks *** and was described as extremely significant.

3. Results and discussion

3.1. Treatment performance

The characteristics of the source wastewater varied greatly over time in concert with seasonal changes and farming operations. With regards to the characteristics of the influent wastewater to the CW system, the range of pollutant concentration were BOD_5 (31–968 mg/L), COD (124–1634 mg/L), PO_4—P (2.8–60 mg-P/L), TN (16–273 mg-N/L) and SS (25–633 mg/L). Fig. 1 shows the trend of pH, temperature and ORP in the influent and effluent wastewater. pH between the influent and effluent varied very little with a standard deviation of ca. 0.1 for both the influent and effluent pH values. However, the influent pH is mostly higher than that for the effluent. It is also noted that during wastewater passage through the system, pH was consistently reduced by between 0.2 and 0.7 units giving relatively stable mean effluent pH values between 6.6–6.9. ORP fluctuated greatly with negative values being more prevalent. However, there was a difference of approximately 200 mV between the influent and effluent OPR values, with the