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Research article

A hybrid constructed wetland for organic-material and nutrient removal from sewage: Process performance and multi-kinetic models

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A R T I C L E I N F O

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A B S T R A C T

A pilot-scale hybrid constructed wetland with vertical flow and horizontal flow in series was constructed and used to investigate organic material and nutrient removal rate constants for wastewater treatment and establish a practical predictive model for use. For this purpose, the performance of multiple parameters was statistically evaluated during the process and predictive models were suggested. The measurement of the kinetic rate constant was based on the use of the first-order derivation and Monod kinetic derivation (Monod) paired with a plug flow reactor (PFR) and a continuously stirred tank reactor (CSTR). Both the Lindeman, Merenda, and Gold (LMG) analysis and Bayesian model averaging (BMA) method were employed for identifying the relative importance of variables and their optimal multiple regression (MR). The results showed that the first-order–PFR (M_2) model did not fit the data ($P > 0.05$, and $R^2 < 0.5$), whereas the first-order–CSTR (M_1) model for the chemical oxygen demand (COD_{Cr}) and Monod–CSTR (M_3) model for the COD_{Cr} and ammonium nitrogen (NH_4-N) showed a high correlation with the experimental data ($R^2 > 0.5$). The pollutant removal rates in the case of M_1 were 0.19 m/d (COD_{Cr}) and those for M_3 were 25.2 g/m^2·d for COD_{Cr} and 2.63 g/m^2·d for NH_4-N. By applying a multi-variable linear regression method, the optimal empirical models were established for predicting the final effluent concentration of five days' biochemical oxygen demand (BOD_5) and NH_4-N. In general, the hydraulic loading rate was considered an important variable having a high value of relative importance, which appeared in all the optimal predictive models.

1. Introduction

The processes of eliminating organic matter and nutrients from polluted wastewaters are quite complicated. They include chemical, physical, and biological factors that demand triply synergistic processes for maximum efficiency. These factors of the constructed wetland (CW) affect the removal efficiency and are affected by shifting local and regional conditions (Gholizadeh et al., 2015; Vo et al., 2018; Vo et al., 2017; Wu et al., 2018a; b). As a result, an appropriate CW design that compares favorably to those of other studies is more difficult to achieve. The misunderstanding of the contaminant dynamics of this system can lead to design failures that usually cause a degraded efficiency of the targeted pollutants' removal, clogging, and short circulation in the design's fluid dynamics (Davoodi et al., 2016; Samsó et al., 2016; Wu et al., 2018a; b). Therefore, the application of the knowledge of pollutant removal kinetics to this data could be expected to ensure positive results if and when these conclusions are effectively applied to the engineering challenges of CW design.

There are several models and methods for predicting pollution removal, and the first-order model (Chan et al., 2008; Trang et al., 2010) and linear regression (Babatunde et al., 2011b; Gholizadeh et al., 2015; Reed and D., 1995; Sheridan et al., 2013) are popular. Some approaches

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recommended recently are the use of artificial neural networks, multi-component reactive transport module, principal component analysis, clustering tree diagrams, classification and regression trees, and redundancy analysis (Akratos et al., 2008; Babatunde et al., 2011b; Dong et al., 2012; Hijosa-Valsero et al., 2011; Huang et al., 2014). However, these may prove to be overly complicated owing to their numerous empirical parameters.

The multiple regression (MR) method has been considered useful for simplified description, analysis of CW performance, and developing predictive models (Murray-Gulde et al., 2008; Tomenko et al., 2007). The majority of the previous studies that were focused on the evaluation of the efficacy of MR (Babatunde et al., 2011b; Chan et al., 2008; Hijosa-Valsero et al., 2011) used the response variables of the effluent concentrations while avoiding the application of the removal rate.

To accurately compute MR, the relative importance and optimal models of the given predictors are required, in which relative importance is the proportionate contribution each predictor makes to R^2 (Johnson, 2000). For selecting the optimal models, the previous research was based primarily on R^2 (Babatunde et al., 2011b; Hijosa-Valsero et al., 2011). However, their methods did not involve the evaluation of the interaction analysis and multi-collinearity, which can influence the accuracy of these results. When a model has a large number of variables, it results in a higher R^2 value, which might cause over-fitting. Bayesian model averaging (BMA) is considered to be a good tool for overcoming these limits. By performing averaging over several different competing models, BMA integrates model uncertainty into the prediction and estimation of the parameters (Fang et al., 2016; Hoeting et al., 1999).

In this work, we used the new technique of BMA to overcome multi-collinearity and obtain the precise R^2 value. The obtained results clarified the relative importance of the influent factors of a hybrid constructed wetland (HCW), and the optimal models that have not been adequately addressed in previous studies were also selected. Furthermore, by applying more response variables such as hydraulic loading rates (HLRs), we developed more effective and accurate predictive models that contributed significantly in the design, management, and maintenance of the HCW system.

The main purpose of this study is to clarify the performance of the HCW and explore the predictive models using kinetics and MR. This study is mainly focused on the comparison of the kinetics, weighting correlation, and relative importance and the development of optimal predictive models for HCW performance using the BMA method.

2. Materials and methods

2.1. Description of hybrid constructed wetland and data collection

To clarify the adaptation and removal performance of HCW, a pilot system was installed at the sewage treatment plant of Dong Ha city, Vietnam, and was then tested in over an operating period of 190 days. The sewer at this location collects the municipal wastewater and runoff water from Dong Ha city. The water level of this sewer fluctuates from 0.5 m in the dry season to 0.9 m in the wet season. The average water flow in the sewer is 181,400 m^3/d with a mean velocity of 1.5 m/s. The pilot HCW system included a vertical flow (VF) (planted with *Canna indica* at a density of 20–25 plants/m^2) and a horizontal flow (HF) (planted with *Colocasia esculenta* at a density of 15 plants/m^2) in series (Fig. 1). Such an arrangement was used to promote the nitrification in the VF and denitrification in the HF in order to reduce the nutrient content in the effluent. Wastewater was pumped from the sewage system (twice a day for an interval of 30 min), stored in the storage tank, and was allowed to flow intermittently to the VF at various HLRs of 0.44 m^3/d (first stage, HLR_1), 0.88 m^3/d (second stage, HLR_2), and 0.66 m^3/d (final stage, HLR_3). The effluent of the VF was drained continuously by gravity into the HF tank. The characteristics of the VF and HF are presented in Table 1. Each tank was built with three filter layers of various particle sizes. The filter layers comprised various gravel grades with the total height of the VF being 0.7 m and that of the HF being 0.5 m. This corresponded to 2.65, 1.32, and 1.76 days of hydraulic retention times for HLR_1, HLR_2, and HLR_3, respectively. More details of the characteristics of the sewage, HCW, and operating procedures are described in a previous report by Nguyen et al. (2017).

Wastewater samples were collected from the influent of the VF (SP1) and effluent of the VF (SP2) and HF (SP3) as shown in Fig. 1 (Nguyen et al., 2017). The sampling rate was once a week for more than 6 months of operation. Twenty-three water samples of HCW were obtained and tested in this experiment. The pH was determined using a multi-parameter water quality meter (HQ40d, Hach, USA). The COD_{Cr}, BOD_5, total suspended solids (TSS), NH_4-N, nitrate nitrogen (NO_3-N), phosphate (PO_4-P), TN, and total coliforms (TCol) were analyzed according to the Standard Methods 5220D, 5210B, 2540D, 4500-NH_3 F, 4500-NO_3 B, 4500-P D, 4500-P J, and 9221 B, respectively (APHA/WEF/AWWA, 2005). The spectrophotometer (Cary 60, Agilent Technologies Inc., USA) was used to measure the COD_{Cr}, NH_4-N, NO_3-N, and PO_4-P.

Owing to the intermittent flow, the aerobic and anoxic conditions were dominant in the HCW. Oxygen is a terminal electron acceptor that is reduced while electron donors (mainly organic matter and ammonia) are oxidized, and CO_2 and H_2O are formed as end products (1). In the bottom layers of the HCW, other reactions (2, 3, and 4) might occur in response to the decrease in oxygen and the redox potential (Kadlec and Wallace, 2009).

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \quad (1)$$

$$5CH_2O + 4NO_3^- \rightarrow 2N_2 + 4HCO_3^- + CO_2 + 3H_2O \quad (2)$$

$$CH_2O + 3CO_2 + H_2O + 2MnO_2 \rightarrow 2Mn^{2+} + 4HCO_3^- \quad (3)$$

$$CH_2O + 4SO_4^{2-} \rightarrow H_2S + 2HCO_3^- \quad (4)$$

2.2. Kinetic models

The first-order and Monod kinetic models were used to describe and evaluate the pollution degradation in this study. The hydrodynamic pattern in the HCW was considered to be the same as that of the plug flow reactor (PFR) and continuously stirred tank reactor (CSTR). Therefore, the new models have been developed by integrating the first-order and Monod models with PFR and CSTR.

2.2.1. First-order k–C* model with PFR (M_1)

By assuming an exponential removal rate to reflect a non-zero background wetland concentration (C^*) (Ali et al., 2018; Kadlec and Knight, 1996), the removal model based on the first-order and C^* models is expressed as follows (Eq. (5)):

$$k_1 = HLR \times Ln\frac{C_i - C^*}{C_o - C^*} \quad (5)$$

2.2.2. First-order model with CSTR (M_2)

To model the correlation between the influents and effluents of CW for nutrients and organic matter, the integrated model that combined first-order kinetics with CSTR (Saeed and Sun, 2011) was established. The combined model is expressed as shown in Eq. (6):

$$k_2 = \frac{HLR \times (C_i - C_o)}{C_o} \quad (6)$$

2.2.3. Monod kinetics with CSTR (M_3)

This model combined the Monod kinetics, which comprises half the saturation constant of the limiting substrate and effluent concentration, with the CSTR flow pattern (Saeed and Sun, 2011). It is expressed as shown in Eq. (7):