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Assessment of removal rate coefficient in vertical flow constructed wetland employing machine learning for low organic loaded systems

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Highlights

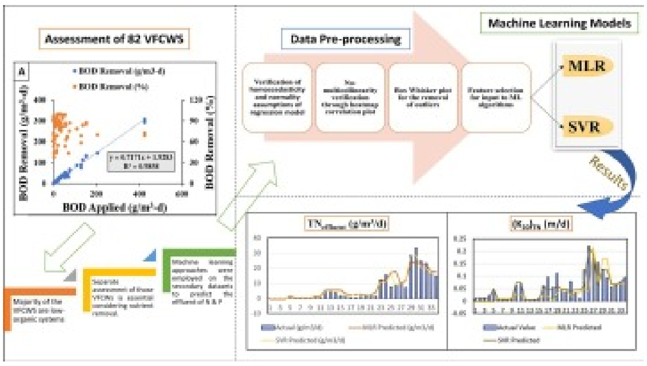
- Areal removal rate coefficients (k_{20}) of LOLVFCWs showed huge deviations up to 130%
- Dataset classification could not reduce the variations satisfactorily.
- Novel machine learning based approach adopted to suggest optimum area in LOLVFCWs.

- SVR (R^2=0.87–0.90) could better predict effluent parameters (EPs) than MLR.
- Predicted EPs used to derive case specific k_{20} values for calculating optimum area.

Abstract

Secondary datasets of 42 low organic loading Vertical flow constructed wetlands (LOLVFCWs) were assessed to optimize their area requirements for N and P (nutrients) removal. Significant variations in removal rate coefficients (k_{20}) (0.002–0.464 md^{-1}) indicated scope for optimization. Data classification based on nitrogen loading rate, temperature and depth could reduce the relative standard deviations of the k_{20} values only in some cases. As an alternative method of deriving k_{20} values, the effluent concentrations of the targeted pollutants were predicted using two machine learning approaches, MLR and SVR. The latter was found to perform better (R^2=0.87–0.9; RMSE=0.08–3.64) as validated using primary data of a lab-scale VFCW. The generated model equations for predicting effluent parameters and computing corresponding k_{20} values can assist in a customized design for nutrient removal employing minimal surface area for such systems for attaining the desired standards.

Graphical abstract



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Introduction

In recent years, constructed wetlands (CWs) have been regarded as one of the major sustainable eco-technologies for wastewater treatment due to their effective remediation of multiple pollutants and low operation and maintenance costs (Vymazal, 2007). As CWs simulate the processes of the natural wetland system, the biofilms formed in these systems may exhibit significant heterogeneity both regarding the microorganisms present and their physicochemical microenvironments owing to the diverse interactions between different components of the wetland system (Wang et al., 2022). This may lead to considerably fluctuating remediation efficiencies as evident in the significant variations in the removal rate coefficient (k) values that range from 0.0003 to 0.822 md^{-1} (Singh et al., 2022a, Soti et al., 2022).

The k values along with the influent characteristics and effluent standards are routinely used for the calculation of one of the critical CW design parameters i.e. area of the CW. Assuming ideal plug flow characteristics and first-order reactions, the area required for the wetland can be calculated using the Kikuth equation (Kadlec and Wallace, 2009) $A = \frac{Q}{k_A} * \ln \frac{C_{in}}{C_{out}}$

Where k_A denotes the areal removal rate coefficient in md^{-1}, Q is the flow in m^3d^{-1}, A is the area of the wetland and C_{in} and C_{out} are the concentration at the inlet and outlet in mgL^{-1}. The outlet concentration of the pollutant may be substituted as per the prevailing standards in the region. During the calculations, the k_A values are derived from the literature (Kadlec and Wallace, 2009). Although these literature derived values are based on input output data of experimental wetlands (62 VFCW as given in Kadlec and Wallace, 2009), large deviations are observed from the mean values. For example, 0.05 and 0.95 percentile of VFCW k values have been reported as 19 and 1694 myr^{-1} or 0.052 and 4.64 md^{-1} (Kadlec and Wallace, 2009). Our recent work has also shown that the k values derived from existing VFCW can be highly variable (Soti et al., 2022) and therefore the corresponding mean values may not be representative of the VFCWs operating under different conditions. This uncertainty culminates in the overdesign of the systems, which is undesirable as the large land requirement is a common constraint, especially in dense cities, that limits the usage of CWs in urban settings compared to other conventional treatment technologies (Zapater-Pereyra et al., 2015).

Further, in our previous study on 82 VFCW, it was found that the variability in the areal removal rate coefficients could be decreased by eliminating the low organic loading rate (OLR) data from the analysis as these low OLR systems may be considered as sub-optimally loaded systems primarily developed for polishing of wastewater i.e., removal of N and P from wastewater deficient in organics. Clearly, the behaviour of these low OLR systems is different from the high OLR counterparts. Moreover, the areal removal rate coefficients for nitrogen and phosphorous are more important to be determined in this case than the removal rate coefficient for organics as N and P removal is the primary target of the treatment of low OLR wastewater.

In the present work, the low OLR dataset of VFCWs was analyzed in detail in order to derive case-specific k values for nutrient removal. The dataset was first classified based on the selected parameters, to see if the relative standard deviations of the k_{20} value could be reduced. As this approach was not found to be satisfactory in lowering the relative standard deviations, it was concluded that it would be more fruitful to generate reliable models for predicting effluent parameters in order to derive the case specific k values that can be used for the design of low OLR VFCWs. The effluent concentrations of the targeted pollutants and the accompanying k_{20} values were calculated by employing two machine learning approaches, multiple linear regression (MLR) and support vector regression (SVR). The generated models were validated using primary data of lab-scale VFCWs. Following validation, the developed protocol was successfully implemented to optimize the area of six VFCWs which were found to be not "optimally utilized" for nutrient removal. To our knowledge, the approach adopted here has been utilized for the first time for areaoptimization in low organic loading VFCWs.

Section snippets

Material and methods

The main objective of this work was to assess secondary data taken from the existing literature in order to make some insightful conclusions and to evaluate the design of existing CWs critically for nitrogen and phosphorous removal. The secondary data was methodically collated in graphical form to derive the most relevant parameters that can be used to obtain the customized removal rate coefficient (k value) of low organic (wastewater polishing) systems by classifying the dataset based on these …

Results and discussion

Previous studies have indicated that the removal rate coefficient (k) is the major factor that affects the sizing calculation of the constructed wetland significantly (Soti et al., 2022). In the study by Soti et al., 2022, the customized k_{20} values were obtained for the removal of different pollutants under different conditions by classifying the VFCWs on the basis of temperature, organic loading and depth. These customized k_{20} values were used to calculate the minimum area required for the …

Conclusion

- The behaviour of low organic loading CWs, which are primarily designed for nutrient removal, is markedly different from that of high organic loading systems which are primarily designed for organics removal. …
- Classification of low OLR dataset on the basis of nitrogen loading, temperature and depth could only reduce the relative standard deviation in k_{20} values up to some extent, and in some cases. …
- Alternative approach based on machine learning algorithms MLR and SVR can be successfully applied to …

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

Acknowledgments

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> …It provides interpretable insights into the relationships between variables and can be applied to make predictions on new data. The general formula for MLR can be expressed as equation (2) (Cao, 2023; Soti et al., 2023). Y = β0+β1X1+β2X2+ … +βnXn+εWhere, Y is the dependent variable, X1, X2, …,Xn are the independent variables, β0 is the intercept term, β1, β2, …, βn are the coefficients (slopes) representing the impact of each independent variable on the dependent variable.…

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> …In this study, the P removal efficiency of each treatment was similar. The substrate in MFC-CWs plays a pivotal role in P removal, particularly through mechanisms such as adsorption or precipitation reactions with P, facilitated by the presence of iron ions, aluminum ions, and calcium ions in the substrate (Wang et al., 2020; Soti et al., 2023). In our study, the uniform application of the same type and size of substrate across all MFC-CWs provides a plausible explanation for the consistency in P removal efficiency.…

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