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ORIGINAL PAPER

Environmental conditions and the performance of free water surface flow constructed wetland: a multivariate statistical approach

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Abstract During the past three decades, constructed wetlands have become an integral part of the suite of technologies for removing domestic and industrial wastewater contaminants. The use of constructed wetlands has disproportionately focused on domestic and agricultural wastewaters and storm water runoff and less on oil and gas-related produced water. In this context, the cumulative effect of environmental factors on the treatment/removal efficiency of contaminants in produced water is underserved by research. Therefore, this study assessed the effect of environmental factors (temperature, dissolved oxygen, oxidation–reduction potential, and pH) on contaminant removal efficiency in free water surface flow constructed wetland (FWSFCW) using ordinary least squares regression and experimental data from a waste treatment facility in Ghana. The results showed that environmental factors did not systematically vary across the experimental group and control set-up. Generally, the environmental factors explained relatively far less of the variance in contaminant removal efficiency compared with the plant species (*Typha latifolia, Ruellia simplex* and *Alternanthera philoxeroides*). Environmental factors cumulatively explained only 1.3%, 16.4%, 22.6%, and 5.6% of the variance in removal efficiency of BOD, COD, oil and grease, and total coliform bacteria, respectively. Temperature was the most important environmental predictor of the removal of BOD and phosphorus whereas DO was most important for removing nitrates and total coliform bacteria. ORP and pH were the most important predictors of COD, and oil and grease, respectively. These findings underscore the complex relationships among environmental factors and contaminant removal efficiency and the need for contaminant management practices and remedial techniques that address these complexities.

Keywords Regression · Removal efficiency · Produced water · Bacteria · Phytoremediation

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Introduction

Wetlands have been used for water purification in different parts of the world for centuries, although in many cases the reasoning behind the usage was more of disposal than treatment (Haberl et al. 2003; Verhoeven and Meuleman 1999). There are more than 650 full-scale constructed wetland systems in place throughout the world. However, they are consistently treated as a black box because specific mechanisms and underlying fundamental variables that affect treatment functionality have been given little attention. This has affected confidence and support for the technology because it's sometimes difficult for one to make apriori predictions in terms of the effectiveness of a proposed wetland for a given flow and input water chemistry (Weber and Legge 2008). Under appropriate conditions, the components (vegetation, soil and hydrology with associated assemblage of microorganisms) can effectively function to provide water quality improvement (Qasaimeh et al. 2015; Wu et al. 2015). The system can also offer flood storage and desynchronization of storm rainfall and surface runoff, cycling of nutrients and other materials, habitat for fish and wildlife, passive recreation and many more (Davis 1995).

According to Almuktar et al. (2018), wetland behaviour and efficiency concerning wastewater treatment is mainly linked to macrophyte composition, substrate, hydrology, surface loading rate, influent feeding mode, microorganism availability, and temperature. Of the lot, hydrology of a constructed wetland is perhaps the most important factor in its effectiveness (Davis 1995). However, the design of constructed wetland treatment systems is still in a state of flux and there remain a number of uncertainties that will not be answered until the results of longer and more numerous operational studies become available. According to Davis (1995), hydrologic factors in wetland design pertain to the volume of water, its reliability and extremes, and its movement through the site. Hydrologic considerations include climate and weather, hydroperiod, hydraulic residence time, hydraulic loading rate, groundwater exchanges (infiltration and exfiltration), losses to the atmosphere (evapotranspiration), and overall water balance (Almuktar et al. 2018; Davis 1995).

Internal environmental conditions of constructed wetlands such as temperature, hydrogen ion concentration (pH), dissolved oxygen (DO) and redox conditions (ORP) influence and modify a variety of key pollutant removal processes such as sedimentation, filtration, precipitation, volatilization, absorption, plant uptake and microbial processes in treatment wetlands (Almuktar et al. 2018; Kadlec and Wallace 2008; Scholz and Lee 2005). These factors can equally regulate water quality parameters of wetland effluents discharged to surface water (El-Refaie 2010; Gorgoglione and Torretta 2018; Scholz and Lee 2005; Stein and Hook 2005; Wu et al. 2015).

Redox potential which is determined by the amount of dissolved oxygen (DO) in the wetland is affected by pH and temperature range at which reactions occur (Scholz and Lee 2005). These factors affect chemical and microbial processes and have a large effect on the biological availability of major and trace nutrients (Wießner et al. 2005). Decomposition of organic matter occurs in the presence of any electron acceptor, but oxygen is considered the most preferred electron acceptor for aerobic microbial respiration (Scholz and Lee 2005), however once oxygen is consumed, the alternative electron acceptor for anaerobic microbial respiration is nitrate followed in sequence by manganese oxide, iron oxide, sulphate, and finally carbon dioxide (Szögi, et al. 2004). Physical and biological processes responsible for biochemical oxygen demand (BOD) removal, nitrification, and de-nitrification depend on temperature (Fu et al. 2017; Kadlec and Wallace 2009). Kuschk et al. (1999) indicate that the aerobic and anaerobic microbial processes allow different oxidation–reduction conditions to exist in the wetland rhizosphere at the same time. In the extant literature, knowledge on how two or more of these environmental factors interact to impact removal efficiency is quite limited. Hitherto, studies have focused almost exclusively on the independent effects of environmental factors (pH, temperature, dissolved oxygen, redox conditions) on contaminant removal efficiency of constructed wetlands. This study, therefore, sought to ascertain the most important predictor of the treatment efficiency of removal of organics (BOD, COD, and oil and grease), nutrients (nitrate and total phosphorus) and coliform bacteria in oilfields produced water in a free water surface flow treatment wetland. The capacity to understand and predict the relative influence of temperature, pH, DO and redox potential on oilfields wastewater contaminant removal in free water surface flow treatment wetland is an essential step in identifying the limits of operation, optimizing the design and improving the efficiency of removal.

Materials and methods

About 5 m × 5 m plot of land was cleared of preexisting vegetation and excavated to a depth of about 0.60 m to create basins to serve as the wetland cells (Vymazal 2007). Four 5 m × 1 m compartmentalized free water surface treatment wetland cells were created to offer tertiary treatment for oil fields wastewater treated with conventional oily wastewater treatment plant (API oil/water separator). The excavated cells were lined with water proof membrane, filled with the excavated soils to about 0.40 m to serve as media and provide support for the roots of the wetland plants. The wetland cells were gently sloped (1°) so that water could move through and exit the wetland via natural streams/gravity (Weber and Legge 2008). The four wetland cells were planted with *Typha latifolia, Ruellia simplex*, *Alternanthera philoxeroides* and unplanted respectively. The unplanted cell was to serve as a control. ***Typha latifolia*** (commonly known as cattail or bulrush) is an emergent, perennial herbaceous plant capable of growing prolifically from thick underground rhizomes to form a dense rhizome mat, with detached portions of rhizomes floating and establishing new colonies (Wu et al. 2015). ***Ruellia simplex*** (commonly called Mexican petunia or Mexican bluebell) is a perennial ornamental emergent herb that has often escaped from cultivation and become naturalized in many natural habitats including waterways, riparian vegetation, dams, ponds, wetlands and drainage ditches (Ezcurra and Daniel 2007). It has one to many stems, glabrous (hairlike), often woody at the base and rhizomatous. It has long and deep fibrous root which is able to penetrate about 1 m deep. ***Alternanthera philoxeroides*** (commonly called alligator weeds or joy weeds) has its roots in a solid substrate and spread in a tangled mat over the water surface. They have hollow stems and can grow to about 1 m tall (Hutchinson and Langeland 2008). The leaves are thick, non-succulent, and oppositely elliptically arranged. Alternanthera *spp* are deemed to have superior contaminants removal efficiency because they have extensive filtration equipment (Srivastava et al. 2017).

Eighty plants were diagonally planted per wetland cell to ensure more than fifty percent coverage (Guo et al. 2017). The newly constructed wetland was maintained with daily watering in the morning and evening to maintain the water level and occasional pruning for a period of four months to ensure proper acclimatization (Kadlac and Wallace 2009; Weber and Legge 2008).

Experimental treatment

Figure 1 shows the schematic diagram of the four free water surface flow constructed wetlands planted with the three native plants. Effluent treated from oily wastewater treatment plant was received in intermediate bulk containers (IBC) tanks. The IBC tanks were connected to the wetland cells through pipes. Hydraulic load of 2000L (2.0 m^3) was introduced slowly into each treatment wetland through the connected pipes at a flow rate of 0.0001m^3/s. Treatment was repeated weekly for a period of five months. Influent was sampled at the wetland entry point to determine the organic, nutrients and coliform characteristics. This is because the removal efficiency of organics, nutrients and coliform bacteria is greatly influenced by internal environmental conditions (Scholz and Lee 2005; Szögi et al. 2004). In situ measurement of environmental conditions (pH, temperature, DO and redox potential in the four wetland cells were taken in triplicate weekly for a period of four months. Gearheart et al. (1999) indicate that knowing the wastewater characteristic is very important in analyzing the performance of the treatment system as the wastewater goes through the various treatment processes. The wastewater was gently released on a pack of river gravels at the entry point of the wetland cells, using the batch feeding mode. This was selected because produced water characteristics are predominantly carbon compounds and ability to alternate the water regime favors the removal of organics and nutrients in free water surface flow constructed wetland (Verhoeven and Meuleman 1999; Mitsch and Gosselink 2009; Zhang et al. 2012). The pulsation of the water regime over time is able to promote wetland biological productivity (Zhang et al. 2012). Effluent from the wetland was sampled from the outlet at the 72 h from time the influent was dispensed into the wetland cells for determination of BOD_5, COD, Oil and grease,

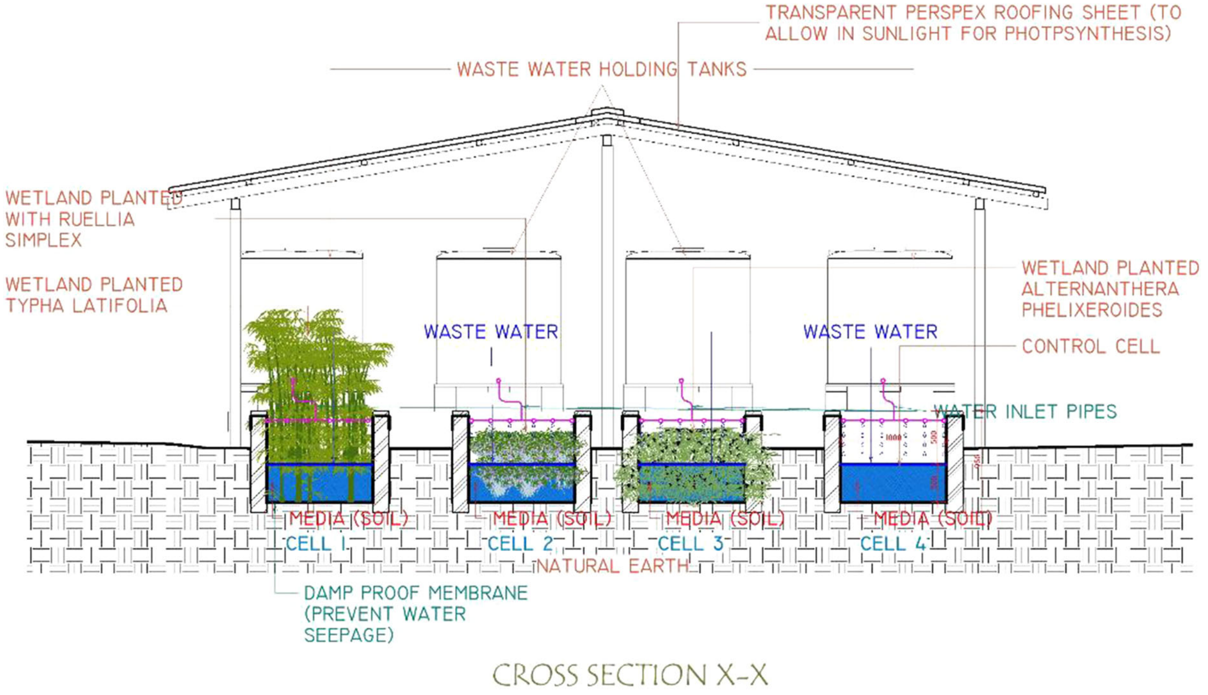


Fig. 1 Schematic diagram of free water surface flow treatment wetland

nitrate, total phosphorus and total coliform after a hydraulic retention time of three days (Merino-Solís et al. 2015). BOD_5 measurement was done using respirometric method based on APHA method 10099, COD measurement by reactor digestion method based on **APHA** 8000. Hexane extractable gravimetric method based on APHA 5520B was used to determine the oil and grease content. Total phosphorus, nitrate and total coliform bacteria measurement were done by acid persulfate digestion method based on APHA 8190, cadmium reduction method based on APHA 8039 and total coliform by plate count method based on (ISO-4833–2, 2013) respectively. Removal efficiency was calculated using this formula: Removal efficiency (RE) % = [(influent concentration − effluent concentration) / influent concentration] × 100.

Statistical modelling and parameter estimates

Using STATA 13SE software, Ordinary Least Squares (OLS) often referred to as linear regression technique was employed for the data analysis. Analyses were preceded by diagnostic tests to establish whether variables met the assumptions of the regression model. Bivariate analysis was initially performed to examine zero-order relationships between the dependent variables (removal efficiency of each contaminant) and theoretically relevant independent variables (temperature, dissolved oxygen, pH and oxidation reduction potential). Further, multivariate models were estimated to explore the net effects of the predictor variables using the stepwise selection approach. For analytical purposes, the unstandardized regression coefficients were estimated. Positive coefficients for any of the predictors indicate higher removal efficiency scores, while negative coefficients show lower removal efficiency scores. Given that the units for environmental factors are not the same; the magnitudes of the unstandardised coefficients cannot be compared. Therefore, standardised coefficients were also estimated to enable comparison of the parameter estimates for the environmental factors. The standardized regression (beta) coefficients of different regression can be compared, because the beta coefficients are expressed in units of standard deviations (SDs). The interpretation of the beta coefficient is as follows: if the standardized IV changes (e.g., temperature) by one standard deviation, the standardized DV (e.g., removal efficiency of total coliform bacteria), on average, changes by beta standard deviation units. Statistical significance was set to $\alpha < 0.05$.

Results and discussion

The results include descriptive statistics of environmental factors, correlogram of environmental factors and contaminant removal efficiency and linear regression models of the four environmental factors and the removal efficiencies of the six parameters examined**.**

Influent and effluent concentrations and plant-specific removal efficiencies

Table S1 shows the influent and effluent concentrations as well as the plant-specific removal efficiencies. Generally, the results show heterogeneity in removal efficiency across plant types with unplanted wetlands recording the least removal efficiency in all parameters; an indication that macrophyte plays an important role in wastewater treatment in treatment wetlands (Brix 2003). Planted wetlands are found to facilitate removal of dissolved solids from wastewater by uptake mechanism (Lariviere et al. 2003). It is observed from Table S1 that the highest removal efficiencies for BOD for the three plant species are *Typha latifolia* (88%), *Ruellia simplex* (79%) and *Alternanthera* (88%). The observed high BOD removal in *Alternanthera* and *Typha spp* could be due to the fact that the former has extensive root system that support excellent sedimentation and bacteria growth, whiles the latter has adequate supporting tissues which are very useful for removal of dissolved organic carbon from wastewater (Abbasi and Abbasi 2010; Vymazy 2007). In a study conducted by Abbasi and Abbasi (2010) 89% COD removal was recorded when a laboratory scale *Alternanthera spp* planted wetland was used to treat grey water. The highest removal efficiencies for COD for the plant species are as follows: *Typha latifolia* (49%), *Ruellia simplex* (57%) and *Alternanthera* (70%). The highest removal efficiencies for oil and grease for the plant species are as follows: *Typha latifolia* (90%), *Ruellia simplex* (91%) and *Alternanthera* (64%). The highest removal efficiencies for nitrates for the plant species are as follows: *Typha latifolia* (39%), *Ruellia simplex* (44%) and *Alternanthera* (42%). The removal efficiency for total coliform was comparable in all the wetland cells, but slightly higher in the wetland planted with *Ruellia simplex*. The observed total coliform removal efficiency is similar to the findings of Garcia et al. (2008), where planted wetlands recorded higher removal efficiencies than unplanted wetland (control). The highest removal efficiencies for total phosphorus for the plant species are as follows: *Typha latifolia* (61%), *Ruellia simplex* (53%) and *Alternanthera* (83%). The highest removal efficiencies for total coliform for the plant species are as follows: *Typha latifolia* (89%), *Ruellia simplex* (73%) and *Alternanthera* (80%).

Descriptive statistics of environmental factors

Figure 2 shows the distribution of the four environmental factors (pH, DO, ORP and temperature) across the four wetland cells (*Typha latifolia*, *Ruellia simplex* and *Alternanthera philoxeroides* and control). The box plots show that there were no statistically significant differences among the environmental factors across the wetland cells. This means environmental conditions did not change significantly across the cells; they were fairly constant. The median pH value in Alternanthera spp and Typha spp planted wetland cells is about 6.20 and 5.40 respectively (see Fig. 2). This suggests that Typha spp planted wetland is more acidic which could be due to the accumulation of litters in the wetland cell. Gearheart et al. (1999) point out that the production of organic substances through the growth, death and decomposition cycle is a source of natural acidity in wetland. Plants with higher rates of these processes are likely to record greater acidity. Dissolved oxygen (DO) was generally low with few high values (outliers) in all the wetland cells, however it was highest in the control, followed by *A. philoxeroides* planted wetland and least in the Typha planted wetland. This observation may be supported by the fact that there is always competition over the use of dissolved oxygen in wetland to meet sediment/ litter oxygen demand, carbonaceous oxygen demand, nitrogenous oxygen demand and respirational oxygen needs (Gearheart et al. 1999). As result, oxygen is quickly depleted in wetland system. The median temperature (26.5 °C) in the control was equal to the lower quartile (26.5 °C). This means about 25% of the temperature recorded in the data set lie below 26.5 °C and about 75% lie above 26.5 °C. Oxidation-reduction potential was more negative (reduced) in the Typha spp planted wetland and more positive (oxidized) in the Alternanthera planted wetland (see

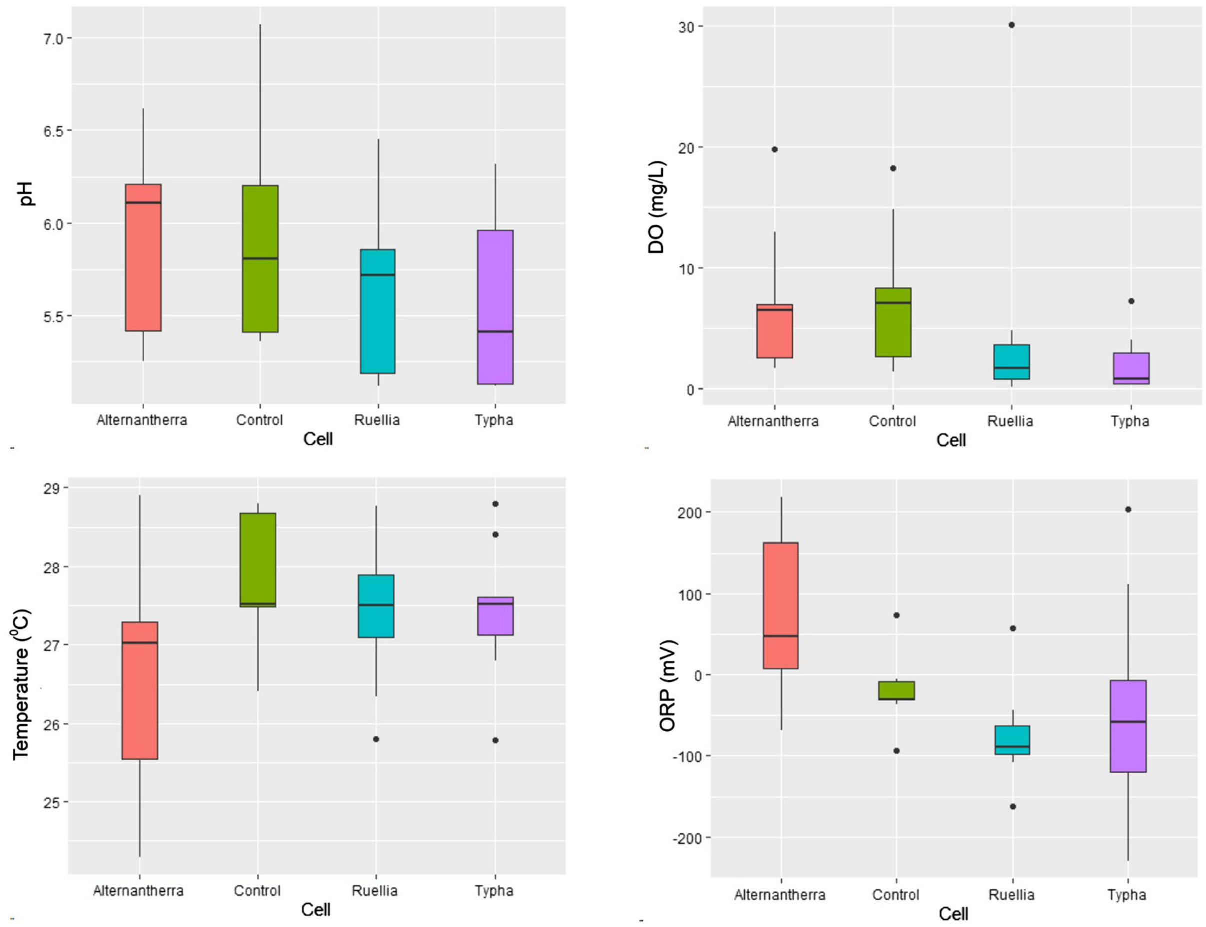


Fig. 2 Distribution of environmental factors across wetland cells

Fig. 2). This may be attributed to the higher production of litter in the Typha planted wetland which is likely to increase the sediment/litter oxygen demand, making the system more reduced. Oxidation reduction potential (ORP) decreases from the aerobic zone into the anaerobic water–sediment interface zone of the wetland (Kadlec and Reddy 2001; Szögi et al. 2004).

Interdependence of environmental factors and removal efficiency of parameters

Correlation analysis was used to assess interdependencies among the environmental variables and removal efficiency of BOD, COD, oil and grease, total coliform bacteria, total phosphorus and nitrate. Temperature had an inverse relationship with pH and removal efficiency of organics (oil and grease BOD, COD). The pH had a positive relationship with DO,

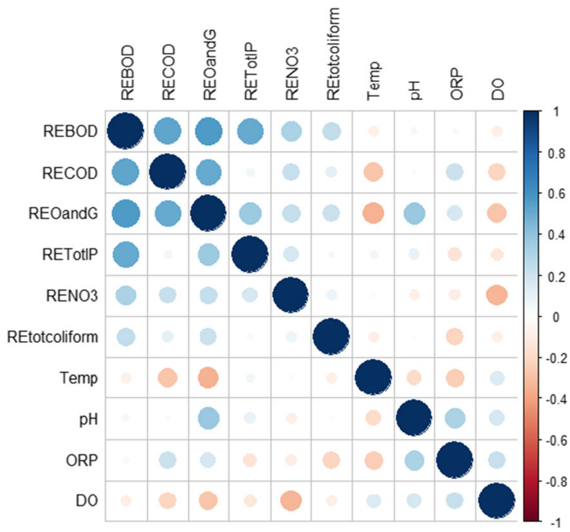


Fig. 3 Correlogram of environmental factors and contaminant removal efficiency

and ORP and removal efficiency of oil and grease. Figure 3 is a correlogram, a graphical representation of the correlation matrix.

Oxidation reduction potential (ORP) correlated positively with removal efficiency of COD and negatively with the removal efficiency of total coliform bacteria. Dissolved oxygen (DO) had positive relationships with removal efficiency of oil and grease, COD and nitrate. The removal efficiency of the parameters positively correlated with one another.

Predicting removal efficiency using environmental factors

Ordinary least squares regression models were used to predict the removal efficiency of important parameters (BOD, COD, oil and grease, total coliform bacteria, total phosphorus and nitrate) in constructed wetlands using four key environmental variables; temperature, dissolved oxygen, pH and oxidation reduction potential. The wetland plant type was controlled for in the regression models given that it could potentially confound the results. The parameter estimates were reported in the models as unstandardized regression coefficients and standardized regression coefficients.

Table 1 presents the parameter estimates of the linear regression models for removal efficiency of BOD and COD. The model 1 for BOD was not statistically significant and none of the environmental variables was also significant, indicating that no linear relationships exist between the environmental factors and removal efficiency of BOD without macrophyte. The model became statistically significant when plant type was controlled for in model 2. This implies that plant type suppresses the linear relationship between environmental factors (temperature, ORP) and removal efficiency of BOD. This is probably because plants control both the removal processes and act as sources and sinks for dissolved and particulate substances found in the wastewater (Kadlec and Reddy 2001).

The coefficient plots showing parameter estimates for removal efficiency of BOD and COD are provided in Fig. 4. Biochemical transformation such as organic decomposition that occur in free water surface flow treatment wetlands are mediated by a variety of microbial species that reside on the leaves, stem and litter provided by the plants (Gearheart et al. 1999). Wetland plants harbour the microorganisms that mediate the treatment processes and depending on the special morphological features, certain plants could harbour more microbes than other plants (Abbasi and Abbasi 2010). It is therefore unsurprising that the wetland plants explained almost three-fifths of the variation in the removal efficiency of BOD. It could be seen in model 2 that only temperature and ORP were significant predictors of BOD removal. The beta coefficient values indicated temperature had higher influence on removal efficiency of BOD than ORP. Although BOD removal processes have generally been found not to exhibit temperature dependence all the time (see Almuktar et al. 2018; Kadlec and Wallace 2009), in this study, BOD removal showed temperature dependence, indicating the temperature dependent (microbial removal processes) such as methanogenesis were not masked by internal loads of decomposition and non-biological mechanisms (Gearheart et al. 1999; Scholz and Lee 2005). The beta coefficient for the removal of BOD showed significant inverse relationship with ORP. This could probably be due to the fact that most of the influent carbonaceous BOD_5 was in the dissolved form as indicated by Bostick (2002) and removal through the pathway of methanogenesis was higher compared with other removal mechanisms (Gearheart et al. 1999). This observation is counter-intuitive because organic particles are generally removed in the highly oxidized zones in the air–water interface in the aerobic zones with more positive ORP values. Wetlands planted with *Alternanthera philoxeroides* had higher ORP values (oxidized conditions) and recorded higher levels of removal of BOD_5.

Unlike BOD, the two models for the removal efficiency of COD were both statistically significant. Explained variance for the model more than doubled when plant species were accounted for in the model indicating that plants are very relevant in the removal efficiency of COD. This is in tandem with observations made by authors including Gearheart et al. (1999) that wetland effluent COD concentration are more associated with the amount and the type of aquatic plants found within the wetland. Temperature and ORP contribute almost equally toward the removal of COD, but in the opposite direction, invariably annulling their effect. Contrarily, ORP was the only significant predictor among the environmental factors in model 2. This observation is probably due to the fact that ORP creates aerobic,

Table 1 Linear regression models for removal efficiency of BOD and COD

Parameters	BOD						COD					
	Model 1: $R^2 = 0.013$, P-Value = 0.684			Model 2: $R^2 = 0.587$, P-Value = 0.000			Model 1: $R^2 = 0.164$, P-Value = 0.000			Model 2: $R^2 = 0.368$, P-Value = 0.000		
	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value
pH	− 1.692	0.265	0.364	1.143	0.049	0.357	− 4.372	− 0.190	**0.011**	− 2.222	− 0.097	0.145
Temperature	− 1.045	− 0.255	0.237	2.308	0.214	**0.000**	− 2.761	− 0.258	**0.001**	− 1.452	− 0.136	0.061
DO	− 0.046	− 0.194	0.743	0.080	0.044	0.420	− 0.022	− 0.012	0.863	0.207	0.113	0.091
ORP	5.62E− 05	0.070	0.995	− 0.018	− 0.159	**0.011**	0.028	0.256	**0.001**	0.031	0.284	**0.000**
Plant Type (Ref: *Typha*)												
Ruellia				− 7.057	− 0.292	**0.000**				− 6.390	− 0.26631	**0.001**
Alternanthera				5.752	0.238	**0.002**				− 5.107	− 0.21282	**0.022**
Control				− 18.150	− 0.751	**0.000**				− 14.335	− 0.59737	**0.000**
Constant	80.770		**0.004**	− 23.308		0.239	136.015		**0.000**	93.286		**0.000**

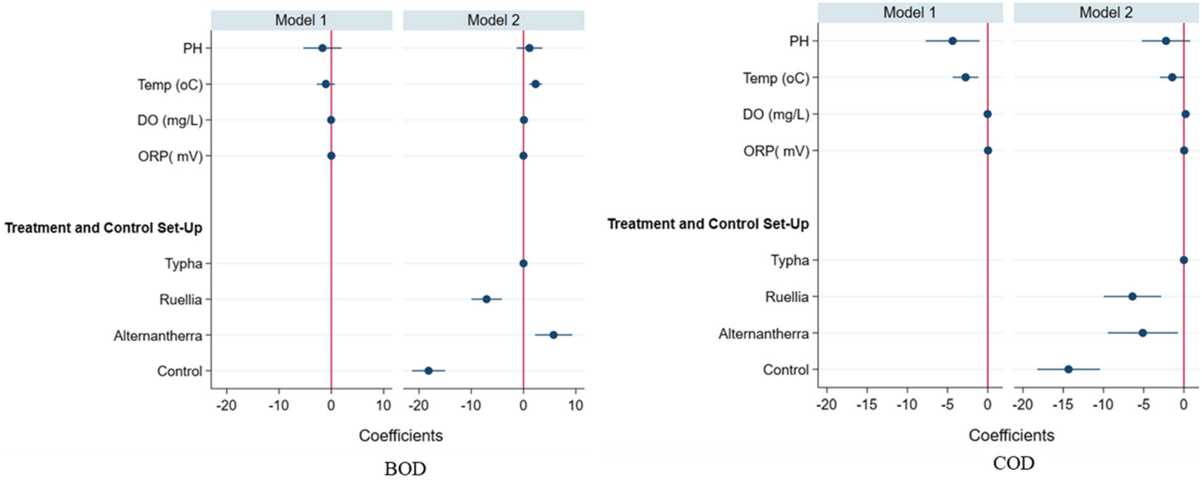


Fig. 4 Coefficient plots for removal efficiency of BOD and COD

facultative anaerobic and anaerobic conditions in the rhizosphere, which provide suitable habitats for different microorganisms to breakdown organics (Wang et al. 2018). Stein and Hook (2005) noted that results of many studies suggest that constructed wetland performance does not respond to temperature as expected. Reviewing available data, Kadlec and Wallace (2008) found there was little, if any, influence of temperature on organic carbon removal (as measured by COD, BOD or DOC tests).

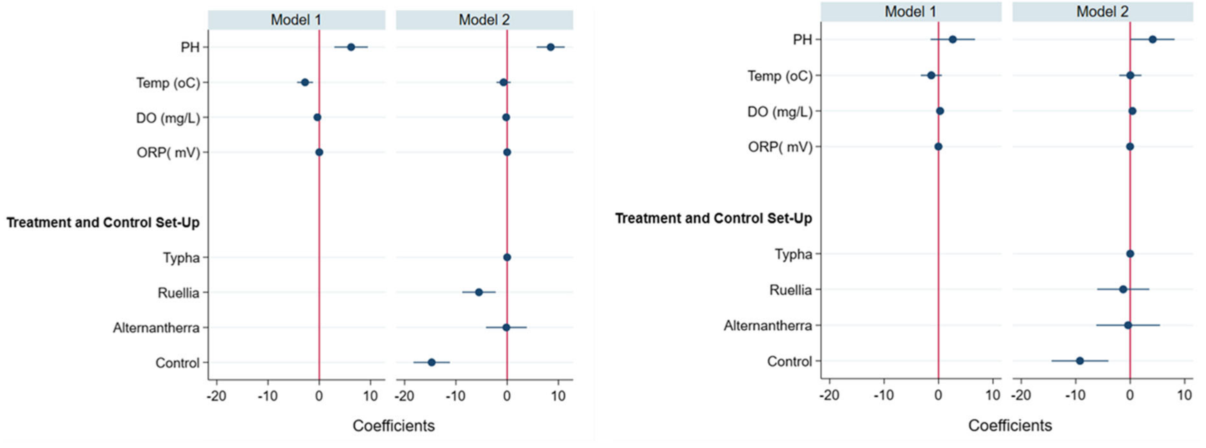
Table 2 provides the results of the OLS regression models for removal efficiency of oil and grease and total coliform bacteria. The coefficient plots of the regression models are found in Fig. 5. The model 1 for oil and grease explained 22.6% of the variation in removal efficiency whereas model 2 explained 49.1%.

The substantial increase in R^2 gives credence to the important role plants play in the removal of oil and grease. Gearheart et al. (1999) suggested that emergent and submerged plants in free water surface flow treatment wetland give it the capability to treat wastewater effectively in a passive manner. In the model 1, temperature and DO recorded positive relationships with removal of oil and grease unlike pH, which had a positive relationship with removal efficiency of oil and grease. The standardized coefficient (beta) values showed that pH had the highest influence on oil and grease removal efficiency in model 1. The only significant predictor among the four environmental factors in model 2 was pH. The coefficient value for pH increased substantially in model 2. This is evident in the coefficient plots in Fig. 5. The observed positive relationship between pH and oil and grease removal could be due to the fact that organic substances generated through the growth, death and decomposition cycles are a source of natural acidity in wetlands. The pH of wastewater is an important factor that may affect the performance of wetlands, mainly in terms of nitrogen and organic matter removal. For example, substantial alkalinity consumption during the nitrification process leads to a significant drop in pH values of the system; subsequently affecting denitrification rates (see Vymazal 2007). The wastewater pH is also important for anaerobic degradation processes of organic matter (Saeed and Sun 2012) given the high sensitivity of bacteria accountable for the formation of methane gas in the system. Wetland bacteria can only survive at pH values between 6.5 and 7.5 (see Almuktar et al. 2018). As a result, the anaerobic degradation process will not complete, if the pH value is not in this range, which leads to volatile fatty acid accumulation in the system and a subsequent drop in the pH and subsequently killing all methanogens available in the wetland system (Vymazal 1999).

Dissolved oil contains polyaromatic hydrocarbons (PAHs) and alkylated phenols, which can add to the buildup of humic substances in the sediment and water column to increase the acidity in the wetland (see Bostick 2002). The two linear regression models for the removal of total coliform bacteria recorded relatively low explanatory power implying that a lot

Table 2 Linear regression models for removal efficiency of oil and grease and total coliform bacteria

Parameters	Oil and Grease						Total Coliform Bacteria					
	Model 1: $R^2 = 0.226$, P-Value = 0.000			Model 2: $R^2 = 0.491$, P-Value = 0.000			Model 1: $R^2 = 0.055$, P-Value = 0.042			Model 2: $R^2 = 0.137$ P-Value = 0.001		
	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value
pH	6.215	0.265	**0.000**	8.497	0.363	**0.000**	2.612	0.099	0.209	4.133	0.156	**0.044**
Temperature	− 2.774	− 0.255	**0.001**	− 0.696	− 0.064	0.323	− 1.333	− 0.109	0.176	0.027	0.002	0.979
DO	− 0.361	− 0.194	**0.005**	− 0.190	− 0.102	0.089	0.279	0.133	0.077	0.405	0.193	**0.014**
ORP	0.008	0.070	0.335	0.003	0.027	0.690	− 0.025	− 0.197	**0.015**	− 0.024	− 0.189	**0.035**
Plant Type (Ref: *Typha*)												
Ruellia				− 5.499	− 0.225	**0.001**				− 1.282	− 0.047	0.598
Alternanthera				− 0.153	− 0.006	0.940				− 0.380	− 0.014	0.898
Control				− 14.718	− 0.603	**0.000**				− 9.221	− 0.335	**0.001**
Constant	92.524		**0.000**	26.748		0.228	68.279		**0.029**	24.506		0.452



Oil and Grease

Total Coliform Bacteria

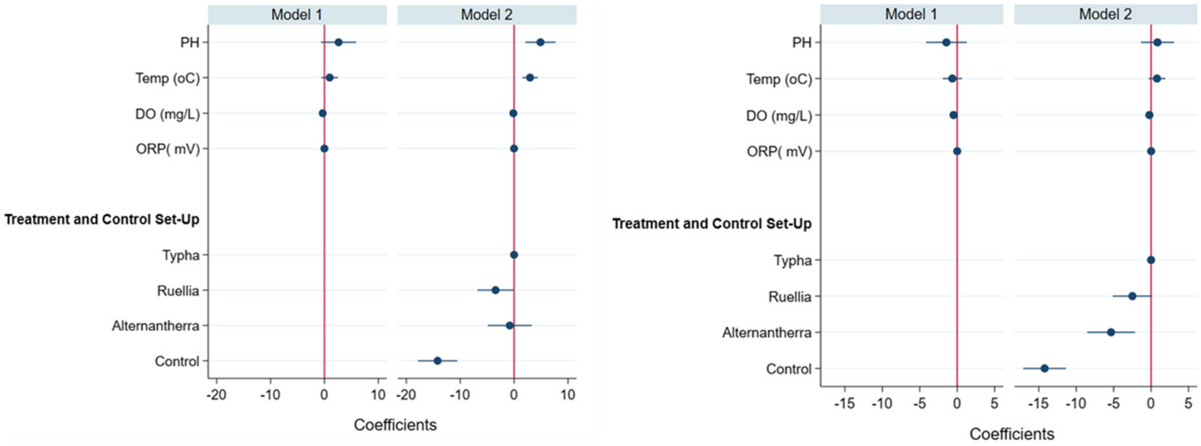
Fig. 5 Coefficient plots for removal efficiency of oil and grease and total coliform bacteria

more factors, which were not considered in this study influence removal efficiency of total coliform bacteria. In model 1, oxidation reduction potential (ORP) was the only significant predictor among the environmental factors considered. Temperature and DO also became significant predictors in addition to ORP in model 2. This indicates that plant species suppressed the relationship between each of the parameters and removal of total coliform bacteria. Garcia et al. (2008) explained that macrophyte-dependent mechanisms are more dominant in causing bacterial die-off. The authors hold the view that the presence of macrophytes indirectly contribute to bacterial die off through conductivity modification, adsorption, aggregation, filtration, gas transport and enhancement of biofilm development. Oxidation reduction potential (ORP) maintained its inverse relationship with removal efficiency of total coliform bacteria in model 2. This could mean that more total coliform bacteria die in the water–sediment interface (anaerobic zone) due to unfavourable wetland chemistry than in the air–water interface. This is consistent with the general belief that poor water chemistry including low ORP and DO cause bacterial die off. Similar findings have been made by Sawaittayothin and Polprasert (2006) in which case removal efficiency of total coliform bacteria is found to be higher in anoxic conditions of subsurface flow constructed wetland. Plant type is therefore considered a very important latent variable that influence the removal efficiencies of pathogens in wetland system (Weber and Legge 2008).

The linear regression models for the removal efficiency of total phosphorus and nitrate are provided in Table 3. Figure 6 presents the coefficient plots for the removal efficiency of total phosphorus and nitrate in the regression models. The two linear regression models for the removal of nitrate were both statistically significant. The substantial increase in the explanatory power in model 2 (more than tripled) compared to model 1 indicates the importance of plants in the removal of nitrate in this free water surface treatment constructed wetland. This could be attributed to the fact that ammonium nitrogen (NH_3-N) is biologically assimilated by plants during the nitrogen transformation process in the free surface water treatment wetland (Brix 2003; Kadlec and Wallace 2009). Dissolved oxygen was the only significant predictor among the four environmental variables in both models. Gearheart et al. (1999) indicate that nitrogen can exist in several oxidation states due to the numerous biological, physical and chemical processes that occur in free surface water flow treatment wetlands. Predominant forms (depending on the type and pretreatment) are organic nitrogen; ammonia, nitrate, nitrite, di-nitrogen oxide and nitrogen gas. The study shows that DO is a significant predictor for the removal of nitrate because the ionized ammonia is oxidized in the aerobic zone into nitrite and further into nitrate in the presence of nitrifying bacteria (Kadlec and Wallace 2008). Adequate DO is needed to complete the nitrification process since there is always competition for oxygen consumption between the degradation of organics (COD) and the

Table 3 Linear regression models for removal efficiency of total phosphorus and nitrate

Parameters	Total phosphorus						Nitrate					
	Model 1: $R^2 = 0.051$, P-Value = 0.054			Model 2: $R^2 = 0.343$, P-Value = 0.000			Model 1: $R^2 = 0.129$, P-Value = 0.000			Model 2: $R^2 = 0.463$, P-Value = 0.000		
	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value	Coef	Beta	P-Value
pH	2.626	0.124	0.115	4.902	0.232	**0.001**	− 1.442	− 0.079	0.298	0.853	0.047	0.445
Temperature	0.968	0.099	0.220	2.966	0.302	**0.000**	− 0.642	− 0.075	0.328	0.788	0.093	0.165
DO	− 0.322	− 0.192	0.011	− 0.135	− 0.081	0.237	− 0.481	− 0.331	**0.000**	− 0.225	− 0.154	**0.013**
ORP	− 0.006	− 0.056	0.490	− 0.006	− 0.060	0.443	0.002	0.022	0.780	0.012	0.133	0.061
Plant Type (Ref: Typha)												
Ruellia				− 3.439	− 0.156	**0.044**				− 2.495	− 0.131	0.062
Alternanthera				− 0.803	− 0.036	0.698				− 5.342	− 0.279	**0.001**
Control				− 14.188	− 0.644	**0.000**				− 14.211	− 0.743	**0.000**
Constant	− 0.566		0.982	− 64.564		**0.005**	64.306		**0.002**	16.494		0.355



Total Phosphorus

Nitrate

Fig. 6 Coefficient plots for removal efficiency of total phosphorus and nitrate

oxidation of ammonia in treatment wetlands. Incomplete nitrification of ammonium can produce a lot of nitrite in the wetland system (Saeed and Sun 2012). Many authors including Vymazal (2007), Kadlec and Wallace (2009), Li et al. (2014) and Liu et al. (2018) have found oxygen to be very significant in the removal of nitrogen in treatment wetlands.

The model 1 for the removal of total phosphorus was not statistically significant indicating that the environmental factors did not have linear relationships with the removal efficiency of total phosphorus. The model became statistically significant when plant type was controlled for in model 2, explaining 34.3% percent of the variation in total phosphorus removal. This result shows that plant species suppress the relationship between environmental conditions and the removal efficiency of total phosphorus in FWSFCW. This is because phosphorus removal is strongly linked to fractional coverage of different community of vegetation types (Kadlec 2016). Temperature and pH were significant predictors in model 2. The beta coefficient values showed that among the environmental variables, temperature had the highest influence on removal efficiency of total phosphorus. This observation could be due to the fact that water temperature can modify microbial processes involved in rapid uptake and release of phosphorus during decomposition of detritus (Kadlec 2016).

Conclusion

The performance of the produced water-related free water surface flow constructed wetland depends on a complex interplay of plant species, intrinsic attributes of contaminants and the interaction with a set of environmental factors. The linear relationships between environmental factors and removal efficiency of organics, nutrients and total coliform were mediated and significantly enhanced by the plant species. On the whole, the environmental factors did not influence removal efficiency of the produced water contaminants as much as the plant species. Plant species mostly suppressed the linear relationship between the environmental factors (pH, temperature, DO and ORP) and degree of removal of contaminants (BOD, COD, oil and grease, total coliform, nitrate and total phosphorus). Plants have the ability to control the removal processes through the provision of a variety of microbial species that mediate the removal process. BOD removal did not exhibit temperature dependence in this study. ORP was the only significant predictor of COD removal due to its ability to create aerobic, facultative anaerobic and anaerobic conditions in the rhizosphere, which in turn provide suitable habitats for different microorganisms to breakdown organics. Lower pH is required for effective removal of oil and grease in this type of constructed wetland.

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