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RESEARCH ARTICLE

Optimization process of organic matter removal from wastewater by using *Eichhornia crassipes*

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Abstract

This study aimed to determine the optimal conditions for organic matter removal from wastewater by *Eichhornia crassipes* (E.C). As a matter of fact, a complete factorial design was used to determine the effect of residence time (X_1), plant density (X_2) and initial chemical oxygen demand (COD) concentration (X_3) on the phytoremediation process. The process's performance was measured on COD (Y_1), NH_4^+ (Y_2) and PO_4^{3-} (Y_3), with the results indicating a reduction of 8.59–81.71% of COD (Y_1); 22.53–95.81% of NH_4^+ (Y_2) and 0.54–99.35% of PO_4^{3-} (Y_3). Then, the first-order models obtained for COD, NH_4^+ and PO_4^{3-} removal were validated using different statistical approaches such as statistical and experimental validation. Moreover, multi-response optimization was carried out through different scenarios. On the whole, the results obtained indicated that two serial ponds are required for an optimum organic matter removal by *Eichhornia crassipes*. Indeed, for the first pond, a residence time of 15 days is needed with a plant density of 60 ft/m^2 and an initial concentration of about 944 mg/L. The second was the same residence time as the first with similar plant density of 60 ft/m^2 and an initial load 192 mg/L (> 200 mg/L). Optimal organic matter removal from wastewater using *Eichhornia crassipes* requires two ponds arranged in chain.

Keywords *Eichhornia crassipes* · Multi-response optimization · Phytoremediation

Introduction

Domestic wastewater management is a serious concern throughout the world, especially in the urban areas of third-world countries (Chirisa et al. 2017). The difficulties observed are related as much to the evacuation as to the treatment of wastewater (Koné 2011). As a matter of fact, this situation poses a threat to public health, especially since domestic wastewater is a vector of diarrheal diseases and breeding sites for mosquitos that transmit the parasite responsible for malaria (WHO 2006). Due to the challenging economic conditions in West African countries, collective sanitation systems are difficult to implement, and as a result, individual sanitation systems are widespread. Indeed, lagoons with floating macrophytes are increasingly used among these extensive processes. It is an inexpensive and rustic process which is based on the function of aquatic plants to uptake mineral elements from wastewater. Through this uptake, plants absorb pollutants and produce a vegetable biomass which contributes to the added value of wastewater treatment (Noukeu et al. 2016; Pena et al. 2017). Thus, the lagoons with floating macrophytes constitute a credible alternative for wastewater treatment in West African urban areas (Ouattara et al. 2008; Rezania et al. 2016a, b). The water hyacinth is one among the plants used that has shown its ability to remove any kind of pollutants, from nutrients to heavy metals (Kiran et al. 1991; Mergaert et al. 1992; Seghezzo et al. 1998; Aina et al. 2012; Swain et al. 2014; Mishra and Maiti 2017; Mojiri et al. 2017). As a matter of fact, the water hyacinth is one

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of the most studied aquatic plants species in literature because it is the most aggressive invasive species in tropical and subtropical lakes and because of its multiple use in medicine and water treatment (Gupta et al. 2012; Loan et al. 2014). Moreover, laboratory and field studies have also demonstrated how water hyacinth is able to remove pollutants from the pig farming wastewater (Delgado et al. 1995; Williams 2009; Chen et al. 2010). However, Finlayson et al. (1987) have shown the plant cannot survive in effluents with a very high polluting load.

It is noted that the major part of the reported studies on phytoremediation with the conventional method, which involves changing one of the independent parameters, maintaining the others fixed. This classic or conventional method of experimentation requires many experiments runs, which are time-consuming, ignores interaction effects between the operating parameters and leads to a low efficiency in optimization. These limitations of the classical method can be avoided by applying the methodology of experimental designs that involves statistical design experiments in which all the factors are varied together over a set of experimental runs. In fact, the complete factorial design that makes up experimental designs is a collection of mathematical and statistical techniques useful for developing, improving and optimising processes, and can be used to evaluate the relative significance of several affecting factors even in the presence of complex interactions (Montgomery 2001). The statistical experimental design method offers several advantages over the frequency used conventional experimental method being rapid and reliable, helps understanding the interaction effects between factors and reduces the total number of experiments enormously resulting in saving time and costs experimentation. Experimental designs have been successfully applied in various scientific and technical fields such as applied chemistry and physics, biochemistry and biology, chemical engineering, environmental protection and science technology (Montgomery 2001; Khayet et al. 2011).

The works of Rezania et al. (2016a, b) and Mayo and Hanai (2017) highlighted the optimal conditions for removal of organic matter by water hyacinth. But, very few studies have focused on the optimization of phytoremediation with water hyacinth. All these justify why the present study was carried out in order to optimise pollutant removal by the water hyacinth based on three parameters: duration (residence time of treatment), plant density and initial concentration in chemical oxygen demand (COD). To this end, a complete factorial design (CFD) was used. The efficiency of the treatment was evaluated through three responses: COD, ammonium (NH_4^+) and orthophosphate (PO_4^{3-}).

Material and methods

Material

The sampling of the wastewater and macrophytes was carried out in the city of Yamoussoukro, in Ivory Coast. The wastewater was collected from the pig farm (6° 56′ 05.5″ N, 5°13′ 18.8″ W) of the National Polytechnic Institute Félix Houphouët Boigny and the macrophytes (water hyacinth plants) from lake no. 8 located between N'Zuessy and habitat (6° 49′ 01″ N, 5° 16′ 27.1″ W). The wastewater produced on the pig farm was a mixture of water from drinking troughs and excretes from pigs. Two mean samplings were carried out, the first mean sampling collection in August 2015 and the second one in April 2016, in order to take into account the probable season variability related to the fact that rainfalls could influence the wastewater produced. A mesocosm experiment was setup and consisted of 24 small containers with internal dimensions of 0.34 × 0.24 × 0.19 m. All the containers were arranged randomly (Fig. 1).

Experimental procedure

The COD was determined by the oxidation method of an excess of hot potassium dichromate (150 °C) for 2 h in an acid medium (NFT Standard 90-101, AFNOR 1994a). BOD_5 was determined using the NFT 90-103 (AFNOR 1994b) manometric method. Ammonium (NH_4^+) and orthophosphate (PO_4^{3-}) were determined by the spectrophotometric method using the Nessler reagent according to NFT 90-015 (AFNOR 1994c) and the molecular absorption spectrometry method according to NFT 90-023 (AFNOR 1994d). The pollutant removal rates (COD, NH_4^+ and PO_4^{3-}) were calculated according to formula 1:

$$\mathrm{TA}\ (\%) = \frac{C_0 - C_1}{\mathrm{CO}} \times 100 \qquad (1)$$

where C_0 and C_1 were respectively the initial and final concentrations of the parameters investigated.

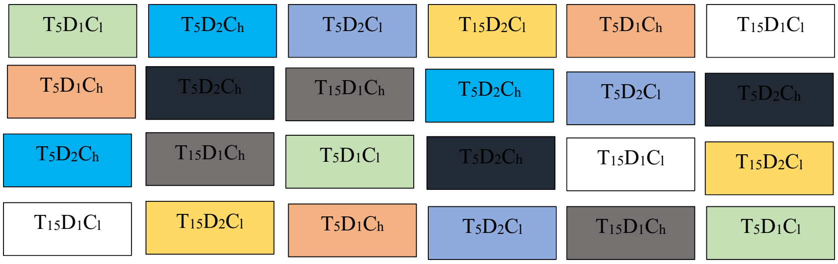

Fig. 1 Random disposition of the eight duplicate experimental trials. T_5: residence time, 5 days. D_1: plant of density, 30 ft/m^2. C_l: low concentration of COD (192 mg/L). T_{15}: residence time, 15 days. D_2: plant of density, 60 ft/m^2 C_h: high concentration of COD (944 mg/L)

$T_5D_1C_l$	$T_5D_2C_h$	$T_5D_2C_l$	$T_{15}D_2C_l$	$T_5D_1C_h$	$T_{15}D_1C_l$
$T_5D_1C_h$	$T_5D_2C_h$	$T_{15}D_1C_h$	$T_5D_2C_h$	$T_5D_2C_l$	$T_5D_2C_h$
$T_5D_2C_h$	$T_{15}D_1C_h$	$T_5D_1C_l$	$T_5D_2C_h$	$T_{15}D_1C_l$	$T_{15}D_2C_l$
$T_{15}D_1C_l$	$T_{15}D_2C_l$	$T_5D_1C_h$	$T_5D_2C_l$	$T_{15}D_1C_h$	$T_5D_1C_l$

Table 1 Experimental design

Coded variables (X_i)	Variables (U_i)	Real variables		$U_{i,0}$	ΔU_i
		Minimal value (− 1)	Maximal value (+ 1)		
X_1	U_1: residence time (Duration of the treatment)	5	15	10	5
X_2	U_2: plant density	30	60	45	15
X_3	U_3: initial COD concentration	192	944	568	376

Experimental design methodology

The methodology conventionally used to study the influence of operating parameters on a variable of interest consists in modifying the value of one parameter while maintaining the others fixed. However, this method is not appropriate when the number of variables and the response is greater than five (Yobouet et al. 2016). Therefore, an "experimental design" was elaborated to efficiently combined the factors considered in the experiment. This technique also allows to obtain a statistically significant model which integrates the interactions between the variables while optimising the number of tests (Yobouet et al. 2016). A complete factorial design (CFD) 2^k was used to determine the optimum operating conditions and write the model for a given response (Y) in the following form:

$$Y = a_0 + \sum a_i.X_i + \sum\sum a_{ij}X_iX_j + \varepsilon \tag{2}$$

where Y is the observed response; a_0, a_i and a_{ij}, respectively, represent the mean coefficient, the main effects and the interactions terms between variables; and ε represents the residual error which was estimated using the least squares method (Feinberg 1996). The test of significance of the coefficients was carried out according to the rule which states that a coefficient is statistically significant when the absolute value of the latter value is greater than or equal to twice the experimental error called the significance test (Feinberg 1996).

Table 2 Experimental design and responses

Run	Real variables			Responses (%)		
	U_1 (day)	U_2 (ft/m^2)	U_3 (mg/L)	Y_1 (COD)	Y_2 (NH_4^+)	Y_3 (PO_4^{3-})
1	5	30	192	79.90	22.53	45.92
2	15	30	192	58.59	92.00	74.33
3	5	60	192	75.13	24.07	80.63
4	15	60	192	62.12	86.25	99.35
5	5	30	944	79.55	40.71	14.86
6	15	30	944	69.95	95.81	0.54
7	5	60	944	81.71	40.71	13.96
8	15	60	944	76.42	93.12	10.09

Table 3 Coefficient estimation

Removal of COD (Y_1)		Removal of NH_4^+ (Y_2)		Removal of PO_4^{3-} (Y_3)	
Coefficients	Values	Coefficients	Values	Coefficients	Values
b_0	72.92	b_0	61.90	b_0	42.46
b_1	− 6.15	b_1	29.89	b_1	3.62
b_2	0.92	b_2	− 0.86	b_2	8.55
b_3	3.99	b_3	5.69	b_3	− 32.60
b_{12}	1.58	b_{12}	− 1.25	b_{12}	0.09
b_{13}	2.43	b_{13}	− 3.02	b_{13}	− 8.17
b_{23}	1.23	b_{23}	0.19	b_{23}	− 6.39
2σ	0.99	2σ	1.15	2σ	5.04

Y_1, Y_2 and Y_3 respectively represent the removal of COD, NH_4^+ and PO_4^{3-}, and the independent variables X_1, X_2 and X_3, respectively, duration of treatment, plant density and initial COD load coded.

The experimental field is shown in Table 1.

$$X_i = \frac{U_i - U_{i,0}}{\Delta U_i} \tag{3}$$

$$U_{i,0} = \frac{U_{i,\max} + U_{i,\min}}{2} \text{ Representing the value at the centre of each factor } U_i \tag{4}$$

Results and discussion

The results of the experiment are presented in Table 2 and the coefficients of the models in Table 3.

The responses measured after treatment (Table 2) are the removal rate of the considered pollutants. COD removal varied between 58.59 and 81.71% with a standard deviation of 8.60%; NH_4^+ removal varied between 22.53 and 95.81% with a standard deviation of 32.73% and the removal of PO_4^{3-} was comprised between 0.54 and 95.35% with a standard deviation of 37.98%. The high removal rate of PO_4^{3-} observed was due to a synergistic effect of the water hyacinth. In fact, the microorganisms contained in the wastewater also use the PO_4^{3}

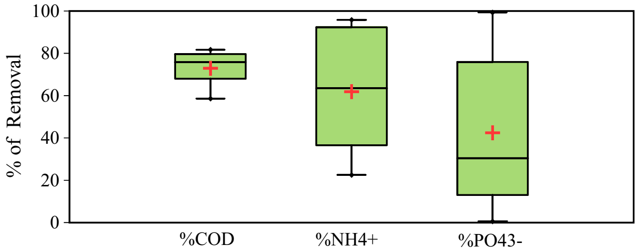

Fig. 2 Box plot of the three responses studied. %COD: removal rate of COD, %NH_4^+: removal rate of NH_4^+ and.%PO_4^{3-}: removal rate of PO_4^{3-}

− as an essential nutrient for their metabolisms, and this combined to the removal by the water hyacinth plants should lead to high PO_4^{3-} removal from the system. Significant phosphorus reduction was also observed in the literature due to the absorption of soluble P and filtration of P the particles through the roots (Fox et al. 2008).

One or more factors influenced the observation of COD, NH_4^+ and PO_4^{3-} removal. High variations of the standard deviations from one response to the other are an indicator of the influence of the observed factors on the responses (Yobouet et al. 2016). The observed standard deviation for each response category fluctuated considerably with 8.60% for COD, 32.73 for NH_4^+ and 37.98% for PO_4^{3-}. Furthermore, the analysis of Fig.2 showed that COD and PO_4^{3-} removal was not homogeneous (asymmetric distribution) while that of NH_4^+ response was distributed homogeneously following a relatively symmetrical pattern.

It could be noted that the removal rate of COD (Fig.3a) was highly dependent on the duration of the treatment. The best performances were obtained during a retention time of 5 days.

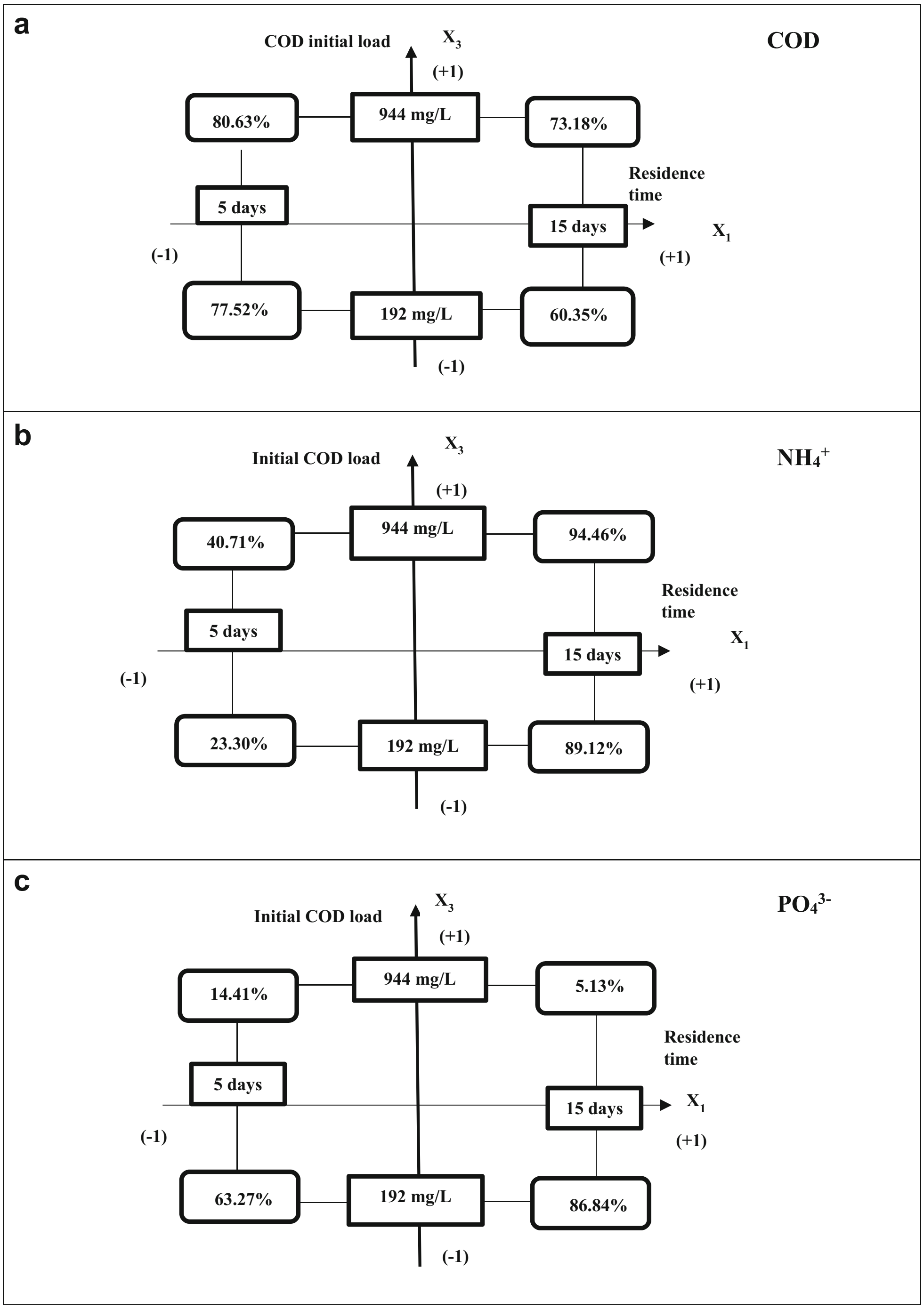

Fig. 3 Interaction between the treatment time and initial COD concentration for (**a**) carbon oxygen demand, (**b**) ammonium and (**c**) orthophosphate

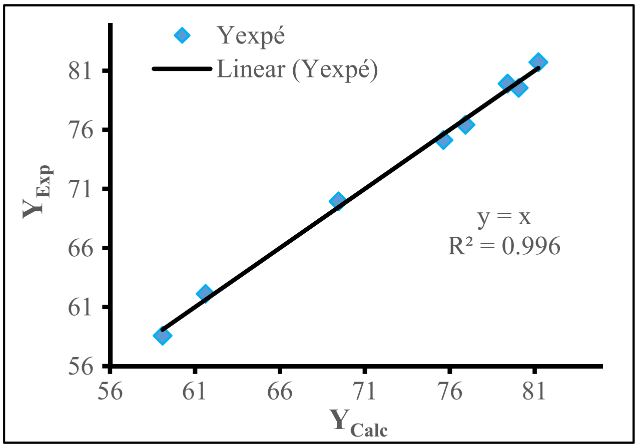

Fig. 4 Correlation graph Y_{calc} and Y_{exp} for Y_1

Shah et al. (2014) made the same observation in their work. COD removal performance was also influenced by the initial COD concentration. The treatments with the higher initial COD produced better removal rate than the treatments with lower initial COD. When compared to the other pollutant, the kinetics of COD removal was faster.

The removal rates of NH_4^+ were highly dependent on the duration of treatment. The best performances were obtained after an experimental period of 15 days. However, the information obtained from the literature indicated that the removal capacity of the water hyacinth is progressively weakened if the residence time of the treatment is too long (Finlayson et al. 1987). The study of the interactions between removal rate and residence time revealed that the influence of the retention time on the removal rate of COD and NH_4^+ was highly dependent on the initial COD concentration. The maximum effect was observed for an initial COD concentration of 192 mg/L. This corresponds to a variation of the rate of reduction of the COD and NH_4^+ from 77.52 to 60.35% and from 23.30 to 89.12%, respectively (Fig. 3a, b).

Observations made from the experiments indicated that the PO_4^{3-} removal rate was also highly dependent on the initial COD concentration. Low initial COD concentration resulted in a better PO_4^{3-} removal. As far as PO_4^{3-} is concerned, the maximum effect of the initial COD concentration on the removal was observed for a retention time of 15-day treatment period, with a variation of this response from 86.84 to 5.13% (Fig. 3a).

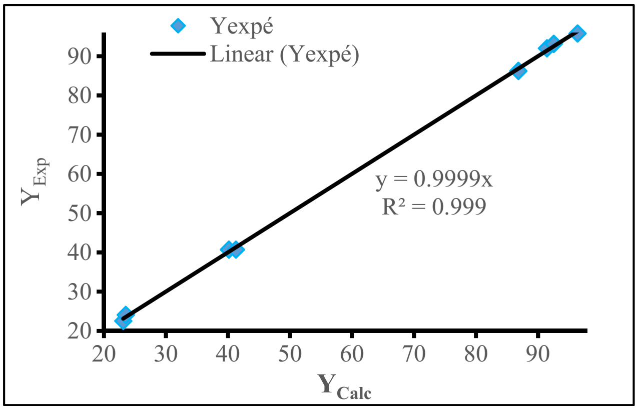

Fig. 5 Correlation graph Y_{calc} and Y_{exp} for Y_2

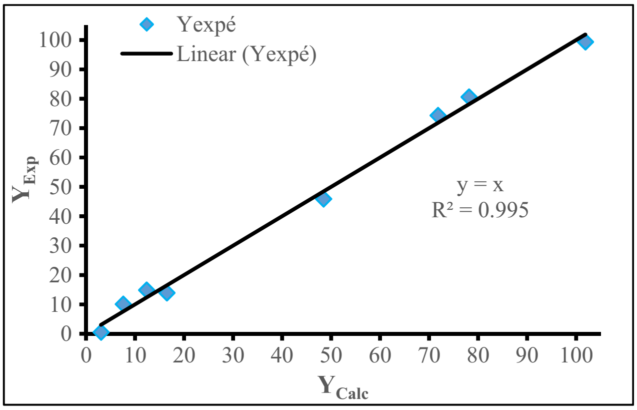

Fig. 6 Correlation graph Y_{calc} and Y_{exp} for Y_3

With regard to the above, it seems that a relatively low initial COD would favour the removal of ammonium (NH_4^+) and orthophosphate (PO_4^{3-}) parameters. Note that the interaction between the initial COD concentration and retention time was significant for the three responses studied (ANOVA, $p < 0.001$). This interaction was positive for the removal of COD and negative for the removal of NH_4^+ and PO_4^{3-}.

As it can be seen in Fig. 3c when the residence time (X_1) was fixed at the lowest level (5 days), the initial COD concentration had a significant influence on the response and the average rate of COD removal passed from 14.4 to 66.3%. If the residence time is maintained at the highest level (15 days), the initial COD concentration had a remarkable influence on the response (important than the first case) and the average rate of phosphate removal passed from 5.13 to 87%. It means that the effect of initial COD concentration was not constant and greatly depended on the residence time of water in the system.

Changes in the COD, NH_4^+ and PO_4^{3-} removal obtained could be explained by microbial assimilation by microorganisms in the rhizosphere. Indeed, aerobic bacteria naturally present in the root system of plants consume organic matter (Rezania et al. 2015). They transform them into minerals matters that can be assimilated by plants. In return, the plants provide oxygen to the bacteria by their roots (Rezania et al. 2015). This phenomenon was confirmed in this research by the growth of macrophytes, which showed high performances to remove COD mainly due to the well-developed root system. Similarly, it has been observed that much of the degradation of COD in wastewater was attributed to

Table 4 Descriptive quality of models

Coefficients	%COD	$\%NH_4^+$	$\%PO_4^{3-}$
R^2	99.6	100	99.5
$R^2_{ajusted}$	97.3	99.8	96.5

Table 5 Results of multiple criteria optimization

No. Scenario	Model	Optimal conditions
Scenario 1	$\left\{\text{Min } \frac{1}{Y_1+Y_2+Y_3} \text{ with}\right.$ $-1 \leq X_1 \leq +1;\ -1 \leq X_2 \leq +1$ and $-1 \leq X_3 \leq +1$	Residence time = 15 days Plants density = 60 ft/m^2 Initial COD = 192 mg/L Maximal removal rate: COD = 62.12% NH_4^+ = 86.25% PO_4^{3-} = 99.35%
Scenario 2	$\left\{\text{Min } \frac{1}{Y_1+Y_2} \text{ with}\right.$ $-1 \leq X_1 \leq +1;\ -1 \leq X_2 \leq +1$ *et* $-1 \leq X_3 \leq +1$	Residence time = 15 days Plants density = 60 ft/m^2 Initial COD = 944 mg/L Maximal removal rate: COD = 76.42% and NH_4^+ = 93.12%
Scenario 3	$\left\{\text{Min } \frac{1}{Y_1+Y_3} \text{ with}\right.$ $-1 \leq X_1 \leq +1;\ -1 \leq X_2 \leq +1$ *et* $-1 \leq X_3 \leq +1$	Residence time = 5 days Plants density = 60 ft/m^2 Initial COD = 192 mg/L Maximal removal rate: COD = 75.13% PO_4^{3-} = 80.63%
Scenario 4	$\left\{\text{Min } \frac{1}{Y_2+Y_3} \text{ with}\right.$ $-1 \leq X_1 \leq +1;\ -1 \leq X_2 \leq +1$ *et* $-1 \leq X_3 \leq +1$	Residence time = 15 days Plants density = 60 ft/m^2 Initial COD = 192 mg/L Maximal removal rate: NH_4^+ = 86.25% PO_4^{3-} = 99.25%

microorganisms that may have established a symbiotic relationship with plants (Li et al. 2011; Shah et al. 2014).

The purification performances obtained in this study corroborate those obtained by Jianbo et al. (2008); Aina et al. (2012) and Rezania et al. (2016a, b). These performances are within the range of performance obtained in other natural water purification systems using water hyacinth (Ghaly et al. 2005; Loan et al. 2014; Akinbile and Yusoff 2012; Rezania et al. 2015; Mojiri et al. 2017). However, they are relatively lower than those obtained by Rezania et al. 2016a, b with the same floating macrophytes (98.52% for COD, 95.08% for NH_4^+ and 69.81% for PO_4^{3-}).

To optimise the parameters for the removal of COD, NH_4^+ and PO_4^{3-}, it was important to ensure the validity of the models obtained:

$$Y_1 = 72.92 - 6.15X_1 + 0.92X_2 + 3.98X_3 + 1.57X_1X_2 + 2.43X_1X_3 + 1.23X_2X_3 \quad (5)$$

$$Y_2 = 61.90 + 29.89X_1 - 0.86X_2 + 5.69X_3 - 1.25X_1X_2 - 3.02X_1X_3 \quad (6)$$

$$Y_3 = 42.46 + 3.62X_1 + 8.55X_2 - 32.60X_3 - 8.17X_1X_3 - 6.40X_2X_3 \quad (7)$$

The validation was made using the plots of the parity graph giving the predicted values as a function of the observed values (Figs. 4, 5 and 6). It was found that the polynomial model of order 1 correlated with the experimental results. In addition, the ANOVA results of the regression model (Table 5) showed that the models were significant at the 5% threshold. This was justified by the fact that the values of the coefficients R^2 and the adjusted R^2 which were close to 100% (Table 4). In the presence of several explanatory variables, the coefficient that was best indicated would be the adjusted R^2. Thus, the quality of the models is satisfactory because of the adjusted R^2 of each model of the three responses close to 100% (Garg et al. 2017; Pooralhossini et al. 2018).

The system was optimised under different scenarios using the STATGRAPHICS Centurion XVI software. With a 0.51 desirability used, the optimal conditions are summarised in Table 5. It appeared that two serial ponds gave better for the results. The characteristics of the treatment would be presented as a retention time of 15 days, a plant density of 60 ft/m^2 and an initial concentration of 944 mg/L in first basin, and in the last basin a retention time of 15 days, a plant density of 60 ft/m^2 and an initial concentration of 192 mg/L.

Conclusion

In this work, the influence of residence time, the plant density and initial concentration of COD on phytoremediation was examined by using an experimental design methodology.

This study showed that the residence time, the initial COD load and their interaction have a great influence on the removal of COD, NH_4^+ and PO_4^{3-}. Using a 2^3 factorial design, the best removal rate of COD (81% of rate removed) was obtained with a residence time of 5 days, a plant density of 60 ft/m^2 and 944 mg/L of initial concentration COD; NH_4^+ (95% of rate removed) was obtained with a residence time of 15 days, a plant density of 30 ft/m^2 and 944 mg/L of initial concentration COD; and PO_4^{3-} (99.35% of rate removed) was obtained with a residence time of 15 days, a plant density of 60 ft/m^2 and 192 mg/L of initial concentration COD. The parameters to be used for a better rate of abatement in COD, NH_4^+ and PO_4^{3-} are the residence time and the initial COD load while setting the plant density at 60 ft/m^2. Moreover, the effect of these factors on each other is not constant but depends on the initial concentration of each of them. Software STATGRAPHICS Centurion XVI was employed to define the multiple criteria optimization operating conditions for phytoremediation. For a better rate of the three responses, 76.42%, 93.12% and 99.25% respectively COD, NH_4^+ and PO_4^{3-}, it takes a residence time of 15 days, a density of 60 ft/m^2 plant and an initial COD concentration of 944 mg/L.

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