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Modeling and optimization of wastewater treatment, from the Ain Chock Faculty in Morocco, using the vertical flow filter filled with pozzolana

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ABSTRACT

In this study, we focused on the modeling and optimization of the purifying power of the vertical filter filled with pozzolana, using the response surface methodology, which is based on the study of the main factors, their effects, and their interaction. Therefore, we applied a rotary and uniform-centered composite plane to three factors while evaluating three responses, namely: the chemical oxygen demand abatement rate, electrical conductivity, turbidity, and discoloration. The contours of iso-response enabled us to define the optimal conditions, in terms of residence time and volume of treated water which are respectively, t_{sj} = 806 min, V = 2 L, and for a reduction greater than 70% of the four responses measured.

Keywords: Purification; Wastewater; Vertical flow; Pozzolana; Modeling; Optimization; Response surface methodology; Decentralized system; JMP software; Sustainable development

1. Introduction

In recent decades, Morocco has experienced significant demographic growth and economic development. As a result of this socio-economic development, water resources, already limited, have reached a very high level of mobilization and exploitation and undergo an increasing and alarming degradation of their quality [1]. Indeed, urban effluents and industrial discharges are often discharged into the natural environment without preliminary treatment.

Mindful of this problem, the Faculty of Sciences Ain Chock has set up an experimental pilot for the treatment of part of its liquid waste in order to reuse it, once purified, for cleaning and watering green spaces. This is a compact rustic treatment process with a relatively low cost, allowing to production of purified wastewater that meets Moroccan standards for reusing wastewater for irrigation [2].

This project is part of a general strategy of the orientation of our university towards applied fields. It allows us to control theoretical and practical knowledge in terms of wastewater treatment processes on a real model.

The various techniques of wastewater treatment, namely lagoons [3], activated sludge, biological disks, etc. [4] are interesting but have some disadvantages in terms of cost, occupied surfaces, olfactory nuisances, etc.

In the case of our pilot and due to the limited budget and limited space [5], we opted for a compact purification system adapted to local conditions:

- Decantation followed by a vertical flow filter alone or combined with a biological system;
- Decantation followed by four moving bed biofilm reactor (MBBR) processes using polyurethane foam as bio-media;
- Decantation followed by two moving bed biofilm reactor (MBBR) processes followed by a vertical flow filter.

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In this work, before the implementation of our pilot, we designed and implemented on a laboratory scale a vertical flow filter planted with reeds, using pozzolana as filter material. This filter is fed by the decanted liquid discharge from the sanitary blocks of our faculty. Preliminary results show that the planted vertical filter using pozzolana as a filter material has significant purifying power [6].

The principle of this process consists of vertical percolation through a filtering mass making it possible to retain suspended solids on the surface where they accumulate [7,8], on the one hand, and the roots of the reeds allow the aeration of the massif and form a support for purifying bacteria which promotes the purification of wastewater, on the other hand.

The choice of the system adopted is based on extensive bibliographic studies comparing the advantages and disadvantages of different wastewater treatment systems. Indeed, the vertical flow filter offers advantages such as inexpensive treatment technology. This technology is suitable for the sustainable use of locally available resources [9–11].

And on the other hand, this choice of this process was made on the basis of the results obtained by following the evolution of the purification efficiency of the planted filters (horizontal and vertical) set up for the treatment of wastewater from hammam Douar Ouled Ahmed (Dar Bouaazza) [12]. This is part of a pilot project initiated by the Morocco–Germany action research program on Urban Agriculture in Casablanca (UFC). The efficiency of the vertical flow filter has been shown to be greater than that of the horizontal flow filter) [12].

The objective of this study is to optimize the purifying efficiency of the vertical flow, using the response surface methodology (RSM) [13], which is based on the study of the main factors, their effects, and their interaction. Therefore, we applied a rotary and uniform-centered composite plan with two factors while evaluating three responses [14–16], namely: the abatement rate of the chemical oxygen demand (COD) and the turbidity and discoloration. And this, in order to determine the optimal conditions, according to the three factors studied such as the residence time "t_{sj}", and the volume of treated water "V_t" in the filter to obtain treated water of good quality, according to Moroccan standards, for reuse without risk for irrigation and watering.

2. Materials and methods

2.1. Description of the sampling site

The wastewater used in this study was collected from sewer juxtaposed to the sanitary blocks of the Ain Chock Faculty of Sciences (FSAC). This sewer will be the only source of wastewater that we will treat with this prototype (Fig. 1).

2.2. Description of the pilot-scale

Among the scenarios proposed for the purification of liquid discharges from our establishment, we built a laboratory-scale prototype of the vertical flow filter planted with reeds using pozzolana as filter material (Fig. 2).

The experimental prototype used, consists of a vertical filter planted with reeds placed in the laboratory with the pozzolana forming the substrate vary from 2 to 40 mm respectively from top to bottom (Fig. 2).

The bin used is plastic, typical high-density polyethylene, 0.215 m high, and 0.432 m^2 of the bed surface. It has a small valve to facilitate the evacuation of the treated water.

The choice of pozzolana as a filtering material is based on the literature that has shown the effectiveness of this rock for the treatment of wastewater and the abundant presence of it in Morocco.

The pozzolana used in this study was recovered from the Middle Atlas (Morocco) [17]. The chemical characterization of this rock using an X-ray fluorescence spectrometer determine the presence of oxide compounds such as calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3), magnesium oxide (MgO) and iron oxide (Fe_2O_3). In addition, minor compounds like SO_3, K_2O and Na_2O have also been determined [18].

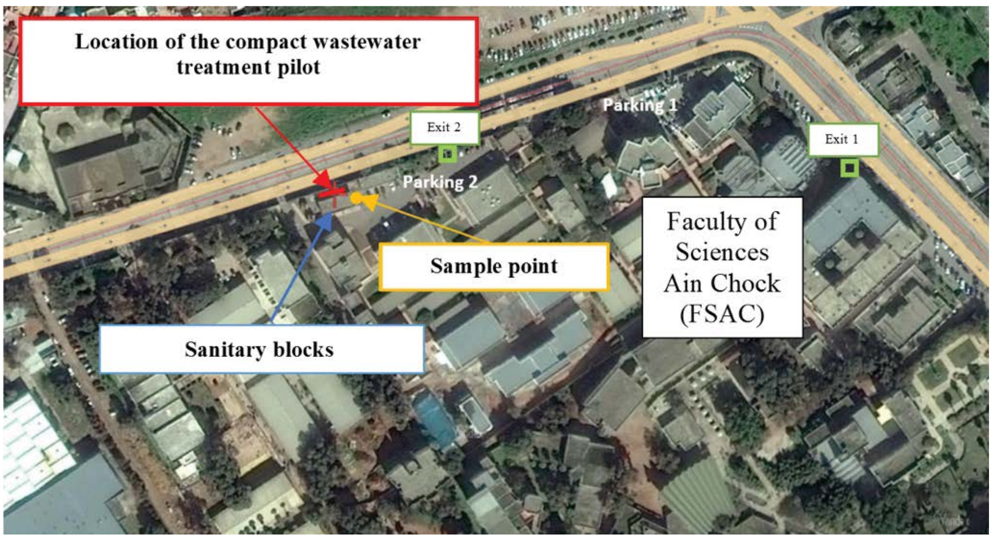

Fig. 1. Location of the compact wastewater treatment pilot and sampling point.

Fig. 2. Laboratory scale prototype of the vertical flow filter with reeds.

2.3. Wastewater analysis

Preliminary tests were carried out in order to anticipate the factors influencing the quality of the treated water, the objective of which is to optimize the purifying power of this process by the combination of the factors likely to act on this treatment [6].

The analyses were carried out according to standardized methods [19,20] in the "Geosciences Applied to Development Engineering" Laboratory (GAIA), by the team working on Waters Treatment and Valorization.

In order to assess the quality of the wastewater before and after treatment, samples were taken and physico-chemical and bacteriological analyses were carried out. These are the:

In-situ measurements of temperature (T), electrical conductivity (EC), pH and dissolved oxygen (DO) using a multi-parameter brand HANNA (HI98194).

Laboratory analysis, according to AFNOR [19] and Rodier [20] standards, of the following parameters: chlorides "Cl^-" (according to the NF Standard T 90-014), sulfates "SO_4^{2-}" (according to the NF Standard T 90-009), nitrites "NO_2^-" (according to the NF Standard T 90-013), nitrates "NO_3^-" (according to the NF Standard ISO 7890-3/1988), ammonium "NH_4^+" (according to the NF Standard T 90-015), orthophosphates "PO_4^{3-}" (according to the NF Standard T 90-023), chemical oxygen demand "COD" (according to the NF Standard T 90-101), total suspended solids "TSS" (according to the NF Standard T 90-105-1), biological oxygen demand 5 d "BOD_5" (according to the instrumental method Rodier), turbidity "Turb" (according to the NF Standard T 90-033), discoloration "Discol" (according to the NF Standard T 90-034), and heavy metals (according to the NF Standard T 90-112).

2.4. Statistical analysis

Through an appropriate experimental field, the objective is to be able to optimize the wastewater treatment system and get purified water that meets the standards of reuse for irrigation. To this effect, we will try to find out which of the following variables (or a combination of these variables) are the most important: the residence time "t_{sj}", and the volume of water treated by the vertical filter "V_t".

The four answers that we have taken into account in the optimization method used are the parameters: chemical oxygen demand (COD), electrical conductivity (EC), turbidity (Turb) and discoloration (Discol).

Usually, the variables used to interact with each other. For this reason, we deliberately used the response surface methodology (RSM) [13,21]. It simplifies optimization by studying the mutual interactions between the variables over a range of statistically validated values. This is generally referred to as the full factorial design [22]. The availability of user-friendly software packages has made this technique increasingly popular among users of optimization methods [22]. We used JMP 11 [15,16] in which we applied a uniform rotating centered composite plane [14–16] based on a 2nd order centered composite model [23].

2.4.1. Choice of plan type

The choice of an appropriate plan remains an open question. The idea is that the design should be tested as best as possible and with the least amount of experience.

In our study, the polynomial second-degree model chosen because of its accuracy in prediction, but also because of its parsimony since it could contain a limited number of coefficients after using an appropriate design. We have adopted the centered composite [24]. It should note that this model could only be used when the variables (or factors) fall within the ranges in which the model was calibrated, at the risk of diverging [24–26].

The composite centered plane is a factorial plane of type 2^k (k being the number of factors) to which axial and central points must be added. The number of center points and the distance between the axial points and the center are determined using JMP Software [15,16], based on the rotational isovariance criterion. The error on the prediction model should be only a function of the distance to the center of the plane.

In our case, the uniformly accurate rotary-centered composite plane reduced [24] the number of experiments. For a 5-level composite design, this number becomes 12 instead of 25 (= 5^2).

2.4.2. Mathematical model

The behavior of the system is explained by the following quadratic Eq. (1):

$$\hat{y} = b_0 + \sum_{j=1}^{n} b_j X_j + \sum_{j=1}^{n} \sum_{i=1;i\neq j}^{n} b_{ji} X_j X_i + \sum_{j=1}^{n} b_{jj} X_j^2 \quad (1)$$

where $\hat{y}$ is the theoretical response represented by the rate of reduction of the chemical oxygen demand "COD", the electrical conductivity "EC", the turbidity "Turb" and the discoloration "Discol".

X_i are the coded variables already defined previously.

b_0, b_j, b_{ji} and b_{jj} are the coefficients of the model where i and j vary according to the number "n" of variables used.

Eq. (1) can also be expressed linearly as follows:

$$\hat{y} = b_0 + \sum_{j=1}^{k} b_u X_u \tag{2}$$

With b_u (u varying from 1 and k) are the k $\left(k = 2n + \frac{n!}{2!(n-2)!}\right)$ regression coefficients obtained by the method of least squares and the X_u are the parameters formed by the factors X_i, or their products X_iX_j (i and j varying the 1 and n). The latter is assumed by independent construction.

The analyzes were carried out using the factor Snedecor "F" [27]. The latter is used to determine the significance of each of the interactions between the variables.

2.4.3. Choice of the experimental field

To carry out this study, the choice of the field of variation for each factor is very important. In this area, there must be [26] sufficient:

- Wide to show significant variations in response.
- Limited to be able to simulate the variations, which may occur uncontrollably during the implementation of the method.

The five levels of each real and non-coded variable "x_i" are calculated from the coded variable X_i determined by the software on the basis of the two appropriate factors used and taking into account the composite system used: orthogonal, centered and uniform. The centering of the experimental domain taken into account is that of the composite plane, centered, rotating and uniform.

3. Results and discussion

Based on the measurements we made in the laboratory according to the experimental field proposed above and all their estimates from Eq. (2) that given by the JMP software. The "b_u" steering coefficients of Eq. (2) we have taken into account are those that are significant at the 95% confidence level.

The four Tables 1–4, below, summarize the importance of the factors (or their interactions) on the abatement rate of the physicochemical parameters considered.

From these tables, we have found that for a significance level of 95%:

- The residence time "t_{sj}" has no effect on electrical conductivity because its directing coefficient is significantly zero. On the other hand, we cannot neglect its effect as well as its quadratic effect "t_{sj}^2" on the model since their guiding coefficients are not significantly zero.

Table 1
Estimation of sorted coefficients for COD

Estimation of the coefficients sorted

Term	Estimation	Error standard	t ratio	Prop. > ltl
Vt	6,4728179	0,790656	8,19	0,0002*
tsj	5,1860197	0,790656	6,56	0,0006*
tsj*tsj	-2,39375	0,88398	-2,71	0,0352*
Vt*Vt	-0,79625	0,88398	-0,90	0,4024
tsj*Vt	-0,8725	1,118157	-0,78	0,4649

Table 2
Estimation of sorted coefficients for EC

Estimation of the coefficients sorted

Term	Estimation	Error standard	t ratio	Prop. > ltl
Vt	29,263413	2,723222	10,75	<,0001*
tsj*tsj	25,948125	3,044654	8,52	0,0001*
Vt*Vt	10,495625	3,044654	3,45	0,0137*
tsj*Vt	-4,71	3,851217	-1,22	0,2672
tsj	-0,5188	2,723222	-0,19	0,8552

Table 3
Estimation of sorted coefficients for discoloration

Estimation of the coefficients sorted

Term	Estimation	Error standard	t ratio	Prop. > ltl
tsj	17,790649	1,765171	10,08	<,0001*
tsj*tsj	-8,18625	1,973521	-4,15	0,0060*
tsj*Vt	-8,415	2,496329	-3,37	0,0150*
Vt*Vt	2,25375	1,973521	1,14	0,2970
Vt	-0,032339	1,765171	-0,02	0,9860

Table 4
Estimation of sorted coefficients for turbidity

Estimation of the coefficients sorted

Term	Estimation	Error standard	t ratio	Prop. > ltl
tsj	13,089828	1,703341	7,68	0,0003*
Vt*Vt	7,775	1,904393	4,08	0,0065*
tsj*tsj	-6,7	1,904393	-3,52	0,0125*
tsj*Vt	-4,47	2,408888	-1,86	0,1129
Vt	-1,639695	1,703341	-0,96	0,3729

- The volume of treated water has no effect on discoloration and turbidity because its directing coefficient is significantly zero. On the other hand, it is significantly non-zero for COD and electrical conductivity. Their quadratic effect "V_t^2" is significant for electrical conductivity and turbidity. Moreover, their interaction with the residence time "$t_{sj} \times V_t$" is significant in the discoloration.

The residence time and their quadratic effect appear to be the main factors for purifying wastewater, in terms of COD abatement rate, electrical conductivity, turbidity, and discoloration.

Consequently, the equations relating to the reduction of these four parameters, taking into account the level of significance of 95% are:

$$\widehat{\text{COD}} = 71.61 + 5.19X_1 + 6.47X_2 - 2.39X_1^2 \quad (3)$$

$$\widehat{\text{EC}} = 31.24 + 29.26X_2 + 25.95X_1^2 + 10.49X_2^2 \quad (4)$$

$$\widehat{\text{Turb}} = 74.80 + 13.09X_1 - 6.70X_1^2 + 7.77X_2^2 \quad (5)$$

$$\widehat{\text{Discol}} = 68.78 + 17.79X_1 - 8.41X_1X_2 - 8.19X_1^2 \quad (6)$$

The following Fig. 3 is the graphic representation of these four forecasts as well as their confidence intervals at the 95% threshold.

This figure shows that after approximately 20 h 40 min of treatment by the vertical flow filter using the pozzolana as filter material, we can reach a reduction rate of 70%; which could already be included in the Moroccan standard (125 mg/L) [28] when the COD is 400 mg/L before treatment.

The two factors studied influence the COD abatement rate in the same way. The latter beliefs in increasing the residence time and the volume of treated water.

For discoloration, its effectiveness is significant and increases by increasing the residence time, on the other hand, it remains constant around 70% by increasing the volume of treated water.

For electrical conductivity, its rate of abatement decreases until the middle of the experimental field and begins to increase by increasing the residence time. This rate, on the other hand, increases when the volume of treated water increases. Note that from the center of the experimental domain, these two factors increase this abatement rate in the same way.

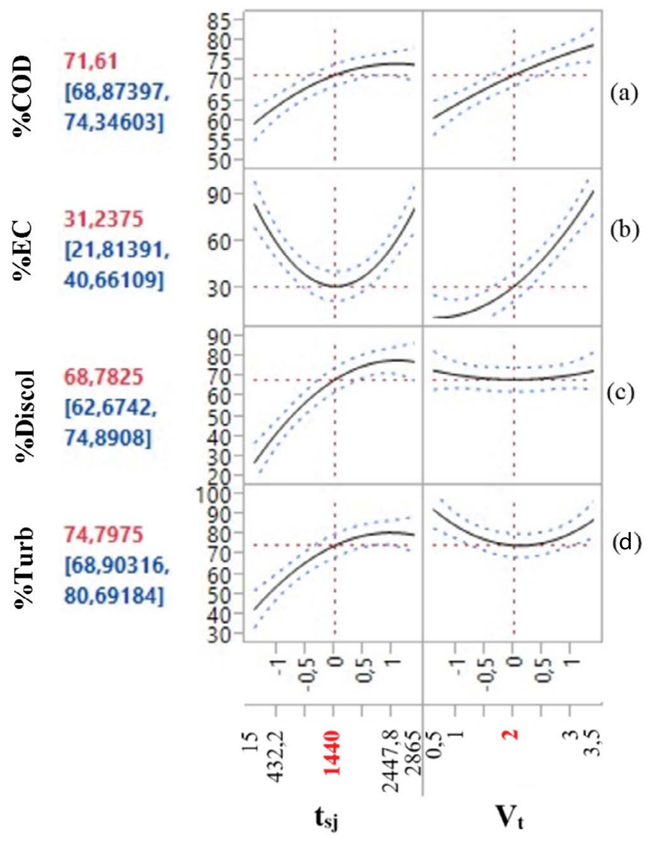

Fig. 3. Diagram of the main effects of the parameters on (a) the COD reduction rate, (b) the electrical conductivity, (c) discoloration and (d) the reduction rate of turbidity.

3.1. Validation of the model

For the centered composite plan, we tested the validity of the model by the appropriate analysis of variance (ANOVA) [13].

Tables 5–8 present the analysis of variance of regression (ANOVA) for the four successively measured responses COD, EC, Turb and Discol.

The model is considered adequate if the variance due to the regression is significantly different from the total variance.

Fig. 4 presents the correlation curves between the experimental results and those predicted for the three responses.

These curves show that the quadratic model used according to the uniform rotational centered composite plane perfectly validates the measured parameters. All the coefficients of determination exceed 95%, a much higher percentage than the one suggested by RABIER, which is 80% [23].

3.2. Optimization

Taking into account the preceding remarks, we have graphically represented in three dimensions the reduction percentages of the three parameters as a function of the residence time "t_{sj}" and the volume of water treated by the vertical filter "V_t" (Fig. 5).

For example, for the response of the discoloration rate (%Discol), Fig. 5c presents the contours of iso-response and surface of this response. The optimal range is 70%–88% for a residence time range of 1,372–2,392 min and a volume range of treated water of 1–3 L.

The superposition of these four figures are represented by Fig. 6, commonly known as an iso-response profiler; this representation makes it possible to find the optimal conditions that could be used in the wastewater treatment system.

The objective of this study is to have an optimal abatement rate of COD, turbidity, and discoloration, which treated wastewater, can be used for irrigation according to Moroccan standards. Under these conditions, and according to the superimposition of the iso-response curves, the estimated optimal values of the two factors are given in the table below.

3.3. Validation of the optimized parameters

Based on the results, the optimal factors for obtaining the best discount rates for the four measured responses are those with the coding of –0.6.

To verify this result, we voluntarily took a coding of 1 for the volume (i.e., 2 L) and coding of –0.63 for the residence time (i.e., around 13 h);

The following table summarizes the optimal conditions verified as well as the results calculated by JMP and those obtained experimentally.

Table 5
Regression analysis of variance for the reduction rate of the COD

Source	Degrees of freedom	Sum of squares	Medium square	Rapport F^a	Prob. > F	S^b
Model	3	58,362,397	194,541	419,391	<0.0001	*c*
Residues	8	3,710,929	4,639			
Total	11	62,073,327				

[a]F_{exp}: Snedecor factor; [b]Significance test; [c]Significant at 0.1% level ($F_{0.001}$(3.8) = 158,295) [13,29].

Table 6
Regression analysis of variance for the reduction rate of the EC

Source	Degrees of freedom	Sum of squares	Medium square	Rapport F^a	Prob. > F	S^b
Model	3	11,347,623	378,254	677,185	<0.0001	*c*
Residues	8	446,855	5,586			
Total	11	11,794,478				

[a]F_{exp}: Snedecor factor; [b]Significance test; [c]Significant at 0.1% level ($F_{0.001}$(3.8) = 158,295) [13,29].

Table 7
Regression analysis of variance for the reduction rate of the discoloration

Source	Degrees of freedom	Sum of squares	Medium square	Rapport F^a	Prob. > F	S^b
Model	3	33,126,248	110,421	485,163	<0.0001	*c*
Residues	8	1,820,762	2,276			
Total	11	3,494,701				

[a]F_{exp}: Snedecor factor; [b]Significance test; [c]Significant at 0.1% level ($F_{0.001}$(3.8) = 158,295) [13,29].

Table 8
Regression analysis of variance for the reduction rate of the turbidity

Source	Degrees of freedom	Sum of squares	Medium square	Rapport F^a	Prob. > F	S^b
Model	3	22,119,329	737,311	245,057	0.0002	*c*
Residues	8	2,406,982	30,087			
Total	11	24,526,311				

[a]F_{exp}: Snedecor factor; [b]Significance test; [c]Significant at 0.1% level ($F_{0.001}$(3.8) = 158,295) [13,29].

Table 10 summarizes the optimal conditions verified as well as the results calculated by JMP and those obtained experimentally.

This table clearly shows that the responses measured experimentally fall within the expected range.

After the validation of the optimal conditions, we proceeded to a physicochemical and biological characterization of the wastewater of the FSAC before and after treatment by the vertical flow filter planted with reeds using pozzolana as filter material while respecting the optimal factors chosen.

The results obtained from different measured parameters are presented in Fig. 7.

Table 9
Optimized values of the two factors

Parameters	Optimized values
t (mn)	806 (–0.63)
V (L)	2 (1)

Taking into account the limit values of water intended for irrigation according to Moroccan standards [30], the parameters analyzed can be classified under three headings:

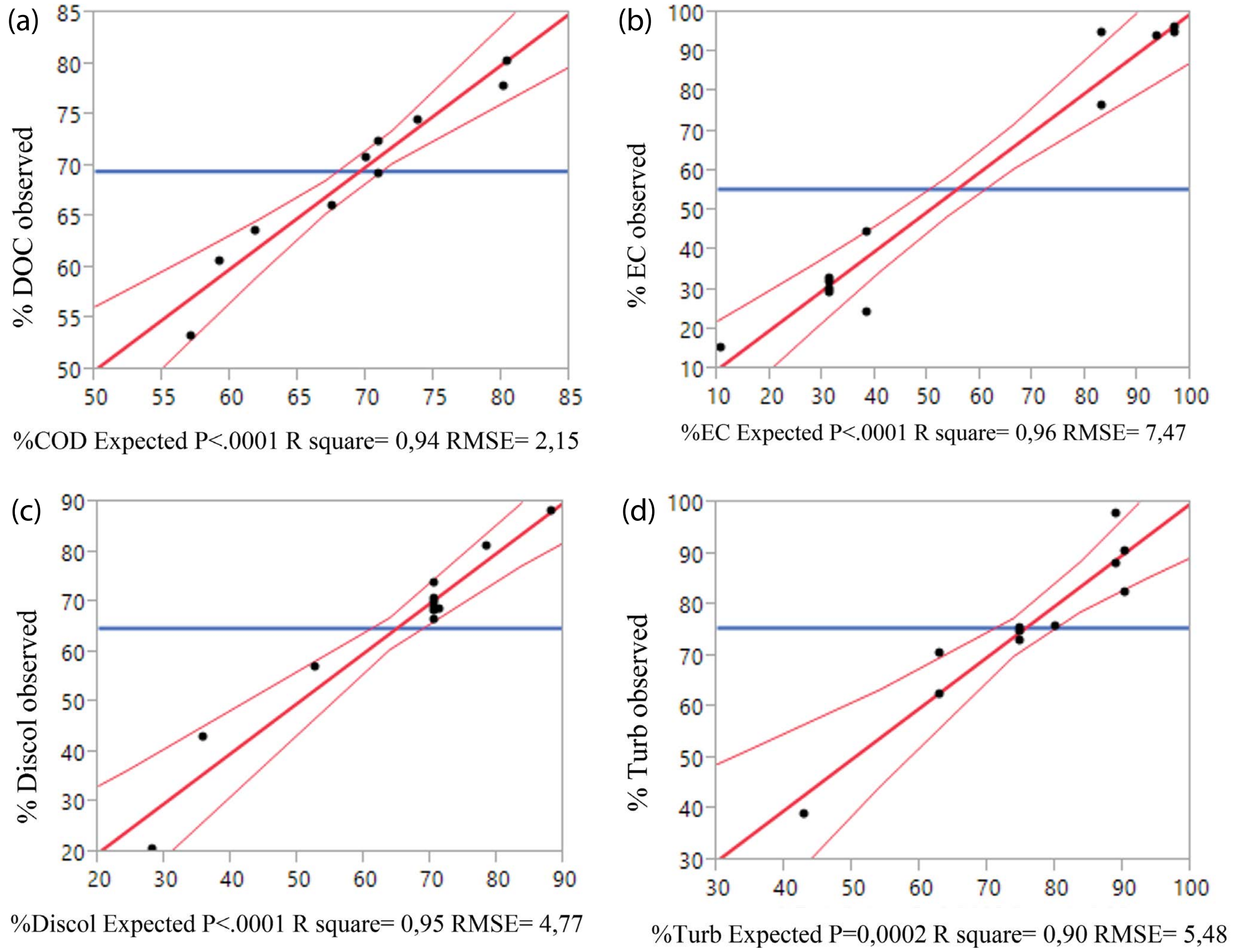

Fig. 4. Correlation between the experimental values and the planned values for the four responses: (a) COD reduction rate (%DCO), (b) EC reduction rate (%CE), (c) discoloration rate (%Discol) and (d) turbidity reduction rate (%Turb).

- Parameters whose concentrations before treatment are lower than the limit values of water intended for irrigation (represented in red in Fig. 7), these are *T*, pH, EC, NO_2^-, SO_4^{2-}, Cr, Pb, Zn, Cu, Fe, and Ni. The reduction of certain parameters in this category (EC, Cr, pH, Zn, Ni) improves the quality of the treated water.
- Parameters whose concentrations after treatment reach the limit values by the MBBR process (represented in green in Fig. 7), these are COD, BOD_5, and TSS with a reduction rate exceeding 70%.
- Parameters whose concentrations, after treatment by the MBBR process do not reach the limit values (shown in orange in Fig. 7). These are Cl^-, Na, Mn, and Cd.

Note that for the parameters which have no limit values associated with the use of water for irrigation (represented in b in Fig. 7), these are: Turb, Col, OD, NH_4^+, NO_3^-, PO_4^{3-} and magnesium, on the other hand, it significantly influences the rate of reduction of the other parameters with a rate of reduction which exceeds 60%.

Fig. 7 shows that the purifying power of the vertical flow filter using pozzolana as filter material is satisfactory with a percentage that exceeds 60% for most of the parameters measured except Zn (8%), Ni (12%), pH and Cd (17%), NO_3^- (21%) and Cr (42%).

The comparison of the results obtained (Fig. 7), of the characterization of the wastewater treated by the chosen purification process, with the limit values of the water intended for irrigation confirms those obtained by, such that, Saidi et al. [12] and Abou-elela and Hellal [31]: Municipal or domestic wastewater treated with a vertical flow filter can be reused in irrigation; however, slight disinfection is required to remove the residual pathogen in the treated effluent.

4. Conclusion

This work was carried out with the aim of developing an optimized process for treating part of the wastewater from the Ain Chock Faculty of Sciences in Casablanca and deducing the influence of the factors studied as well as their interaction on the purifying power. Of the wastewater treatment process. The modeling and optimization of the purifying power of the vertical flow filter planted with

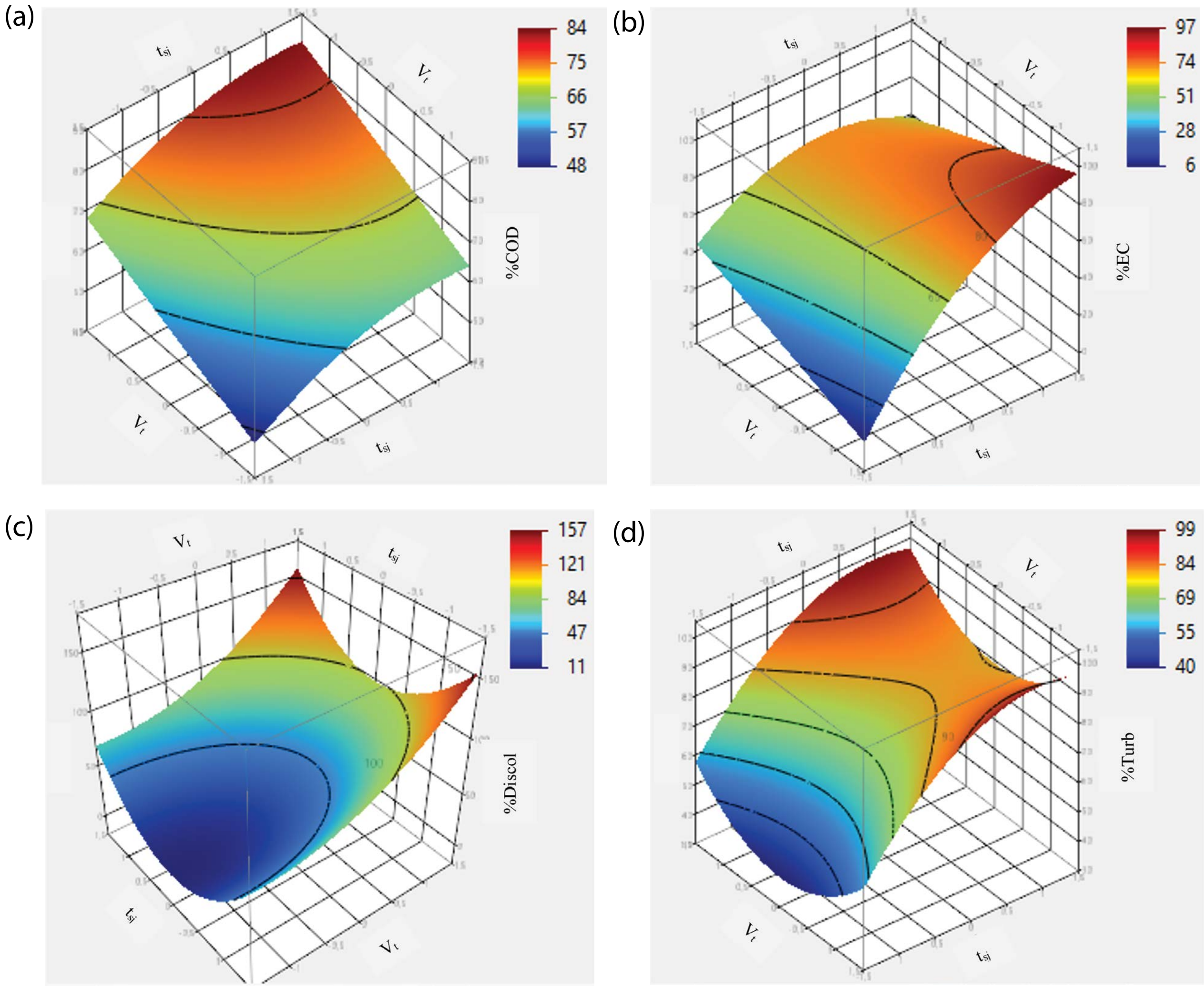

Fig. 5. Iso-response curves and response surfaces of the four responses: (a) COD abatement rate (%COD), (b) EC abatement rate (%CE), (c) discoloration rate (%Discol) and (d) turbidity abatement rate (%Turb).

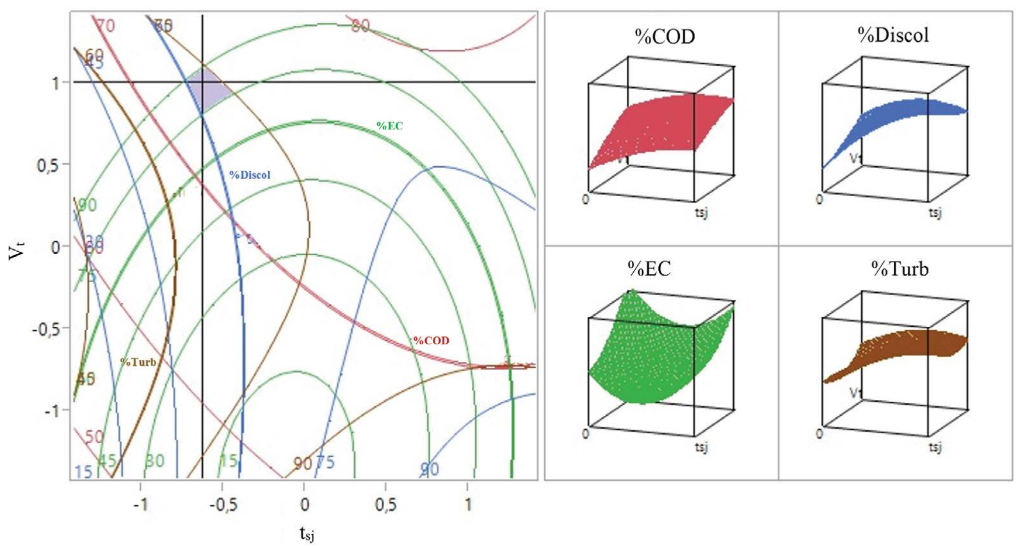

Fig. 6. Iso-response profiler.

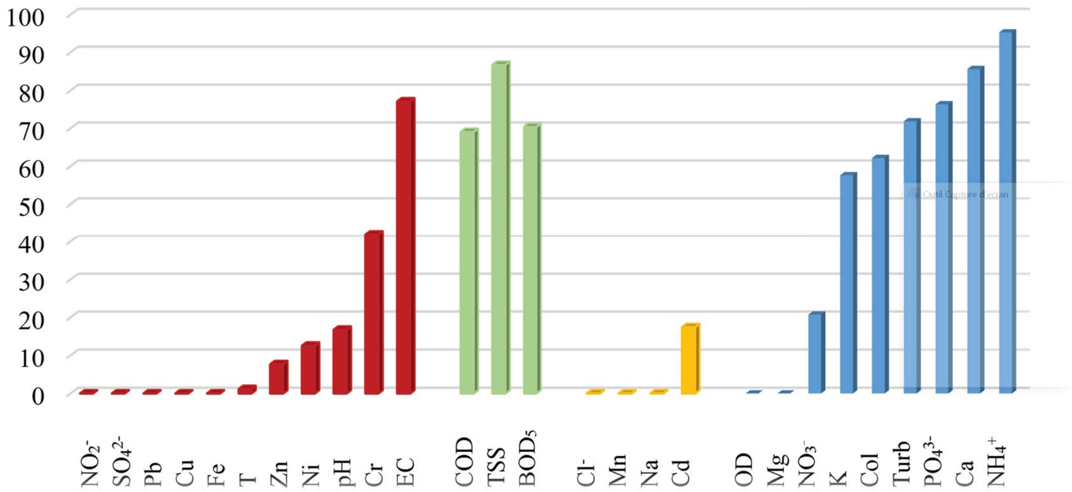

Fig. 7. Abatement rate of physicochemical and biological parameters after treatment.

Table 10
Values of the optimized parameters and its measured responses

Factor	Value of x	Answer	y calculated according to JMP	y measured experimentally
t_{sj} (mn)	806 (–0.63)	%COD	74	69
V_t (L)	2 (1)	%EC	80	77
–	–	%Discol	62	62
–	–	%Turb	73	71

reeds using pozzolana as filter material was carried out using the response surface methodology. According to this study, we find that: The effect of the residence time-thickness interaction of the pozzolana has a significant effect on the purifying power of the process chosen for the treatment of wastewater from our Faculty. Indeed, the optimal abatement yields of COD, EC, turbidity, and discoloration are successively 69%, 77%, 62%, and 71%, which were obtained for a residence time of 806 min, and a volume of water treated by the vertical filter of 2 L.

In perspective, an in-depth study of pozzolana must be carried out, in order to know the adsorption mechanism, and how this material is used for the purification of wastewater.

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