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Optimization of Kinetic Model for High Rate Algal Pond Design

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A B S T R A C T

The integrated system anaerobic reactor high rate algal pond (AR-HRAP) is an extensive treatment of the wastewater system which has many advantages, namely, a low occupation of land, possible energy self-sufficiency and a low cost of investment. In order to optimize the design of the system and adapt it to the regional context, we developed a design model based on the balance sheets of removing organic matter. This model is based on an engineering concept as taking into account the parameters of reactor design (flow rate, load, and retention time). However, this model ignores the night period during which photosynthesis does not take place; this can lead to oversize reactors. Therefore, this model was performed by introducing an operating coefficient ω_0 which represents the ratio of oxygen consumption in daytime and night. This model approaches and checked for retention time of 1.5 to 2 days in an anaerobic reactor and 3 to 4 days in the HRAP. The incoming raw organic loads to the system were in the order of 550 mg.l^{-1}. The comparative study of the theoretical and experimental results confirms the interest of such approach.

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INTRODUCTION[1]

Due to its geographical position, Morocco is characterized by a semi-arid climate over much of its territory. Water resources are therefore limited, especially as the growing needs of the population, along with drought conditions in recent years mean that the water deficit is becoming more acute.

The wastewater reuse could well after proper treatment, help reduce the deficit. Indeed, wastewater is a significant potential that will continue to grow in the future and that must be used, even in part, considering the savings that would result. Estimations are expected to reach 700 million m^3 by the year 2020 [1]. In the hypothesis of a recycling of all this volume, 50 000 hectares could be irrigated near the main cities in the country allowing a permanent production and supply of fresh vegetables[2]. Thus, important work has been initiated in all the institutions and government agencies to overcome this situation. One objective is to check the reliability of the natural low-rate wastewater treatment systems particularly waste stabilization ponds and some of their variants such as the high rate algal pond and the aerated lagoons.

High rate algal pond (HRAP) technology for urban wastewater treatment was developed in California 50 years ago and essentially consists of a shallow raceway reactor 0.3–0.4m in depth with mechanical mixing to promote algal growth [3]. Full scale applications exist all over the world, but the technology is especially suitable for arid and semiarid areas, such as the Mediterranean [4].

When the weather permits, the integrated system: anaerobic reactor - high rate algal pond (AR-HRAP) is an interesting alternative that supersedes conventional treatment systems, in view of its advantages. It requires less than half the land of conventional ponds. It uses solar energy efficiently for oxygenation and hence requires from 50 to 75% less electrical energy than mechanical aeration of sewage. It removes organic nitrogen compounds from sewage without producing nitrate and minimizes biosolids production. It provides advanced degrees of treatment at little or no addition cost to its low construction, operation, and maintenance costs.

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It is sufficiently nuisance-free and fail safe to permit integration into parks and recreational area [5]. It also allows a significant reduction not only of the influent organic matter, but also of nitrogen and phosphorus [6-8]. This system is usually combined with other ponds such as maturation ponds to meet effluent requirements prior to effluent discharge. Regarding its potential use of the algae, this technology has a substantial algal productivity (45 g m^{-2} d^{-1}) [9] which is equivalent to 80 tons of protein per year and can thus be a source of animal feed. This algal biomass can also be used in aquaculture or organic fertilizer in agriculture and also as a basis for cosmetics. However, recovery and harvest algae challenging by present technical and economic difficulties [10].

Our study aims to optimize and adapt this system to our regional context. It led to the development of a design model based on kinetics of organic matter removal.

Parallel with the approach of Oswald, which is based on the energy balance of algae [11], this model was developed based on an engineering concept which considers the design parameters of the reactor (flow, load, retention time). The modeling approach adopted is based on the study of the growth of the algo-bacterial biomass as the major component responsible for the pollution in HRAP [12].

However, this design model can lead to oversized reactors. Indeed, the γ parameter, which expresses the symbiosis algae-bacteria doesn't consider night time, during which photosynthesis doesn't occur [13]. Our contribution to this research is to improve performance of this design model by introducing operating coefficients heeding material balances during daytime and night time periods.

MATERIALS AND METHODS

Pilot plant

The pilot plant in which the tests were conducted is the same type as the one that was designed by Oswald at the University of California, with the difference that the anaerobic reactor in the first compartment is open air while it is covered in the second one. It positioned at Agronomic and Veterinary Institute Hassan II in Rabat (latitude 32° N, longitude 6°30 W) with an average light intensity of 500 Wm^{-2} during winter.

Wastewater

The system was fed by a domestic wastewater taken from a secondary collector of sewerage system in Rabat at Takadoum neighborhood.

Reservoir

With a capacity of 5 m^3, it serves as both storage and flow control.

TABLE 1. Raw wastewater characteristics

Parameters	values
COD ($mgO_2.l^{-1}$)	500 – 800
MVS ($mg.l^{-1}$)	480
O_2 dissolved ($mg.l^{-1}$)	0
Temperature (°C)	16 – 18
pH	7.2 – 7.8
Fecal coliforms (germs.100 ml^{-1})	$2.1x10^7$ – $6.6x10^7$

Anaerobic Reactors

There were two anaerobic reactors in series. They provide anaerobic treatment of 500 population equivalent. Their sections are circular with a diameter of 1.2 m and a depth of 5.70 m. This design allows for a perfect aerobiosis depth and aerobic zone with algae growth above. Thus prevent the development of unpleasant odors. It also enables varying residence time in the HRAP during testing.

High Rate Algal Pond

It has an area of 25 m^2 and a depth of 40 cm. Continuous stirring is provided with a paddle wheel driven by an electric motor with power of 0.5 KW. The movement of the wheel allows the paddles to push water in turns (4 turns min^{-1}) causing a flow of water with a velocity of 0.2 m s^{-1}. The study of the state of mixture by measuring dissolved oxygen, chemical oxygen demand, volatile suspended solids and algal activity at different points of HRAP [14] shows that this velocity ensures an excellent mix and maintains a permanent suspension of algal biomass.

Maturation pond

It has an area of 3 m^2 and a depth of 1 m. Its main function is to reduce the number of pathogens in the HRAP effluent. It also serves as a storage tank of the effluent providing a self-pumping of 5 to 8 hours depending on the residence time.

Wastewater treatment plant of Ouarzazate

It includes two wastewater treatment spinnerets: waste stabilization pond and HRAP. The two spinnerets are fed from an anaerobic pond. In this study we focus on the treatment sector by HRAP.

Anaerobic pond

It is covering an area of 844.8 m^2 and has a capacity of 1663.2 m^3 and 3 m in depth.

High Rate Algal Pond

This HRAP was designed for a residence time of six days in winter and three days in the summer. It is serpentine shaped. It includes 10 compartments with 80 m in average length, 3.70 m in width and 0.45 m in depth. Its volume is 1316 m^3, its surface is 3024 m^2. It is fed from the anaerobic pond with a flow of $3x10^{-3}$ m^3s^{-1}.

Analytical procedures

During testing, the physico-chemical characteristics of wastewater were followed before and after each treatment unit. For purified wastewater from the channel, the analysis of the physico-chemical characteristics is performed on a sample got rid of algae by centrifugation at 3000.g (g = 9.81 $m.s^{-2}$) for 10 minutes.

COD is an assessment of organic carbon based on oxidation during two hours of organic and mineral matter in hot acid medium (reflux heating). The oxidizing agent was potassium dichromate in excess, in the presence of silver sulfate as a catalyst, and Mercury sulfate as complexing agent for chlorides. The **e**xcess of $K_2Cr_2O_7$ is titrated with a solution of Mohr's salt (double salt of iron and ammonium sulphate) using ferroin as indicator. Results are expressed as described by Rodier [15].

Samples from raw sewage have undergone a preliminary settling for two hours, then filtered in vacuo on a filter ream using Millipore membranes with a porosity of 0.8 mm.

Basic model

It has been established from material balances in the integrated system. It is based on the study of the removal of organic matter [12].

The model equations are:

$$S_1 - S_2 = \frac{53.7}{D_H + 0.29} = \frac{9990 \times T_H}{54 \times T_H + 185} \quad (1)$$

$$A_2 = \frac{0.32}{D_H + 0.29} \quad (2)$$

$$X_2 = \frac{32}{D_H + 0.29} \quad (3)$$

Where A_2 (mg l^{-1}) is the algal biomass at HRAP outlet; X_2 (mg l^{-1}) is the bacterial biomass at HRAP outlet; T_H (d) is the residence time in HRAP; S_1 (mg l^{-1}) is substrate concentration of the influent outgoing AR and entering HRAP; S_2 (mg l^{-1}) is substrate concentration of the effluent leaving HRAP and D_H (d^{-1}) is the dilution ratio, $D_H = 1/T_H$.

DESIGN MODEL OPTIMIZATION

Modelization of Oxygen uptake in HRAP

To determine the operating coefficient which will link nocturnal and diurnal balance sheets, we consider Oxygen as a main factor. The question is: Does HRAP can be in a situation of critical oxygen deficit during night time?

The first step in our approach is to calculate the time at which this deficit will be achieved.

Assumptions and considerations

Variations in dissolved oxygen concentration and BOD are mainly due to biodegradation and re-aeration by surface. HRAP is assimilated to a waterway in steady state, which allows neglecting the diffusion terms.

The critical oxygen deficit

In a waterway**,** variation of organic pollution load L with time is governed by the equations of Streeter and Phelps [16]:

$$\frac{\partial L}{\partial t} = D_L \frac{\partial^2 L}{\partial x^2} - U \frac{\partial L}{\partial x} - K_1.L + L_A \quad (4)$$

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - U \frac{\partial c}{\partial x} - K_1.L + K_2.(c_A - c) + c_A \quad (5)$$

Where L (mg/l) is the ultimate BOD; L_A (mg $l^{-1}d^{-1}$) is the organic matter input; D_L (m^2d^{-1}) is long diffusion coefficient; K_1 and K_2 (per day) are respectively biodegradation and reaeration coefficients to the base e; c_A (mg l^{-1}) is the renewal rate of dissolved Oxygen and U (m d^{-1}) the mean flow velocity.

In our case, the system is stationary. The equation (5) becomes:

$$\frac{dc}{dt} = -K_1.L + K_2.(c_s - c) \quad (6)$$

c_s (mg/l) is DO concentration at 100% saturation wish is a function of temperature, salinity and atmospheric pressure.

If we consider that D (mg l^{-1}) is the oxygen deficit, so D = (c_s - c). Equation (6) becomes:

$$\frac{dD}{dt} = K_1.L - K_2.D \quad (7)$$

After integration in decimal base (K = 2, 3 k):

$$D = \frac{k_1 L_0}{k_2 - k_1}(10^{-k_1 t} - 10^{-k_2 t}) + D_0 10^{-k_2 t} \quad (8)$$

k_1 and k_2 are respectively estimated using the equations developed by O'Connor and Dobbins [17]:

$$k_1(T) = k_1(20°) \times 1.047^{(T-20)} \quad (9)$$

$$k_2(T) = k_2(20°) \times 1.016^{(T-20)} \quad (10)$$

Equation (8) provides an optimum corresponding to the critical time t_c, time after which the quantity of dissolved oxygen is minimal:

$$t_c = \frac{1}{k_1(f-1)} \log\left[f(1-(f-1).\frac{D_0}{L_O}) \right] \quad (11)$$

Where: $f = \frac{k_2}{k_1}$.

Discussion: Due to alga-bacterial synergy of HRAP, its operating mode changes in night. Indeed, during the night, the photosynthetic activity ceased, while bacterial degradation continued its activity. The only sources of oxygen available are aeration by agitation and aeration by superficial absorption.

The risk of a possible anaerobic mode during the night must be rejected. Indeed, because of the presence of facultative bacteria, anaerobic mode is governed by other equations of organic matter degradation and this is greatly affected the assumptions used in the development kinetic model.

The calculation of the critical time after which the channel reaches this mode gives a value of 1.06 days, well above the night time period. Therefore, it was concluded that theoretically nocturnal sources of oxygen are sufficient to avoid anaerobic conditions during the night.

This conclusion is confirmed by a study conducted at the pilot plant of Rabat, provided we avoid overconcentration of algae [18].

Operating coefficient ω_0

The operating coefficient is defined ω_0 as the ratio of the amount of oxygen consumed during the night that consumed during the day and we consider the most adverse conditions where oxygen produced by algae corresponds to the strict anaerobic condition required by bacteria.

The algae-bacteria symbiosis is a HRAP characteristic which is activated during daytime in the presence of light. The reaction generating process was established by Oswald:

$$6H_2O + 6CO_2 \xrightarrow[light]{algae} C_6H_{12}O_6 + 6O_2 \quad (1)$$

Biodegradation of organic compounds by microorganisms occurs in the presence of nutrients according to the following reaction:

$$C_8H_{12}N_2O_3 + 3O_2 \rightarrow C_5H_7O_2N + NH_3 + 3CO_2 + H_2O \quad (2)$$

Note that at night only the reaction (2) occurs. If K_P and K_D are respectively the equilibrium constants of photosynthesis reaction and substrate degradation reaction, the law of mass action and matter conservation allow deducing that:

$$\omega_o = \frac{[O_2]_{night}}{[O_2]_{day}} = \frac{1}{2}\frac{K_D}{K_P} \quad (12)$$

The equilibrium constants of biological reactions are generally ranging from 0.4 to 0.7. Roques recommends taking a value of 0.6 [19], one hand because bacterial activity is very high in conditions where there is no inhibition and on the other, Oswald concluded that the photosynthesis reaction is very active. Therefore, we can consider: $K_P = K_D = 0.6$. In the stated conditions: $\omega_0 = 1/2$.

Introduction of the operating ratio in the material balance

We consider the equations of basic model:

$$A_2 = \frac{b_H}{D_H + a_H} \quad (13)$$

$$S_1 - S_2 = \frac{\alpha}{\gamma} \cdot \left(\frac{b_H}{D_H + a_H} \right) \quad (14)$$

D_H the dilution rate in the HRAP (d^{-1}) is given by the relation: $D_H = Q/V$ where Q is inflow in the pond and V its total working volume.

α, the biomass substrate conversion rate is given by the equation:

$$\alpha = -\frac{dS}{dt} \Big/ \frac{dX}{dt}$$

γ: parameter linked in growth of bacterial and algal biomasses. It's the ratio of the amounts of CO_2 and O_2 and reflects the symbiosis between the two species. It's expressed by the following relations:

$$\gamma = \frac{dA}{dt} \Big/ \frac{dX}{dt}$$

a_H and b_H are kinetic constants.

In the absence of light, photosynthesis stops during the night time, so we have the following balances:

$$\left.\frac{d(VX)}{dt}\right)_{acc} = Q.(X_1 - X_2) + \left.\frac{d(VX)}{dt}\right)_{reac} \quad (15)$$

$$\left.\frac{d(VS)}{dt}\right)_{acc} = Q.(S_1 - S_2) + \left.\frac{d(VS)}{dt}\right)_{reac} \quad (16)$$

The ratio of oxygen amounts consumed overnight and during the day is related to the activities of bacterial biomass during both daytime and nighttime periods. The operating coefficient ω_0 can so be expressed as follows:

$$\frac{dX}{dt}_{night} = w_o . \frac{dX}{dt}_{day} \quad (17)$$

Balances (15) and (16) become:

$$D_H(X_1 - X_2) + w_o . \frac{dX}{dt}_{Day} = 0 \quad (18)$$

$$D_H(S_1 - S_2) - w_o . \alpha . \frac{dX}{dt}_{Day} = 0 \quad (19)$$

The elimination kinetics of the substrate in HRAP allows establish the following relation:

$$(S_1 - S_2) = \frac{\alpha . w_o}{\gamma} \left(\frac{b_{NH}}{D_H + a_{NH}} \right) \quad (20)$$

b_{NH} and a_{NH} are the new kinetic constants of the model.

To determine b_{NH} and a_{NH}, Table 2 was used [10]. Each experimental value shown in this table is the average of a series of measurements for three months.

TABLE 2. Experimental organic COD load in the HRAP of Ouarzazate Plant.

T_H (days)	COD (mg/l)	
	S1 (mg l^{-1}), AR	S_2 (mg l^{-1}), HRAP
5.24	210	102
3.14	228	142
4	219	112
4 .5	220	116

The following equation is exploited:

$$\frac{1}{S_1 - S_2} = \frac{\gamma}{\alpha . w_o . b_{NH}} . D_H + \frac{\gamma}{\alpha . w_o} . (\frac{a_{NH}}{b_{NH}}) \quad (21)$$

We deduce: a_{NH} = 0.145 d^{-1}; b_{NH} = 0.64 mg l^{-1}.

As a result, the kinetic model of algal growth in HRAP becomes:

$$\frac{dA}{dt} = -0.145A + 0.64 \quad (22)$$

The inverse ratio of (S_1-S_2) as a function of D_H is shown in Figure 1.

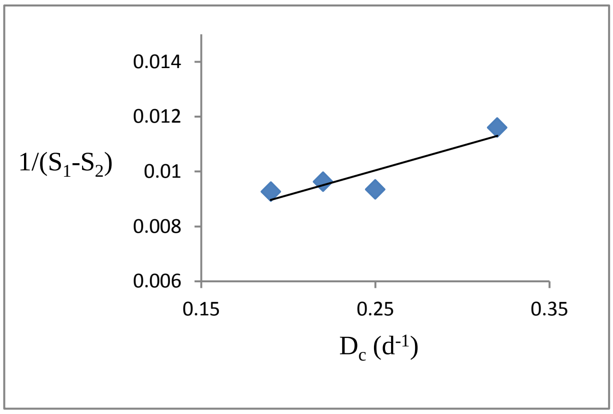

Figure 1. 1/(S_1-S_2) depending on D_H in the HRAP of the treatment plant of Ouarzazate.

The first order of growth model establishes the following relations:

$$S_1 - S_2 = \frac{53,7}{D_H + 0,145} = \frac{9990 \times T_H}{27 \times T_H + 185} \quad (23)$$

$$A_2 = \frac{0.64}{D_H + 0.145} \quad (24)$$

$$X_2 = \frac{64}{D_H + 0.145} \quad (25)$$

$$S_2 = S_0 - \left(\frac{9990 \times T_H}{27 \times T_H + 185} + \frac{1000 \times T_A}{1.73 \times T_A + 1.7} \right) \quad (26)$$

Where T_A is the residence time in AR; S_0 is substrate concentration in raw influent.

DESIGN MODEL AUDIT

Audit by residence times

We conduct this audit by comparing different residence times: experimental T_{exp}, according to Oswald T_{OS}, calculated through our design model T_{DM}, calculated by model without taking into account operating coefficient T_M and optimal residence time wish is calculated from the oxygen balance in the HRAP. Results are summarized in the Table 3.

TABLE 3. Experimental and theoretical residence times in HRAP of pilot plant (IAV, Rabat).

Test	R* (%)	T_A** (d)	T_{exp} (d)	T_{DM} (d)	T_{OS} (d)	T_M (d)	T_{opt} (d)
1	52,5	3	6	3,75	2,83	3,16	2,76
2	38,9	3	3	3,74	2,77	3,22	2,64
3	68,8	2	4	3,54	3,25	3,22	4,08
4	57,6	2	2	3,53	3,15	3,56	1,5
5	61,2	1,5	4	4,26	4,08	4,12	3,87

* Carbon pollution abatement yield in HRAP.
** Experimental residence time in Anaerobic Reactor

Audit by comparison of organic load abatements

As shown in Table 4 below, organic loads at the output of HRAP calculated by our model are closer to measured values than those calculated by the initial model. Therefore, for residence times in HRAP from three to four days, the purifying efficiencies provided by the fitted model are more reliable than those provided by the initial model.

TABLE 4. Theoretical and experimental organic load abatements in HRAP of pilot plant.

T_H (d)	S_1 (mg/l)	S_{2M} (mg/l)	S_{2DM} (mg/l)	S_{2exp} (mg/l)
3	287	201	174	176
3	270	184	158	164
3	262	177	150	162
4	253	153	140	130

S_1: organic load entering the HRAP; S_{2M}: organic load to the output of HRAP calculated by M; S_{2DM}: organic load to the output of HRAP calculated by DM; S_{2exp}: organic load measured to the output of HRAP.

Influence of operating coefficient on the performance of HRAP

In order to investigate the influence of operating coefficient related to the oxygen in HRAP, the performance of algal pond before and after introducing the coefficient in the balance sheets should be compared. Thus, following the same approach, and according to the balance sheet (14) the following relation is established:

$$S_1 - S_2 = \frac{53.7}{D_H + 0.29} = \frac{9990 \times T_H}{54 \times T_H + 185} \quad (27)$$

For a load S_0 set at 550 mg/l, and varying the residence time in anaerobic reactor T_a, curves representing the variation of performance versus the residence time in the algal pond T_{HR} are shown in Figures 2 and 3.

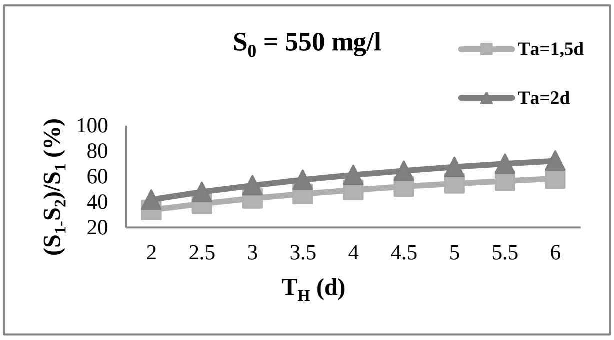

Figure 2. variation in performance depending on the residence time T_H before introduction of ω_0.

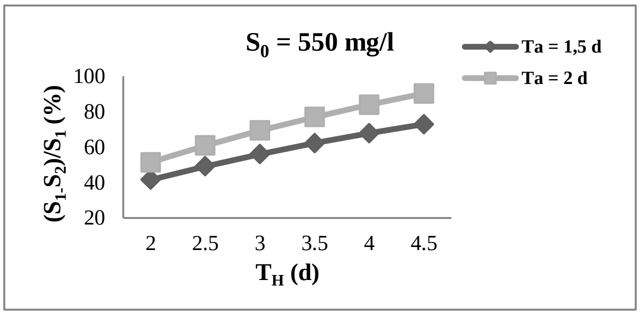

Figure 3. variation in performance depending on the residence time T_H after introduction of ω_0.

RESULTS AND DISCUSSION

The joint review of all of the results allowed us to propose the following conclusions:

Analysis obtained from Figures 2 and 3 showed that the introduction of the operating coefficient in the mass balance sheets enables to achieve high removal rates and above all, the projected model is closer to experimental results. For example, considering the most residence times indicated for design, namely T_A = 1.5 d and T_H = 4 d, the removal rate of the substrate given by Figure 2 is 50%, while that given by Figure 3 is 68%.

The approach for the development of the model is an approach based on the principle of conservation of mass in a continuous flow reactor, the equations considered for the reaction mechanisms have been developed with justified and based assumptions.

The established model takes into account the reactor design parameters (load, speed, residence time). It takes also into account biological phenomena in the algal reactor, including the symbiosis between algae and bacteria, which is represented by the parameter γ.

This model allows, from the removal efficiency in HRAP imposed by the set of specifications and from the incoming organic load, to calculate the residence time in the algal pond, and hence to size the reactor.

By analyzing Table 3 we can see that the residence times calculated by the design model, the basic model and that proposed by Oswald are in the same order of size, despite the difference in approach between the three models. However the model of Oswald based on the energy balance of algae provides residence times that tend to deviate from the optimal value for low residence times, i.e. 2 days in AR and 4 days in HRAP. Contrariwise for residence times of about six days the values approach the optimum time. This can be explained by the design approach that is based on the maximum production of algae in conjunction with the reduction of the carbonaceous matter.

Regarding the values calculated by the design model it is found that they are near the optimum for residence time values of about four days. The kinetics proposed by highlights the influence of the passage time in the anaerobic pond, allowing the torque value (1.5 d; 4 d) which provides a passage time substantially equal to the optimum and experimental time.

The values calculated by the design model confirm that for high removal efficiencies (Tests 3 and 5) the residence time in the algal pond approaches the optimized one for efficient removal of BOD.

CONCLUSIONS

The development of this design model mainly based on the kinetics of elimination of organic matter and which takes into account both the alga-bacterial synergy and the difference of day and night mode is justified by a sake of optimization in order to have a reliable tool for sizing the high rate algal Pond especially and the integrated AR-HRAP system in general.

The comparative study of theoretical and experimental results confirms the relevance of the approach.

Through this work, we hope to have made our contribution to the optimization of the design of promising method for waste water treatment: AR-HRAP, which design is adapted to the North African context.

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Persian Abstract

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چکیده

سیستم تلفیق شده ی برکه جلبکی با راکتور بی هوازی بانرخ بالا، یک سیستم تصفیه فاضلاب گسترده با مزایای فراوان، اشغال فضای کم، امکان خود کفایی در مصرف انرژی و سرمایه گذاری اندک است. به منظور طراحی بهینه سیستم و آداپته کردن آن به مشخصات محلی، یک مدل بر مبنای صفحات تعادل جهت حذف مواد آلی ایجاد شد. این مدل بر مبنای مفهوم مهندسی که پارامترهای طراحی راکتور(دبی، بارآلی، زمان ماند)رادرنظر می گیرد ایجاد شده است. از آنجائیکه این مدل فتوسنتز را که در طول شب اتفاق نمی افتد نادیده می گیرد، باعث افزایش اندازه راکتور می گردد. بنابراین این مدل به وسیله معرفی یک ضریب عملیاتی ω_o که نسبت مصرف اکسیژن در شب و روز را نشان می دهد اصلاح شده و کار می کند. این مدل برای زمان ماند ۱/۵ تا ۲ روز در راکتور بی هوازی و ۳ تا ۴ روز در HRAP بررسی و چک شد. مقدار مواد آلی خام ورودی در این سیستم۵۵۰mg/L بوده است.مطالعه مقایسه ای بین نتایج تئوری و عملی، چنین رویکردی را اثبات کرد.