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Wastewater treatment performances and hydrodynamic of a real-scale airlift HRAP

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ABSTRACT

In this study, wastewater treatment performances as well as the hydrodynamic state of an experimental high-rate algal pond (HRAP) were studied. The hydrodynamic study revealed that the mean water velocity in the HRAP is equal to 0.15 m/s. Based on different literatures, this value is recommended for a balanced growth between microalgae and bacteria, and hence, for a good functioning of such a system. The analysis of both meteorological and physicochemical data showed the influence of climatic condition on the seasonal algal productivity and the weak treatment performances of the HRAP. The low removal efficiencies for both BOD_5 and COD may be explained by the fact that this experimental HRAP lacks an algal harvesting system at the end of the treatment process. However, the recovery of the biomass at the exit of the system increased the removal efficiencies of both COD and BOD_5 by more than 80%.

Keywords: HRAP; Hydrodynamic; Wastewater treatment; Water quality; Modeling; Biomass removal

1. Introduction

The lack of water resources in semi-arid climate regions represents a major economic and social issue. For this reason, wastewater treatment techniques are very important and should receive even more attention in order to protect our natural resources for future generations. Wastewater treatment is a process where contaminants are removed from wastewater to produce solid or stream waste that can be discharged in the environment [1,2]. Secondary effluents from wastewater treatment plant still containing high concentration of nutrients have been identified as the main cause leading to eutrophication in natural water bodies [3–5]. Thus, before discharging, the effluents must receive appropriate treatment [6,7]. Tertiary biological treatments such as high-rate algal pond (HRAP) are considered the most environmentally compatible and the least expensive of both chemical

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and physical wastewater treatment methods. These kinds of processes use micro-organisms that have the ability to grow in N- and P-rich water such as wastewater and to efficiently accumulate nutrients and toxic metals from wastewaters [8]. Algae are already used all over the world to treat wastewater, but it is mostly applied on small-scale systems.

A HRAP is a shallow (0.2–0.5 m deep) and open raceway pond used for the treatment of domestic, industrial, and agricultural wastewaters [9]. Mixing is provided either by a paddlewheel or by an airlift system to reach an optimal mean water velocity of 0.15–0.3 m/s [10]. Raceway configuration may be in a single or multiple loops separated by central dividing walls. In some cases, CO_2 is added into a countercurrent gas pump creating a turbulent flow in the pond [11]. HRAP are designed to enhance algal growth by allowing maximum light penetration (shallowness) and by keeping the cells in suspension (mixing) to be periodically exposed to light. They usually operate with a relatively short retention time (4–10 d) and use reduced surface area. HRAPs are by far the most cost-effective systems used for wastewater treatment and are very efficient in capturing solar energy [12]. This system is considered as a photosynthetic reactor where microalgae live together with heterotrophic bacteria in a symbiotic interaction: the microalgae produce oxygen via photosynthesis which in turn is used by the bacteria that degrade organic matter present in wastewater. This degradation process produces carbon dioxide (via respiration) and nutrients which help to sustain the algal productivity within the system.

The water mixing in a HRAP is a very important physical parameter. Most of the studies on HRAP deal with ponds aerated by a paddle wheel. The airlift is a system that injects compressed air into a liquid via an immersed membrane diffuser and presents the main advantage of aerating and mixing at the same time as well as space saving, better treatment performances, and low energy consumption [13]. Besides the positive effect on the photosynthetic activity of algal biomass, the airlift improves the oxygenation of the system by enhancing the oxygen transfer from the atmosphere to the water [14].

To evaluate the effectiveness of a HRAP it is very important to set the adequate hydrodynamic conditions, and thus, to acquire hydrodynamic data through physical modeling and/or computational fluid dynamic (CFD) modelling. CFD analysis of raceway ponds is a subject that has not been extensively reported in the recent literature, especially for HRAP aerated by an airlift [15]. The mixing performances can be determined by different hydrodynamic factors such as water velocity, shear stress, and dead zones [16]. A uniform mixing is required to achieve a high algal productivity by ensuring algal cells to frequent exposure to light, avoid algal settling, and homogenize nutrients distribution in the pond [17].

The algal productivity in a HRAP may be affected by various physical and chemical parameters such as light availability, temperature, pH, CO_2, dissolved oxygen, nutrients, zooplanktons grazers, and pathogens. In fact, when nutrients are available, photosynthesis increases with increasing light intensity, and the maximum growth rate is reached at the light saturation point [18]. Algal productivity also increases with increasing pond temperature up to an optimum temperature above which the growth rate starts to decrease [19]. The optimal temperature for most algal species grown under optimal nutrients and light conditions vary between 28 and 35°C [20]. Pond water pH depends on algal productivity, algal/bacterial respiration, and ionic composition of the culture medium. The optimal pH of many freshwater algae has been shown to be around 8 [21]. The availability of CO_2 in a HRAP depends on heterotrophic oxidation of organic matter by bacteria. But, in domestic wastewater, carbon content is usually insufficient to fully support optimal algal production (3–7 C:N ratio in wastewater vs. 6–15 C:N in algal biomass) [22]. The N to P ratio of algal biomass can vary from 4:1 to 40:1 depending on the species and nutrients availability in the culture medium, and thus, high algal productivity may still be achieved even at low N:P ratio in HRAP's water [23]. Moreover, the presence of fungi, viruses, and zooplankton can significantly reduce algal concentration in HRAP within just a few days and trigger changes in algal cell structure, diversity, and succession [24,25].

Microalgal biomass usually form stable suspensions in growth medium due to their negative surface charge [26]. Thus, the flocculation of microalgae is sensitive to pH of culture suspension. The increase in pH may also influence the charge of microalgal cells and transform the existing form of metal cations present in the water due to their hydrolysis [27]. Algae growing in the HRAP assimilate nutrients, and thus the harvesting of this algal biomass removes the nutrients from wastewater [28,29]. During this aerobic treatment process, the produced biomass may be considered as a potential source of protein, biochemical, fertilizer, etc., and the result is a biologically treated wastewater with a relatively low BOD [30].

The present study aimed to evaluate the hydrodynamic state of the HRAP of the wastewater treatment of Sidi Bou Ali (Sousse, Tunisia) and to determine the treatment performances of this system. In fact, the mean water velocity in a HRAP is a key parameter that may directly influence algal productivity, and hence, treatment performances. In addition to that, the weekly analysis over a 1-year period (from July 2012 to June 2013) of various physicochemical parameters such as chemical oxygen demand (COD), biological oxygen demand (BOD_5), nutrients, pH, and climatic condition helped to better understand the functioning of the HRAP.

2. Methods

2.1. Description of the HRAP

The wastewater treatment plant of Sidi Bou Ali (Sousse, Tunisia) handle a volume of 500 m^3/d of wastewater. This raw wastewater goes through a primary treatment, then an anaerobic stage, and after that, 400 m^3/d are treated in facultative ponds and the 100 m^3 left are directed toward the pilot HRAP. This HRAP is 150 m long, 4.6 m wide, and 0.5 m deep. A central concrete wall divides the pond into two symmetric parts (raceway design). This dividing wall is 0.2 m thick and 141.6 m long (Fig. 1(a)).

The airlift has a height of 2 m and located in a pit below the bottom of the pond. This design enables a directed circulation of the treated water. The airlift is made up of two parts: a downcomer receiving the non-aerated water mass and a riser where the air is injected through eight membrane diffusers allowing the reintroduction of the water mass into the HRAP. These two compartments are separated by a 0.1 m thick dividing wall which stops at 0.3 m above the bottom of the airlift reactor in order to allow the movement of the water mass from the downcomer to the riser (Fig. 1(b)).

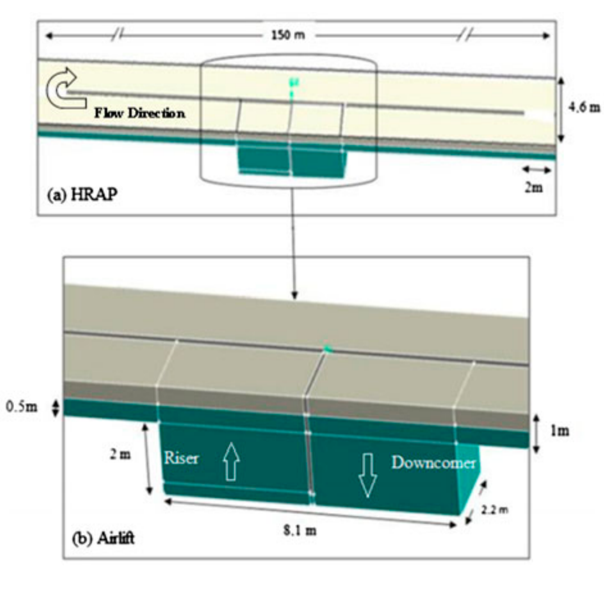

Fig. 1. Geometry of (a) HRAP and its (b) airlift.

2.2. Hydrodynamic study

2.2.1. Mesh and boundary conditions

A hydraulic study of the channel was conducted by CFD. This study enabled to estimate the water flow velocity everywhere in the HRAP. To do this, the channel was modeled using the software FLUENT, and the analysis of the fluid dynamic provided interesting results on gas retention in the airlift and water velocity in all the channel.

The computational domain was created using the software GAMBIT provided with FLUENT, which enabled the meshing of the domain into two- or three-dimensional geometric shapes. The meshing was performed with 700,000 grids in total and was tighten up in the airlift zone (322,000 hexagonal shaped grid) and the water flow deviation zones (Fig. 2). Therefore, the airlift represents only 7.4% of the total system's volume and about 43% of the total meshing of the domain. The simulated water velocity is the average of all the velocities obtained in each grid as given in the following equation:

$$\bar{V} = \frac{1}{j}\sum_{i=1}^{j} V_i \tag{1}$$

The air injection is modeled as an entry with a variable speed and an air volumetric fraction of 1. All water velocity components at the entry of the diffusers are assumed to be equal to zero. For the modeling of the free surface, a large volume of air was added just above the domain in order to avoid convergence issues. The dividing walls of both the airlift reactor and the HRAP were considered as standard walls.

2.2.2. Governing equations of the HRAP model

In order to study the flow in our domain and the different thermodynamic quantities of this flow, a simulation model and the Euler–Euler multiphase were used. The movement of a water mass consists of two processes: transport and diffusion [31]. Equations governing this problem can be obtained by the Favre decomposition as given in Eqs. (1) and (2) [32,33].

$$\frac{\partial(\bar{\rho}\tilde{u}_j)}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial(\bar{\rho}\tilde{u}_j\tilde{u}_i)}{\partial x_j} = -\frac{\partial\bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(\bar{\tau}_{ij} - \overline{\rho u''_i u''_j}) \tag{3}$$

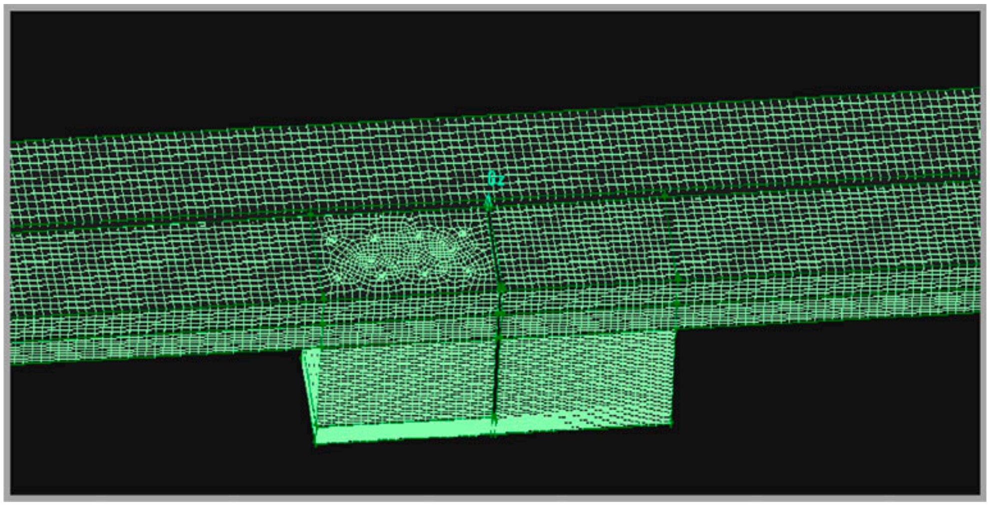

Fig. 2. Meshing of the domain of the HRAP using Gambit/Fluent.

Unlike other models, the Euler model solves equations of transport and continuity for each phase. The coupling is then achieved through pressure and heat transfer coefficients between phases. In this study, a three-dimensional simulation was performed for an air–water multiphase system. The turbulence generated in the system is modeled using the turbulence model *k-ε* derived from the Reynolds Averaged Navier Stokes (RANS) which is appropriate in the case of flows with fully developed turbulence (high Reynolds number). The air–water interaction phases are of a Morsi–Alexander type since it is the most accurate and complete.

The *k-ε* model is a semi-empirical model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The model transport equation for k is derived from the exact equation, while the model transport equation for ε was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart. The turbulence kinetic energy (k) and its rate of dissipation (ε) are obtained from the equations given in Eqs. (3) and (4), respectively.

$$\frac{\partial}{\partial x_i}(\rho k \tilde{u}_i) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\mathrm{Pr}_k}\right)\frac{\partial k}{\partial x_j}\right) + \tilde{P} + \tilde{G} - \bar{\rho}\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_i}(\bar{\rho}\varepsilon\tilde{u}_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\mathrm{Pr}_s}\right)\left(\frac{\partial \varepsilon}{\partial x_j}\right)\right] + C_{1s}\frac{\varepsilon}{k}(\tilde{P} + C_{3s}\tilde{G}) - C_{2s}\bar{\rho}\frac{\varepsilon^2}{k} - R \tag{5}$$

2.2.3. Physical tracing for flow rate determination

A floating body having a density close to the water was used as a physical tracer because of the complexity of the medium (mixed liquor with biological suspended solids: microalgae and bacteria). Thus, to measure the water flow, the time taken by the tracer to travel from point A to point B of a known distance was measured using a stopwatch. This step was repeated for different airflow rate within the airlift, and the mean experimental free surface water velocities for each airflow rate was determined as the average velocity of 10 measurements as given in Eq. (6) below. For each different airflow, the system was allowed to reach a stationary flow before starting the experiment.

$$\bar{u} = \frac{1}{k}\sum_{i=1}^{k}\frac{d_i}{t_i} \tag{6}$$

2.3. Physicochemical analysis of wastewater

The physicochemical study of the HRAP was conducted over a period of twelve months going from July 2012 to June 2013. Water samples at the entry and exit of the system were collected weekly from the top layer of the pond (between 0 and 20 cm deep). In addition to that, a small-scale harvesting system was installed *in situ* to harvest microalgae from treated wastewater at the exit of the HRAP. A volume of 1 m^3 of wastewater was transferred in a high-density polyethylene conical-shaped tank. The water pH was adjusted to 11.5 by adding 1 g/L of sodium hydroxide, and the mixture was left to settle for about 2 h. The biomass was then recovered for drying and further processing and samples of the remaining water were collected. All samples were kept at 4˚C in a cooler and brought to the laboratory within an hour for chemical analysis.

Average monthly temperatures, insolation, and rainfall data were collected from the official website of the National Tunisian Institute of Meteorology. The pH was determined using a Mettler-Toledo pH meter. Total suspended solids (TSS), COD, BOD_5, ammonium, and phosphates were determined by standard analytical methods as described in Rodier et al. [34].

3. Results and discussion

3.1. The water flow in the HRAP

The water mass circulation is controlled by the continuous and quasi-isotherm ascension of the air bubbles from the eight diffusers of the airlift providing the necessary energy for a homogenous water circulation in the HRAP [35,36]. The water mass velocity in this tertiary treatment system plays a very important role in the quality of the produced effluent. Indeed, an appropriate water velocity will avoid sludge accumulation and emission of bad odors, and also will balance the bacterial growth in respect to the microalgae productivity within the system.

It can be seen from Fig. 3 that the mean water velocity is high close to the airlift and extremely reduced near the dividing walls and the corners of the pond. These areas with no water movement are called "dark zones" and could be problematic for the hydrodynamic of the HRAP and the water quality of the treated effluent. Thus, Fig. 3(b) clearly shows that an increase in the rate of the air injected (from 5 to

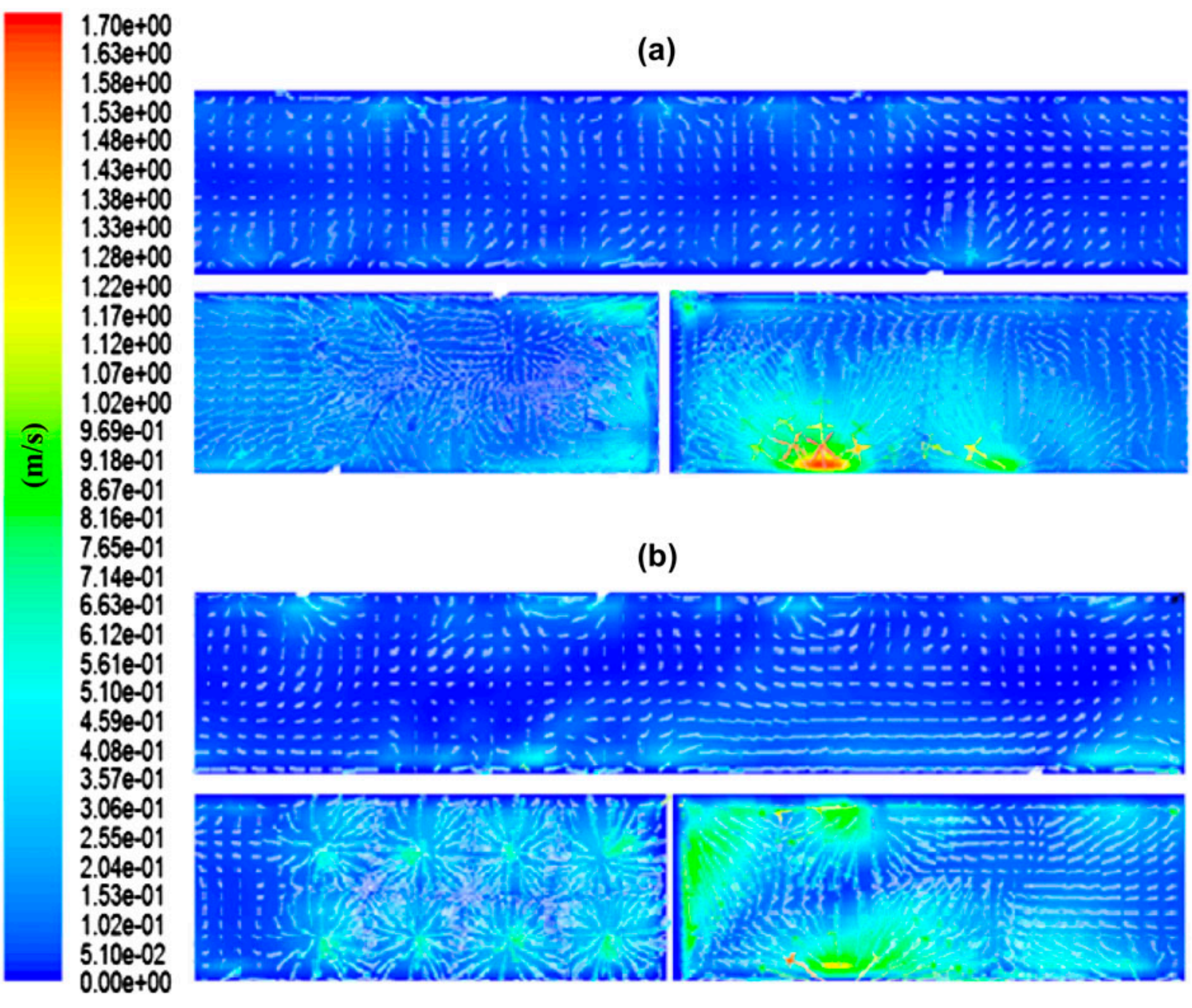

Fig. 3. Simulation of the mean water velocity (m/s) in the HRAP for an injected air rate of (a) 5 N m^3/h and (b) 25 N m^3/h.

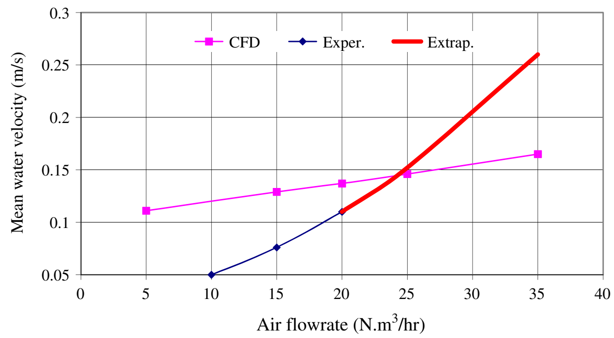

Fig. 4. Experimental and CFD mean water velocity vs. injected air rate in the HRAP.

25 N m^3/h) by the airlift will solve the problem and totally get rid of these dark zones near the dividing wall and the corners of the HRAP.

In fact, one of the most important parameter to control in the HRAP is the mean water velocity that was determined for each air injection rate. It can be seen from Fig. 4 that the mean water velocity in the system increases as the air rate increases. The pink line in this same figure corresponds to the mean water velocity in the HRAP obtained by FLUENT, and the blue one with its extrapolation in red is the experimental velocity measured *in situ* at the water surface. The airlift of the HRAP of the wastewater treatment plant of Sidi Bou Ali is currently working at 25 N m^3/h, and the important conclusion to draw from this figure is that the intersection between the experimental and the model curves corresponds to the air flow rate injected by the airlift and indicates a mean water velocity in the pond of about 0.15 m/s. Based on different literatures, this value of 0.15 m/s is the recommended mean water velocity for such a system to obtain a balanced growth between the algae and the bacteria. In addition to that, and for each 1 N m^3/h of air, the increase in the mean water velocity in the HRAP is equal to 0.0018 m/s.

3.2. Environmental and physicochemical parameters

The monthly average water temperature ranged from 12.5 to 28°C. The highest temperatures occurred in the summer season (July and August) and the lowest ones were observed during the winter (December and January). Similarly, the quantity of solar radiation exhibits the exact same trend as the water temperature shown in Fig. 5. Contrarily, the highest precipitation occurred in the winter (59 mm) and the lowest in the summer (1–7 mm), with an average rainfall of about 30 mm in the autumn and spring months. It can be seen from this same figure that the HRAP's water color is much less intense (brown yellow) during the winter period than for the rest of the year. However, the months where the water in the HRAP gets greener, corresponding to a high microalgal density, are observed around October (autumn) and May (spring).

Fig. 6 shows that high TSS values correspond to high algal density and vice versa. The relatively low TSS values observed in December and January may

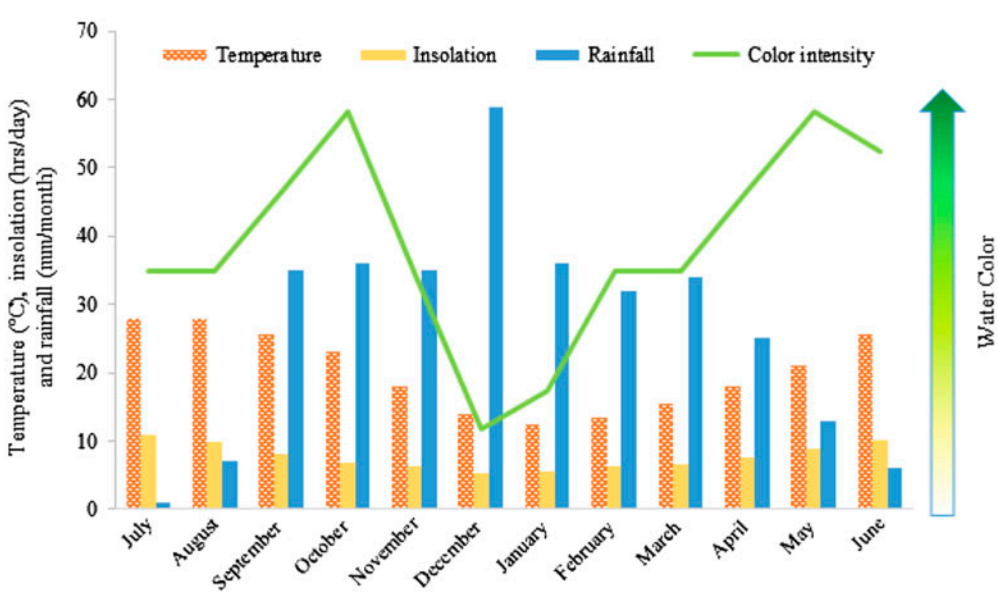

Fig. 5. Monthly average temperature, insolation, rainfall in Sidi Bou Ali (Tunisia) and HRAP's water color intensity.

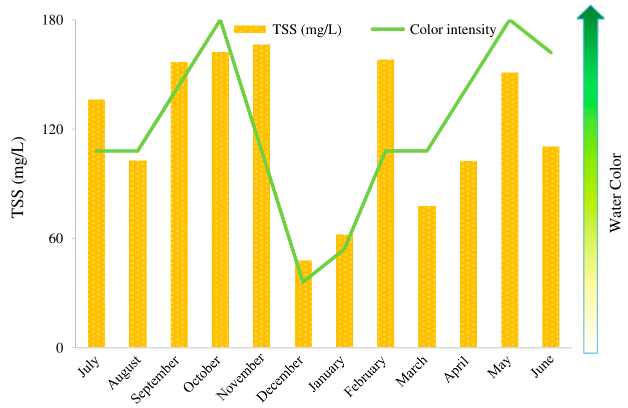

Fig. 6. Monthly average TSS and water color intensity in the HRAP.

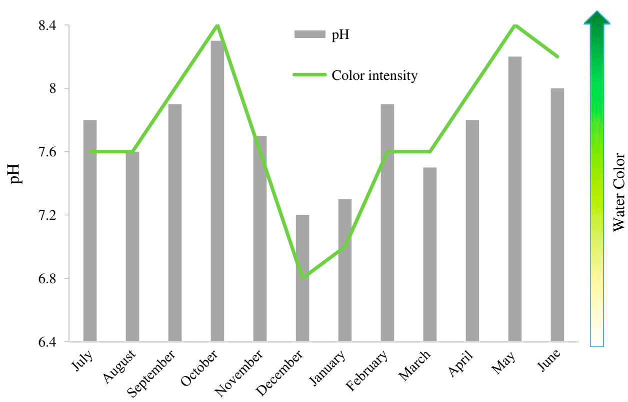

Fig. 7. Monthly average pH and water color intensity in the HRAP.

also be explained by the high precipitation during these months resulting in more diluted wastewater. In a study conducted on the effect of pond depth on algal productivity and nutrient removal in wastewater treatment HRAP, Sutherland et al. [37] determined a seasonal ratio of organic matter to Chl-a in the HRAP's top layer (0–20 cm). Based on these ratios and according to the experimental values of suspended matter in this study (more than 95% are organic), the Chl-a concentration was estimated to 1,440, 2,160, 1810, and 3,130 mg/m^3 in the winter, spring, summer, and autumn, respectively. In addition to that, pH ranged from 7.2 to 8.3 and the highest values were observed during periods of relatively high algal density (Fig. 7). In fact, microalgae are photosynthetic organisms which consume CO_2 during day time, leading to an increase in water pH, especially during episodes of high algal productivity, which occurs in the present study during spring and autumn seasons.

3.3. HRAP treatment performances

Fig. 8 illustrates monthly values of BOD_5 and COD at the entry and exit of the HRAP. The BOD_5 varied between 12 and 60 mg O_2/L and COD ranged from 175 to 300 mg O_2/L at the entry and from 185 to 400 mg O_2/L at the exit of the HRAP. These values are very often above national standards for discharged wastewater which are set to 30 and 90 mg O_2/L for BOD and COD, respectively.

Typically, raw domestic wastewater has a COD/BOD ratio of about 2. However, depending on the treatment technique, this ratio may vary considerably. It is well known that after an anaerobic stage, domestic

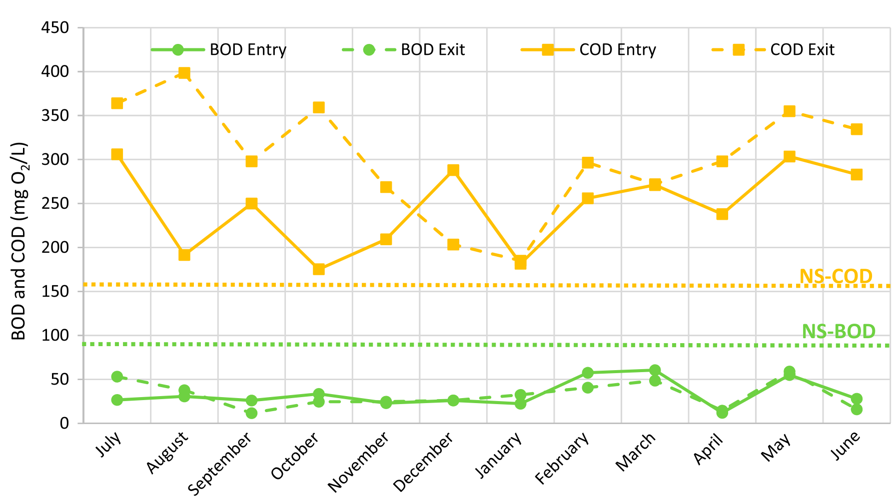

Fig. 8. Monthly COD and BOD_5 at the entry and exit of the HRAP (Orange and green horizontal dashed line corresponds to national standards of wastewater discharge for COD and BOD, respectively).

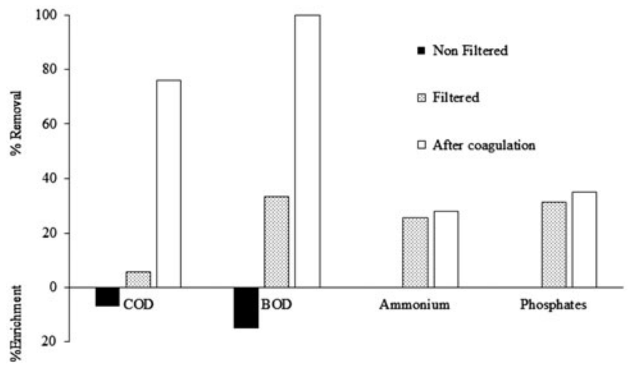

Fig. 9. Removal efficiencies of COD, BOD_5, ammonium and phosphates in the HRAP.

wastewater will keep a similar COD/BOD ratio, but after an aerobic stage which is more efficient in removing biological organic matter, it is very common to observe an increase in the COD/BOD ratio that may get as high as 10 or 12 [38].

The treatment performances of the HRAP of the wastewater treatment plant of Sidi Bou Ali are determined based on removal efficiencies of COD, BOD_5, and nutrients (ammonium and phosphates). Fig. 9 reports that the average removal efficiency over a 12-month period for filtered water is equal to 5, 33, 25, and 31% for COD, BOD, ammonium, and phosphates, respectively. These results are very low compared to values reported in other studies, with removal efficiencies of about 44, 70, and 90% for BOD_5, phosphates, and ammonium, respectively [39–41]. The treated wastewater going out of the HRAP (in this study) is not filtered and it can be seen from Fig. 9 that the actual treatment performances are not satisfying in comparison to the literature. A small-scale harvesting system for microalgae (after treatment) was installed and tested *in situ* at the exit of the HRAP, and it can be clearly observed how the treatment performances considerably improved, especially for COD and BOD, up to 76 and 100%, respectively.

4. Conclusion

The hydrodynamic study by CFD of the HRAP of the wastewater treatment plant of Sidi Bou Ali revealed that the mean water velocity at an injected air rate of 25 N m^3/h by the airlift is equal to 0.15 m/s. This value corresponds to what is recommended for a good functioning of such a system. In addition to that, climatic conditions such as rainfall, insolation time, and air and water temperature may also affect the algal productivity in the HRAP. Moreover, the actual treatment performances of this experimental HRAP are not satisfying compared to what is reported in the literature and do not meet the limits set by local law for discharged water . The major reason is that a major part of the treatment is performed via the presence of microalgae which have the ability to grow and to accumulate nutrients and other toxic compounds in wastewater, and therefore, the lack of an algal recovery system at the exit of the HRAP will not highlight the real treatment performances. In fact, the actual enrichment in COD and BOD_5 of 5 and 15%, respectively, is changed to a removal efficiency of up to 80–100%, respectively, when the biomass is removed from the treated wastewater. In addition to that, after harvesting, this algal biomass can be used and valorized in multiple by-products.

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List of symbols

ρ	—	density (kg/m^3)
u	—	velocity component (m/s)
x	—	longitudinal component (m)
P	—	turbulence kinetic energy production term (kg/ms^3)
k	—	turbulence kinetic energy (m^2/s^2)
Pr	—	Prandtl number (no unit)
G	—	buoyancy production term (kg/ms^3)
C	—	concentration (kg/m^3)
R	—	velocity ratio v_0/u_∞
$\bar{V}$	—	average simulated velocity (m/s)
j	—	grids number
V_i	—	is the modeled water velocity for each grid (m/s)
$\bar{u}$	—	experimental mean free surface water velocity (m/s)
k	—	number of measurements (=10)
d_i	—	distance for each measurement (m)
t_i	—	time for each measurement (s)
$\overline{\rho u_i'' u_j''}$	—	Reynolds tension

Greek symbols

ε	—	turbulent dissipation rate (m^2/s^3)
μ	—	kinematic viscosity (m^2/s)

Indices

-	—	mean
~	—	Le Favre mean

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