

Article

# Oxygen Consumption in Two Subsurface Wastewater Infiltration Systems under Continuous Operation Mode

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**Abstract:** In this work, an innovative arrangement of a vertical subsurface flow wastewater infiltration system (SWIS) was studied. The principal objective of this study was to evaluate the oxygen transfer rate (OTR) in two different pilot-scale arrangements of an SWIS. The two pilot plants were composed of four filter beds in series, one with a vertical arrangement of the beds (one over the other) and the other with a horizontal arrangement of the beds (one next to the other). Furthermore, two kinetic models were applied for correlating the COD and  $\text{NH}_4^+\text{-N}$  concentrations at the inlet and outlet of each treatment step in both pilot plants. The fitting of experimental data to the models allowed the calculation of the areal rate constants. The OTR values obtained were  $54.69 \text{ g m}^{-2} \text{ h}^{-1}$  and  $28.84 \text{ g m}^{-2} \text{ h}^{-1}$  for horizontal and vertical arrangement, respectively. These values were considerably higher than those obtained by other authors. The plug flow model describes the behaviour of these SWISs better, and the best fits were achieved for the vertical arrangement. The areal rate constant values obtained in this study were higher than those reported in the bibliography, which indicates a great removal efficiency and therefore lower surface area needed for the treatment.

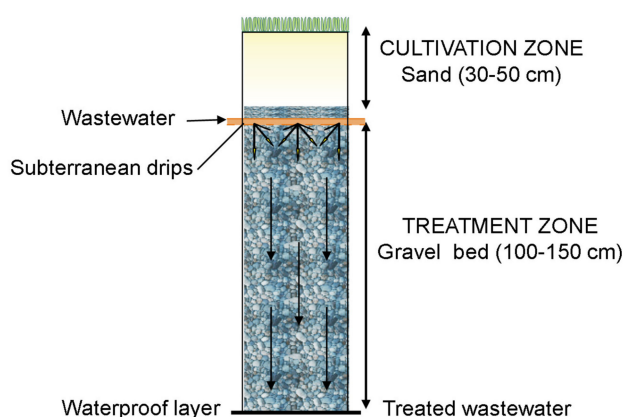
**Keywords:** oxygen transfer rate; subsurface wastewater infiltration system; kinetic models; areal rate constants

## 1. Introduction

Conventional wastewater treatment technologies present some disadvantages, such as high cost and operational difficulties, thanks to changes in wastewater flowrate and contaminant loads [1]. Considering the necessity to hunt alternative options to standard systems, the technologies that have a minimum or null energy cost have had preference, with easy operational and maintenance procedures, and which guarantee efficacy and great versatility in the face of both large flow and load fluctuations, simplifying sludge treatment and disposal management. The treatment technologies that compile all of these characteristics are usually referred to as non-conventional technologies [2,3]. However, the large land requirement area of these technologies is a major limitation of their application. They can require up to ten times more land area ( $0.5\text{--}20 \text{ m}^2 \text{ pe}^{-1}$ ) than conventional systems, such as activated sludge ( $0.2\text{--}0.3 \text{ m}^2 \text{ pe}^{-1}$ ). Vertical subsurface flow constructed wetlands are among the non-conventional technologies that require less area, between  $0.8$  and  $5.5 \text{ m}^2 \text{ pe}^{-1}$  [4]. The Environmental Protection Agency (EPA) design recommends reducing the surface requirements. Ilyas and Masih (2017) [5] reviewed various strategies applied to reduce the area requirements in constructed wetlands. The lowest area requirements were found for vertical subsurface flow wetlands with effluent recirculation ( $1.1 \pm 0.5 \text{ m}^2 \text{ pe}^{-1}$ ) and vertical subsurface flow wetlands with tidal flow

( $2.1 \pm 1.8 \text{ m}^2 \text{ pe}^{-1}$ ). A subsurface wastewater infiltration system (SWIS) is an ecological process applied for decentralized household wastewater treatment in villages, small towns or scattered site housing, and has proved to be a suitable alternative for wastewater advanced treatment [6–8]. In SWIS treatment, wastewater is initially treated by means of conventional physicochemical or biological treatment and then infiltrates through an aerated unsaturated zone, wherein takes place the depuration through processes like filtration, adsorption, reaction and biodegradation. The SWI system has shown good behavior to degrade organic matter, which is determined as biochemical oxygen demand ( $\text{BOD}_5$ ) and chemical oxygen demand (COD). Compared to the traditional activated sludge process, SWIS presents many benefits, like simple construction, low operation and maintenance costs, plus easy operation [9,10].

In this work, an innovative arrangement of a vertical subsurface wastewater infiltration system was studied. This technology, named hybrid constructed soil filter (HCSF) [11], includes a natural and subterranean treatment with the creation of green zones on its surface. Fundamentally, in the treatment, two clearly differentiated zones can be distinguished: the cultivation zone and the treatment zone (Figure 1). The treatment zone is made up of a gravel bed and is isolated from the ground by an impermeable sheet. An important aspect to notice is that the wastewater to be treated is continuously supplied using a network of underground drippers, uniformly distributed, that are located over the gravel bed. This feeding system ensures that the gravel bed is not saturated, and it is fundamental to make sure that the system remains in aerobic conditions [12,13]. The wastewater slowly infiltrates the treatment zone and comes into contact with bacteria that have grown on the surface of the gravel particles. The treated wastewater is collected at the base of the gravel bed. The treatment area is covered by a layer of sand called the cultivation area. This zone avoids the danger of human contact with the wastewater to be treated and eliminates odor emissions. A combination of several filter beds might be placed serially, in the function of the organic influent loading. For urban wastewaters, a pretreatment followed by four filter beds serially is typically needed. The number of treatment steps increases as the wastewater load increases.



**Figure 1.** Scheme of a hybrid constructed soil filter.

The principal objective of this study was to evaluate the oxygen consumption, mainly due to both the nitrification process and the biodegradation of organic matter, in two different pilot-scale combinations of a subsurface wastewater infiltration system (SWIS). The pilot plants were installed in the Campus of Espinardo (University of Murcia, Murcia, Spain). Furthermore, two kinetic models were applied for correlating the COD and  $\text{NH}_4^+\text{-N}$  concentrations at the inlet and outlet of each treatment step in both pilot plants. The fitting of experimental data to the models allowed the calculation of the areal rate constants.

## 2. Materials and Methods

### 2.1. Description of Pilot Plants

Previous treatment to pilot plants consists of two subsequent rotating screens, 0.5 mm and 0.25 mm sieve mesh sizes, respectively, a clarifier and a 130  $\mu\text{m}$  mesh ring filter. The pretreated wastewater is fed simultaneously to the two pilot plants. Each plant features a different arrangement of four filter beds serially. Figure 2 shows the layout of the two pilot plants; the primary one features a vertical arrangement of the filter beds, and the other features a horizontal arrangement of the filter beds.

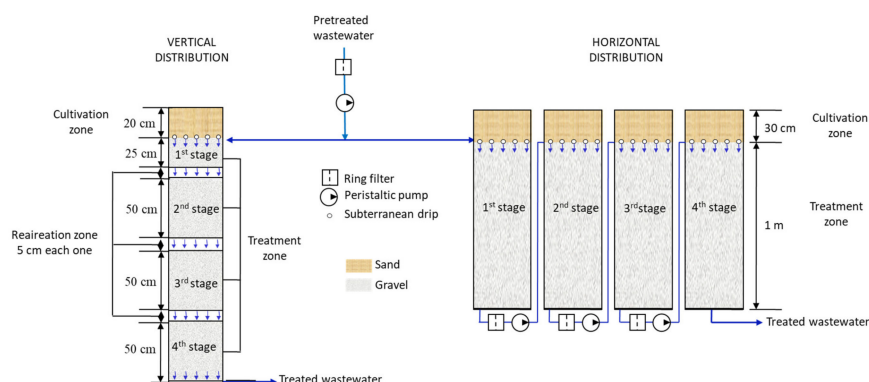


Figure 2. Layout of the pilot plants.

#### 2.1.1. Pilot Plant with Horizontal Arrangement

The horizontal arrangement (Figure 3) is composed by four filter beds arranged serially, and the effluent of every stage requires to be filtered before entering the subsequent stage. Each filter consists of a gravel bed 100 cm in depth, isolated from the ground by an impermeable sheet. The gravel beds are composed of a random mixture of gravel particles, with diameters ranged between 12 and 30 mm (nominal mean diameter = 20 mm). In this arrangement, all of the stages are identical and have a treatment zone and a cultivation zone. Wastewater is applied in each stage by means of subterranean drippers, situated directly over the gravel. The surface of each filter is  $0.071 \text{ m}^2$  and receives  $8 \text{ L}\cdot\text{h}^{-1}$  of wastewater, so that the arrangement is feeding at a hydraulic load of  $0.113 \text{ m}^3\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ . The pretreated wastewater is supplied to the first column through the drippers, and then falls by gravity through the gravel bed until it reaches the bottom waterproof layer. The effluent of every column passes through a 130  $\mu\text{m}$  mesh ring filter before being pumped to the subsequent column.



Figure 3. Picture of the pilot plant with horizontal arrangement.

#### 2.1.2. Pilot Plant with Vertical Arrangement

The vertical arrangement (Figure 4) consists of four gravel beds, located serially and arranged one below the other. In this arrangement, the gravel beds have a depth of 50 cm. The cultivation zone and the distribution system to supply wastewater are only situated in the first filter (the one above). The pretreated wastewater goes to the first stage through the drippers, then falls by gravity through

the gravel bed. The effluent of every stage falls by gravity to the subsequent stage, without filtering, crossing a void zone placed between two consecutive stages. This void area favors the oxygen transfer. The hydraulic loading is  $0.082 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$ , since the pilot plant receives  $48 \text{ L h}^{-1}$  and has a surface of  $0.585 \text{ m}^2$ . In this arrangement, the waterproof layer is only placed at the bottom of the fourth filter.



**Figure 4.** Picture of the pilot plant with vertical arrangement.

The effluent from the last stage in both pilot plants gets collected and constitutes the treated water. It is important to indicate that the wastewater inlet in both arrangements is carried out continuously by means of drippers. This fact, along with the continual drainage, prevents the saturation of the gravel beds and provides a very uniform distribution of wastewater flow through the pores of the media.

## 2.2. Sampling and Methods

Water samples were collected from both pilot plants fortnightly (from June 2018 to June 2019) from the pre-treated wastewater (IC) and from the exit of the four filter beds (E1 to E4). The target parameters measured were the following: dissolved oxygen (DO), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia nitrogen ( $\text{NH}_4^+\text{-N}$ ), nitrates and nitrites. All water samples were measured as per the standard procedure of the Standard Methods for the Examination of Water and Wastewater [14].

## 2.3. Dissolved Oxygen Transfer Rate

The theoretical oxygen transfer rate (OTR,  $\text{g m}^{-2} \text{ h}^{-1}$ ) was calculated by means of Equation (1) [15–18]:

$$\text{OTR} = \text{HLR} \times (0.7 \times [\text{COD}_{\text{in}} - \text{COD}_{\text{out}}] + 4.3 \times [\text{NH}_4^+\text{-N}_{\text{in}} - \text{NH}_4^+\text{-N}_{\text{out}}]) \quad (1)$$

in which  $[\text{COD}_{\text{in}} - \text{COD}_{\text{out}}]$  is the COD removed ( $\text{mg L}^{-1}$ ),  $[\text{NH}_4^+\text{-N}_{\text{in}} - \text{NH}_4^+\text{-N}_{\text{out}}]$  is the nitrogen ( $\text{mg L}^{-1}$ ) nitrified in the gravel beds and HLR is the hydraulic loading rate ( $\text{m h}^{-1}$ ). The factor 0.7 is enclosed to compensate for the fact that BOD rather than COD is more commonly utilized in this equation [16,18]. The factor 4.3 comes from the stoichiometry of ammonia oxidation with  $\text{O}_2$ .

## 2.4. Removal Rate Constants

A great number of subsurface flow wetlands have shown an exponential diminution in organic matter and ammonia nitrogen concentrations during the course of time [19–22]. This behaviour is in accordance with a first-order kinetic model, where removal rate is proportional to contaminant concentration [21].

In a reactor, first order kinetics is expressed as follows:

$$\frac{dC}{dt} = -k_v \cdot C_{\text{out}} \quad (2)$$

where  $C_{\text{out}}$  = outlet contaminant concentration ( $\text{mg L}^{-1}$ ), and  $k_v$  = volumetric rate constant ( $\text{h}^{-1}$ )

Two kinetic models were applied for correlating both COD and ammonia nitrogen values from the influent and effluent of the four stages of treatment in both pilot plants. The models were developed by combining first-order kinetic with plug flow and CSTR patterns.

#### 2.4.1. Model 1: First Order Kinetic with Plug Flow Pattern

Considering idealized plug flow conditions in Equation (2) leads to:

$$\int_{C_{in}}^{C_{out}} \frac{dC}{dt} = -k_v \int_0^t dt \quad (3)$$

The arrangement of Equation (3) in terms of areal rate constant ( $K_1$ ,  $m\ h^{-1}$ ) leads to a first-order plug flow model (Kickuth equation) for correlating both COD and ammonia nitrogen values from the influent and effluent of the four filter beds in both pilot plants, as expressed in Equation (4) [23]

$$K_1 = HLR \cdot Ln \frac{C_{in}}{C_{out}} \quad (4)$$

#### 2.4.2. Model 2: First Order Kinetic with CSTR Flow Pattern

The plug flow pattern might not be appropriate because of the presence of gravel bed. The filter bed is likely to diffuse flow in all directions as it moves towards the outlet, but short circuiting and the existence of dead zones also contradicts the ideal plug flow model [24].

In a reactor, the CSTR flow pattern is often expressed as:

$$\frac{dC}{dt} + \frac{1}{\tau} C_{in} = \frac{1}{\tau} C_{out} \quad (5)$$

where  $C_{in}$  = inlet pollutant concentration ( $mg\ L^{-1}$ ), and  $\tau$  = hydraulic retention time (h).

The combination of Equations (2) and (5) results in simplified first-order kinetics combined with CSTR flow pattern (in terms of areal rate constant  $K_2$ ,  $m\ h^{-1}$ ) as presented in Equation (6), for correlating both COD and ammonia nitrogen values from the influent and effluent of the gravel beds in the two pilot plants.

$$K_2 = HLR \cdot \frac{C_{in} - C_{out}}{C_{out}} \quad (6)$$

#### 2.5. Comparison of the Two Models and Obtention of Removal Rate Constants

To allow statistical analyses, the CSTR flow pattern model (Equation (6)) has been organized in the form of Equation (7).

$$C_{in} = C_{out} \cdot \left( \frac{K_2}{HLR} + 1 \right) \quad (7)$$

The general form of Equation (7) allows comparison between the experimental data and the data predicted by the model. The slope of the linear regression allows the calculation of the areal rate constant ( $K_2$ ,  $m\ h^{-1}$ ).

In the case of the plug flow pattern model, Equation (4) may be transformed in Equation (8).

$$Ln C_{in} = \frac{K_1}{HLR} + Ln C_{out} \quad (8)$$

The areal rate constant is calculated from the y-intercept value ( $K_1$ ,  $m\ h^{-1}$ ). For data analysis, Sigma Plot software was used.

### 3. Results and Discussion

#### 3.1. Performance of SWIS Pilot Plants

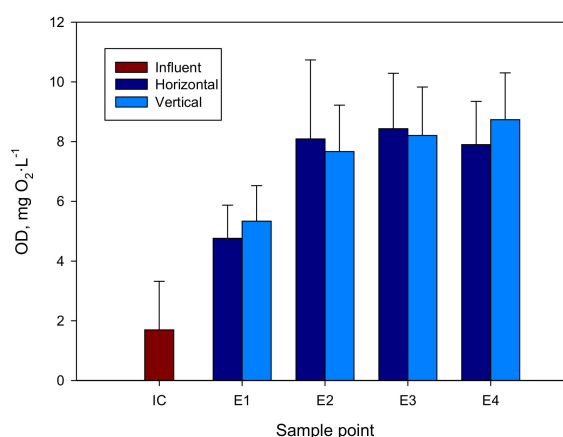
Both pilot plants were operated for over a year and their performances were monitored. Table 1 reports the average value  $\pm$  standard deviation of each of the water quality parameters studied for the pretreated wastewater and for the effluents of both pilot plants.

**Table 1.** Parameters measured for the pretreated wastewater and the effluent of both pilot plants.

Parameter	Pretreated Wastewater <sup>a</sup>	Effluent Horizontal Arrangement <sup>a</sup>	Effluent Vertical Arrangement <sup>a</sup>
OD (mg O <sub>2</sub> L <sup>-1</sup> )	1.7 $\pm$ 1.11	8.73 $\pm$ 1.57	7.90 $\pm$ 1.45
COD (mg O <sub>2</sub> L <sup>-1</sup> )	472.92 $\pm$ 190.86	32.27 $\pm$ 17.61	96.98 $\pm$ 72.06
TKN (mg N L <sup>-1</sup> )	52.33 $\pm$ 16.21	5.50 $\pm$ 12.13	16.10 $\pm$ 9.30
NH <sub>4</sub> <sup>+</sup> -N (mg N L <sup>-1</sup> )	43.48 $\pm$ 12.79	4.13 $\pm$ 10.84	14.58 $\pm$ 8.85
Nitrates (mg N L <sup>-1</sup> )	0	41.63 $\pm$ 19.13	30.66 $\pm$ 17.42
Nitrites (mg N L <sup>-1</sup> )	0.81 $\pm$ 0.36	0.55 $\pm$ 0.30	0.42 $\pm$ 0.17

<sup>a</sup> average value  $\pm$  standard deviation.

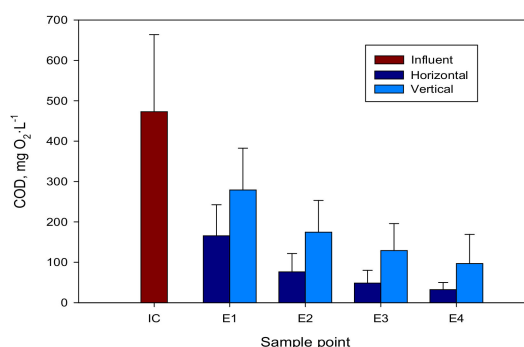
In this system, among the foremost important parameters is dissolved oxygen. The system is fed drop to drop to ensure that the hollows of the gravel bed are always full of air. This allows a perfect contact between the wastewater and the air contained in the filter media voids. The oxygen is dissolved in the liquid and is used for both degradation of organic matter and nitrification. As oxygen is consumed by microorganisms, fresh air refills the hollows of the filter media. At all times, the gravel beds are not saturated with water, and therefore the water which irrigates the gravel beds is usually in touch with air, thus the depuration is produced in aerobic conditions. Figure 5 shows that dissolved oxygen increases along the stages of both pilot plants and is higher for the horizontal arrangement, despite receiving organic and volumetric loads somewhat higher than the vertical arrangement. The activity of heterotrophic and autotrophic bacteria was enhanced with the increase in dissolved oxygen concentration, and therefore the organic matter oxidation, the hydrolysis of organic nitrogen compounds and the nitrification process was improved.



**Figure 5.** Evolution of the dissolved oxygen along the treatment in the two pilot plants.

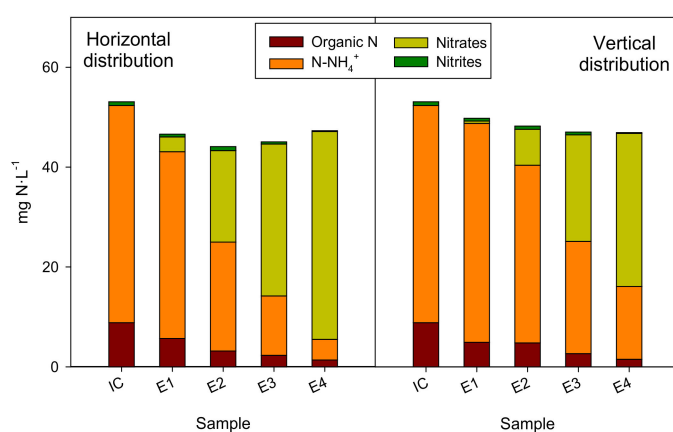
Figure 6 depicts that the COD values progressively diminished throughout the treatment stages. The retention of organic suspended solids by both the ring filters and within the filter beds, as well as the biodegradation of organic matter by heterotrophic bacteria adhered to the gravel bed, are the main causes of the reduction in organic matter. The surface of the gravel particles is covered by a biofilm that is responsible for the removal of soluble organic matter. Oxidation is carried out by tight contact between heterotrophic bacteria and wastewater flow. The configuration of both pilot plants

allows continuous entry of oxygen to the stages of treatment, and the degradation of organic matter takes place under aerobic conditions. For sewage effluents, the EC Directive 91/271/EEC sets limits for COD of  $125 \text{ mg O}_2 \text{ L}^{-1}$ . Observing Figure 6, it can be noticed that the effluent from the third stage of horizontal plant already achieves the standards laid down in the directive. However, the plant with vertical arrangement would need the four stages of treatment to reach that COD value. The vertical arrangement gives 79.5% COD removal from influent, while the horizontal arrangement produces 93.2% COD removal. Similar values have been reported by other researchers. Zhang et al., (2007) [25] have reported 94.5% COD removal from wastewater in a soil infiltration treatment. Nemade et al., (2009) [26] gives 94% COD removal in the performance of a constructed soil filter plant at Worli, Mumbai, India. Similarly, Foladori et al., (2012) [27] report 82% COD removal in a vertical flow filter, which constitutes the first stage of a hybrid constructed wetland.



**Figure 6.** Evolution of the chemical oxygen demand along the treatment in the two pilot plants.

The evolution of the different nitrogen species throughout the stages of treatment in both pilot plants is shown in Figure 7. Nitrite concentration was always very low. This fact is also produced in other similar systems in such vertical subsurface constructed wetlands, as is reported by Arias et al., (2001) [28] and Prochaska et al., (2007) [29]. As it can be seen,  $\text{NH}_4^+\text{-N}$  and organic nitrogen concentrations considerably diminished in the two pilot plants, and the higher removal happened in the plant with the horizontal arrangement. This can be due to the longer retention time of the water within the bed, which is directly related to the greater depth of the gravel bed.



**Figure 7.** Evolution of the nitrogen species along the treatment in the two pilot plants.

The transformations of nitrogen species that take place within the filter beds are the same as those that happen in wetlands [30,31]. Among them can be mentioned: uptake by microorganisms, nitrification, denitrification, ammonia volatilization, adsorption and cation exchange for ammonium.

The increase of nitrate concentration throughout the treatment is almost balanced with the reduction of ammonia-nitrogen and organic nitrogen. First, the organic nitrogen is transformed to

ammonia nitrogen, and then ammonium is oxidized to nitrites and nitrates. Nitrification is probably the main process to get rid of ammonia nitrogen during this study. The vertical arrangement produces 66.4%  $\text{NH}_4^+$ -N removal, while the horizontal one gives 90.5%  $\text{NH}_4^+$ -N removal. Foladori et al., (2012) [27] obtained 70%  $\text{NH}_4^+$ -N removal in a vertical flow filter that is part of a hybrid constructed wetland. Zapater-Pereyra et al., (2015) [32] have studied a hybrid system with a vertical flow constructed wetland (VFCW) on top of a horizontal flow filter (HFF), and they have obtained 55–85% of  $\text{NH}_4^+$ -N removal, with a greater contribution of VFCW to the removal of ammonia.

### 3.2. Oxygen Transfer Rate

The transfer of oxygen from the atmosphere to the filter beds is produced by convective air diffusion. Many researchers account that the knowledge of the oxygen transfer rate (OTR) is of great importance, since the supply of oxygen must be enough for the oxidation of both organic matter and ammonia nitrogen to nitrates. Figure 8 shows that the oxygen transfer rate decreases through the stages of treatment, and this decrease is more pronounced for the plant with the horizontal arrangement. In the first stage of treatment of the horizontal arrangement (E1) and in the two firsts stages of the vertical one (E1–E2), the oxygen is mainly used for the degradation of organic matter. The oxygen consumption for biological nitrification is predominant within the remaining stages of treatment of both pilot plants. This fact can be verified with the results obtained in Section 3.1.

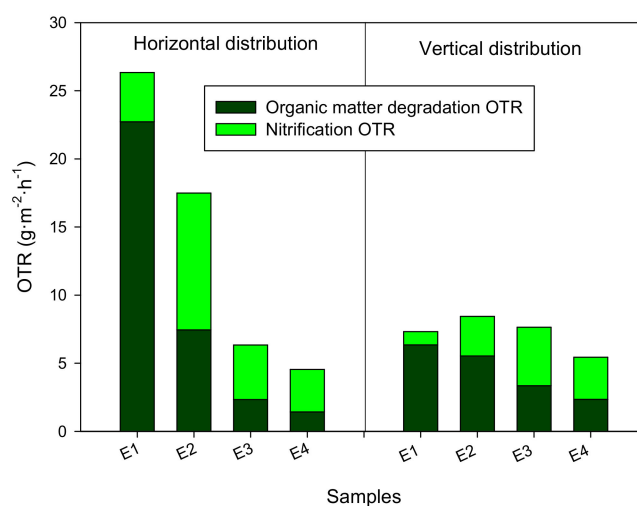


Figure 8. Oxygen transfer rate along the treatment in both pilot plants.

The OTR values are often used for design purposes. OTR values of around  $30 \text{ g}\cdot\text{m}^{-2} \text{ d}^{-1}$  are recommended for the proper operation of a wetland [16,33,34]. Table 2 shows the OTR values obtained in this study for the two pilot plants. These values are considerably higher than those obtained by other authors. Kantawanichkul et al., (2009) [16] obtained OTR values between 60 and  $80 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for the treatment of high load wastewater under tropical conditions with vertical flow constructed wetlands, and Herrera et al., (2010) [35] obtained OTR values of  $155 \text{ g}\cdot\text{m}^{-2} \text{ d}^{-1}$  for a vertical flow constructed wetland installed in the Canary Islands.

In a wetland system, aerobic degradation of organic matter occurs at a higher rate than nitrification. The specific growth rate of bacteria responsible for organic matter degradation is higher than that of microorganisms causing oxidation of ammonia nitrogen to nitrates [36]. This implies that oxygen consumption is high for such microorganisms whose specific growth rate is high. If the oxygen utilization were higher than the atmospheric diffusion rate towards the void spaces of the gravel beds, both the organic matter degradation and the nitrification could be affected.



**Table 2.** Oxygen transfer rate expressed in  $\text{g m}^{-2} \text{h}^{-1}$  for the four stages of treatment of both pilot plants.

		1st Stage <sup>a</sup>	2nd Stage <sup>a</sup>	3rd Stage <sup>a</sup>	4th Stage <sup>a</sup>	Whole Plant <sup>b</sup>	Total OTR <sup>b</sup>
Horizontal arrangement	Organic matter degradation	22.72±0.85	7.45±6.10	2.33±2.12	1.43±1.60	33.91	54.69
	Nitrification	3.62±2.91	10.04±7.70	4.01±3.26	3.11±3.08	20.78	
Vertical arrangement	Organic matter degradation	6.35±2.37	5.53±3.12	3.35±1.63	2.35±1.95	17.58	28.84
	Nitrification	0.97±0.80	2.91±1.28	4.29±2.57	3.09±2.00	11.26	

<sup>a</sup> average value ± standard deviation; <sup>b</sup> average value.

In the pilot plants, oxygen transfer towards the gravel beds was very high and did not restrict treatment performance. This is true because, as it can be seen in Figure 5, the gravel beds in the two pilot plants were always in aerobic conditions. This is possible because the way of wastewater feeding prevents the saturation of the filter beds and ensures that the pilot plants function in aerobic conditions.

### 3.3. Models Verification Results

Areal rate constants for ammonia nitrogen and organic matter removal along the four stages of treatment of both pilot plants are presented in Table 3.

**Table 3.** Areal rate constants for the four stages of treatment of both pilot plants.

		COD				NH <sub>4</sub> <sup>+</sup> -N			
		Plug Flow		CSTR		Plug Flow		CSTR	
		K <sub>1</sub> , m h <sup>-1</sup>	R <sup>2</sup>	K <sub>2</sub> , m h <sup>-1</sup>	R <sup>2</sup>	K <sub>1</sub> , m h <sup>-1</sup>	R <sup>2</sup>	K <sub>2</sub> , m h <sup>-1</sup>	R <sup>2</sup>
HORIZONTAL	E1	0.331	0.5024	0.072	0.5095	0.103	0.8619	-0.013	0.8970
	E2	0.286	0.6445	-0.027	0.3432	0.291	0.7943	0.015	0.9571
	E3	0.068	0.9195	0.018	0.6550	0.212	0.9441	-0.007	0.6652
	E4	0.039	0.7602	0.046	0.6006	0.185	0.4439	0.008	0.713
VERTICAL	E1	0.149	0.8988	0.005	0.8713	0.061	0.9087	0.0001	0.8520
	E2	0.115	0.7544	0.005	0.6593	0.067	0.9574	0.007	0.6398
	E3	0.131	0.7845	-0.001	0.7052	0.156	0.8708	0.054	0.8436
	E4	0.122	0.7337	-0.027	0.6222	0.093	0.9748	0.028	0.2548

The best fits are achieved with the plug flow model and, in general, for the vertical arrangement of the treatment stages ( $R^2 = 0.73$ – $0.90$  for COD removal and  $R^2 = 0.91$ – $0.98$  for NH<sub>4</sub><sup>+</sup>-N removal).

The calculated values of K<sub>1</sub> and K<sub>2</sub> are greater for COD removal than for nitrification. For COD, the highest values of K<sub>1</sub> and K<sub>2</sub> are obtained in the first stage of treatment of both pilot plants, where the highest removal of organic matter is attained. However, for nitrification, the highest values of K<sub>1</sub> and K<sub>2</sub> correspond to the last stages of treatment, in which a higher production of nitrates is observed (Figure 7); on the other hand, in the last stages, organic load is lower than in the first stages. This is according to several authors who have reported that high organic loads could be harmful to nitrification because of the competition for oxygen between heterotrophic and autotrophic microorganisms [18,37,38].

The K values obtained in this study for COD removal and nitrification are higher than those reported in the bibliography [21,33]. Vymazal et al., (1998) [33] reported areal rate constant values obtained from constructed wetlands (with different design and operation) that ranged from  $0.027 \text{ m d}^{-1}$  to  $0.11 \text{ m d}^{-1}$  for both COD and NH<sub>4</sub><sup>+</sup>-N removal. In some stages of the studied system, the calculated areal rate constants reached values of  $\approx 7 \text{ m d}^{-1}$  for NH<sub>4</sub><sup>+</sup>-N removal and  $\approx 8 \text{ m d}^{-1}$  for COD removal. The K values depend on operation parameters and construction and design of the constructed soil filters [21,33,39].

High K values indicate a more efficient removal, and therefore lower surface area needed for the treatment [21,23,33]. The area requirement for this installation ( $0.3 \text{ m}^2 \text{ pe}^{-1}$  for the horizontal

arrangement and  $0.1 \text{ m}^2 \text{ pe}^{-1}$  for the vertical arrangement) is significantly lower than those found for VFCW (between  $0.8$  and  $5.5 \text{ m}^2 \text{ pe}^{-1}$ ) [4,5].

#### 4. Conclusions

The most important aspects to highlight of this work are summarized as follows.

Dissolved oxygen increases along the stages of treatment in both pilot plants, and is higher for the horizontal arrangement despite receiving organic and volumetric loads somewhat higher than the vertical arrangement.

The two pilot plants have shown very good behavior for the removal of organic matter. The effluent from the third stage of the horizontal arrangement already achieves the standards laid down in EC Directive 91/271/EEC, however, the plant with the vertical arrangement would need the four stages of treatment.

The  $\text{NH}_4^+\text{-N}$  and organic nitrogen concentrations considerably diminish in the two pilot plants, and the higher removal happened in the plant with the horizontal arrangement. This can be due to the longer retention time of the water within the bed, which is directly related to the greater depth of the gravel bed. The increase of nitrate concentration throughout the treatment is almost balanced with the reduction of ammonia nitrogen and organic nitrogen. Nitrification is probably the main removal process of ammonia nitrogen.

The oxygen transfer rate (OTR) decreases through the stages of treatment, and this decrease is more pronounced for the plant with the horizontal arrangement. In the first stages of treatment of both plants, the oxygen is mainly used for the degradation of organic matter, and the oxygen consumption for biological nitrification is predominant within the remaining stages of treatment. The OTR values obtained in this study are considerably higher than those obtained for other authors, which is directly related to the high removal of organic matter and ammonia nitrogen. It is important to point out that the oxygen transfer towards the gravel beds was very high and did not restrict treatment performance.

The plug flow model describes the behavior of this system better, and the best fits are achieved for the vertical arrangement. The areal rate constants (K) for COD removal are higher than those corresponding to nitrification. The K values obtained in this study are considerably higher than those reported in the bibliography. High K values indicate a more efficient removal, and therefore lower surface area requirements for the treatment. The area surface requirements for this system are considerably lower than those corresponding to comparable systems, such as subsurface flow constructed wetlands. The results obtained allow the affirmation that the area demand is approximately 10 times lower for the horizontal arrangement and 20 times lower for the vertical one.

Due to the intense nitrification, it is important to note that the effluent of this system has a high concentration of nitrates. If the effluent is going to be discharged in a sensitive zone, it would be necessary to carry out denitrification, since it could cause a problem of eutrophication of the aquatic environment. Therefore, the study of denitrification is of great interest. The combination of the technology studied in this work with a stage of biological denitrification of attached growth could avoid the discharge of nitrates to the aquatic environment.

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