Nitrogen transformation in two vertical subsurface flow pilot plants

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Abstract

Nitrogen removal and transformations were studied in two pilot-scale combinations of a special configuration of a subsurface wastewater infiltration system with vertical flow named symbiotic treatment®. Both pilot-scale combinations operated in parallel and each one consists of four stages in series, one of them with a vertical distribution of stages and the other one with a horizontal distribution. The main differences between them were the separation between stages (presence (the horizontal distribution)/absence (the vertical distribution) of filtration between steps), the hydraulic load (0.113 $m^3/m^2 \cdot h$ and 0.082 $m^3/m^2 \cdot h$ for the horizontal and the vertical distribution, respectively) and the depth of the soil filters (1 m each stage in the horizontal distribution whereas the depths in the vertical distribution ranges from 20 cm to 40 cm). Results of both configurations showed elevated dissolved oxygen concentration, and high removal of organic matter and total suspended solids (with mean removal values of 96 % for COD for both plants and 90 % and 98 % for TSS for the vertical and the horizontal distribution, respectively). High total kjeldahl nitrogen removals were obtained in both configurations (mean removals of 70 % and 90 % for the vertical and the horizontal distribution, respectively). Whereas the nitrification potential was higher in the configuration with horizontal distribution which includes pumping and filtering between stages and higher depth of the soil filters, both tested configurations showed promise for nitrification of wastewater, ammonium nitrogen was efficiently transformed to nitrate.

Keywords: innovative technology, subsurface infiltration system, urban wastewater, small village, nitrification

1. INTRODUCTION

Wastewater treatment is becoming ever more critical due to diminishing water resources, increasing wastewater disposal costs, and stricter discharge regulations that have lowered permissible contaminant levels in waste streams (Xiao et al., 2009). The treatment of wastewater for reuse and disposal is particularly important. In this sense, the Directive 91/271/EEC concerning urban wastewater treatment requires all towns with less than 2000 equivalent inhabitants to have a collection system in place to treat adequately their effluent.

The conventional treatment systems have some disadvantages such as high cost, and operational difficulties due to fluctuations in wastewater flow rate and pollution loads (Ayaz, 2008). Given the need to seek alternative solutions to conventional systems, priority has been given to those technologies which have a minimum or null energy cost, with simple operational and maintenance procedures, and which guarantee efficiency and a high level of inertia when faced with large fluctuations in the flow and the effluent load to be treated, and which simplify sludge handling processes. The treatment technologies which bring together all of these characteristics are generally known as non-conventional technologies (Puigagut et al., 2007; Fahd et al., 2006).

A subsurface wastewater infiltration system is a process suitable for domestic wastewater treatment. It is an effective way to treat wastewater according to integrated mechanisms of chemical, physical and biological reactions if the infiltration system is carefully designed and managed (Zhang et al., 2005). The symbiotic treatment® is a novelty configuration of a subsurface wastewater infiltration system. This technology combines a natural and subterranean treatment with the generation of green areas over its surface (Fabregas, 2005). And so, the treatment plant basically consists of two clearly differentiated parts: the treatment zone and the cultivation zone (Figure 1). The treatment zone consists of a gravel bed, which is isolated from the ground by a waterproof layer. An interesting point to note was that the wastewater to be treated is continuously applied by means of a network of underground drips, uniformly distributed, lying over the gravel bed. The cited feeding system avoids saturating the gravel bed and it is essential to ensure that the system functions in fully aerobic conditions (Pérez-Marín et al., 2009). The wastewater slowly percolates downwards through the gravel media undergoing filtration and coming into contact with the dense microbial populations on the surface of the media particles. Treated wastewater is collected at the bottom of the treatment zone. The cultivation zone is situated over the treatment zone and it is composed of a sandy substrate. This configuration eliminates the risk of public contact with the partially treated wastewater and avoids smells. A combination of symbiotic treatments could be placed in series, depending on the organic load of the wastewaters being treated. For urban wastewaters a pretreatment step followed by a four-step procedure is usually needed.

The main purpose of this manuscript is to evaluate the nitrogen removal and its transformation in two different pilot-scale combinations of the symbiotic treatment® installed in the Wastewater Treatment Experimental Centre located in the Campus of Espinardo (University of Murcia, Spain), as well as to evaluate the overall performance of the two pilot plants.

2. MATERIALS AND METHODS

2.1. Description of pilot plants

Before the symbiotic treatment, wastewater is pretreated. The pretreatment consists of two subsequent rotary sieves with 0.5 and 0.25 mm sieve openings, respectively, a clarifier and a 130 μm mesh ring filter. Pretreated wastewater enters simultaneously to two parallel pilot plants. Each one of them has a different combination of four symbiotic treatments in series. Figures 2 and 3 show the layouts of the two pilot plants. Details of both configurations are given in Table 1.

2.1.1. Pilot plant with horizontal distribution

The horizontal distribution (Figure 2) consists of four symbiotic treatments located in series, being necessary filtering the effluent from one stage, through a 130 µm mesh ring filter, before entering the next one. The filtered effluent from each symbiotic treatment flows to the next stage by pumping with a peristaltic pump. All the stages in this distribution are identical and have two differential zones (Figure 1): the treatment and the cultivation zone. The symbiotic treatment frames are cylindrical (30 cm diameter) and are filled with carbonate gravel, 12 mm to 30 mm in diameter, with an average porosity of 40 percent. The layer of carbonate gravel is 1 m and it corresponds with the treatment zone. The cultivation zone is situated over the treatment zone and it is composed by 20 cm depth of sandy substrate, 0.5 mm to 1 mm in diameter. The feeding system is located between the two zones and it consists of two underground drips (4L/h·drip), uniformly distributed over the gravel bed surface. Each stage has a surface of 0.071 m^2 and treats 8 L/h of wastewater, therefore this configuration is feeding at a hydraulic load of 0.113 $m^3/m^2 \cdot h$. This pilot plant operates with specific loads (mean value ± standard deviation) of 59.1 ± 32 g $COD/m^2 \cdot h$ and 5.8 ± 2.2 g $TKN/m^2 \cdot h$.

2.1.2. Pilot plant with vertical distribution

The vertical distribution (Figure 3) consists of four symbiotic treatments located in series and arranged one below the other. Each symbiotic treatment is placed inside a plastic container, 90 cm wide x 65 cm long x 50 cm depth, which is perforated at the bottom. In this configuration, the cultivation zone and the distribution system for feeding wastewater are only placed in the first stage (the top one). This stage is composed by 20 cm depth of sandy substrate (the cultivation zone) located over 20 cm depth of carbonate gravel (the treatment zone). The soils (sand and carbonate gravel) were identical to those used in the pilot plant with horizontal distribution. The feeding system is located between the two zones and it consists of 12 undergrounds drips (4L/h·drip), uniformly distributed over the gravel bed surface. The rest of stages are only composed by the treatment zone, a 40 cm depth of gravel (nominal mean diameter of particles, 20 mm). The effluent of each stage falls by gravity to next stage, without filtering, going through a void zone (10 cm) which is situated between two consecutives stages, favoring the oxygen supply. This pilot plant treats 48 L/h and has a surface of 0.585 m^2, therefore its hydraulic load is 0.082 $m^3/m^2 \cdot h$. This configuration operates with specific loads (mean value ± standard deviation) of 37.2 ± 20 g $COD/m^2 \cdot h$ and 3.6 ± 1.4 g $TKN/m^2 \cdot h$

The effluent of the fourth stage in both pilot plants is considered the final effluent.

It is interesting to point out that wastewater were continuously feeding by means of drips, drop to drop, in both configurations. This fact, associated to the continuous drainage, avoids saturating the gravel beds and provides a high uniformity of wastewater flow through the pores of the media.

2.2. Sampling and methods.

Spot water samples were taken from both symbiotic treatment pilot plants twice a month for one year (from June 2007), from the raw wastewater (RW), the filtered wastewater (IC) and the exit of the four stages of treatment (E1HC to E4HC for the horizontal distribution and E1VC to E4VC for vertical distribution). The following analytical determinations were made to all the samples: dissolved oxygen, total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4^+-N), nitrates, nitrites and biochemical oxygen demand (BOD_5). Raw wastewater and effluents of the fourth stage in the two pilot plants were also analyzed for: pH, conductivity, total suspended solids (TSS), chemical oxygen demand (COD), total phosphorous (TP) and phosphates (PO_4^{3-}). All water samples were analyzed in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 1995).

3. RESULTS AND DISCUSSION

3.1. Overall pilot plants performance.

Both pilot plants were operated for over a year and their performances were monitored. Table 2 reports the minimum, maximum and average value ± standard deviation (parenthesis) of each one of the water quality parameters studied for the raw wastewaterter (RW), the filtered wastewater (IC) and the effluent of the two pilot plants (E4HC and E4VC) and for the pollutant percentage removal of each pilot plant.

As it can be seen, water quality varied considerably over the experimental period due to the variable discharge of wastewater coming from some installations located at the University Campus like the veterinary hospital, the laundry, the laboratories of the faculty of fine arts, etc., which alters the typical raw wastewater quality. With these levels of pollutants, the wastewater can be classified as a strong domestic wastewater according to Metcalf&Eddy (Metcalf&Eddy, 1995). The influent was characterized by a high BOD_5/COD ratio, ranging from 0.2 to 0.7, which means that most of the organic compounds in influent are biodegradable. This fact facilitates the treatment in the symbiotic beds.

After the treatment in the two pilot plants, the pH values were similar to the initial ones and within the acceptable ranges for the growth of the microorganisms for digesting organic matter (6.6–8.5). Water conductivity did not change greatly with the treatment and its value oscillates, in the study period, between 1.5 and 3.6 mS/cm. Dissolved oxygen was higher in effluent than in influent as the results of passive oxygenation and it was noticeable that treatment takes place in aerobic conditions. Whereas the horizontal distribution provided the greater removals for TSS, COD, BOD_5, TKN, NH_4^+-N and TP, both configurations efficiently removed these parameters. In general terms, effluents of both configurations comply with the standards´ criteria set by the 91/271/EEC Directive for the disposal of treated domestic effluents.

3.2. Nitrogen transformation in the two symbiotic treatment pilot plants.

Figure 4 depicts the variation of the different nitrogen species along the symbiotic stages in the two pilot plants. In the box plots, the upper and lower box indicate 25th and 75th percentile, the whiskers are the 5th and 95th percentile, the symbols represent the outliers, the solid line is the median and the dotted line is the mean. Nitrite concentration is not showed because no significant levels of nitrite were observed along the treatment. The low concentration in nitrite is in agreement with the results reported by Arias et al. (2001) and Prochaska et al (2007) for the operation of similar systems, vertical subsurface constructed wetlands. As it can be seen, the concentration of TKN and NH_4^+-N decreased significantly through the treatment, in both pilot plants. Greater removals for TKN and NH_4^+-N took place in the horizontal distribution. This fact indicates that the greater depth of gravel bed in the horizontal distribution and so, the higher retention time, favor the removal of TKN and NH_4^+-N.

Nitrogen transformations in the symbiotic treatment could include uptake by living organisms, nitrification, denitrification, ammonia volatilization, adsorption and cation exchange for ammonium. These mechanisms have been demonstrated to be important in wetlands (Yang et al., 2001; Sun et al., 2005; Vymazal, 2007; Lavrova and Koumanova, 2009). The reduction of organic nitrogen and ammonia-nitrogen is almost balanced by the increase in nitrite and nitrate concentrations in wastewater, as it can be seen in Figure 5 which depicts the total nitrogen concentration along the symbiotic stages in the two pilot plants. It seems that the organic nitrogen is decomposed by microorganisms to ammonia nitrogen and ammonium is oxidized to other form of nitrogen (nitrites and nitrates). Nitrification is likely to be a major process to remove ammonia nitrogen in this study.

There are several factors that can influence in nitrification like pH, temperature, dissolved oxygen or organic matter load.

With regard to pH, an optimal pH of 7.5 and 8.5 has been reported for nitrification (Mara and Horan, 2003). And so, the pH conditions in the symbiotic treatment (Table 2) are adequate to get the main route of ammonia nitrogen removal.

By other way, several studies have shown that nitrification is inhibited by water temperatures <10 ºC and drops off rapidly below 6 ºC (Herskowitz et al., 1987; Xie et al., 2003), although Cookson et al. (2002) suggested that nitrifying communities can adapt to temperature changes and may maintain their activity at lower temperatures by metabolic adaptation. No effects of temperature in nitrification have been observed in this study where temperature in both pilot plants ranged between 10 ºC and 33 ºC (Table 2).

Sasikala et al. (2009) found that in vertical subsurface wetlands the oxygen levels were lower in static systems than for fluctuating regimes. In the first ones soils are water-saturated whereas in the last ones soils are water-unsaturated and the draining-off of porewater induced the atmospheric oxygen to enter the bed (Tanner et al., 1999). The gravel in symbiotic treatment is always water-unsaturated, and so nitrification is enhanced. The continuous feeding and drainage of the system, drop to drop, ensures that the void spaces of the bed media can be filled up with air simultaneously to the treatment. And so, although the oxygen is trapped by the liquid for the degradation of the organic matter and the nitrification, the air in the void spaces is rapidly replaced by fresh air. Summarizing, the symbiotic treatment assures that the beds should function in fully aerobic conditions, guaranties the existence of an important air-filled pore space; and so enhance the oxygen supply when comparing with similar systems like wetlands. This fact could be corroborated by the high content of dissolved oxygen in all the samples and by the increase in dissolved oxygen along the treatment (Figure 6).

Similar that occurs in wetlands (Faulwetter et al., 2009; Fountoulakis et al., 2009), organic mass loading rates are supposed to affect nitrification in symbiotic treatment. There is competition for oxygen between heterotrophic and nitrifying bacteria which should be more intense at elevated organic matter concentrations (van Niel et al., 1993; Dalhammar et al., 1999; Truu et al., 2005). Nitrification rates (g-N/m^2·h) and BOD_5/TKN ratios were calculated throughout the treatment (Figure 7). A relationship between nitrification rates and BOD_5/TKN ratio were observed. The highest nitrification rates were produced in the three last stages of treatment which correspond with the smaller values of the BOD_5/TKN ratio. It was confirmed that nitrifying bacteria requires low concentrations of organic matter to transform ammonia nitrogen in nitrates (condition that is achieved in the last stages). Besides, comparing the effluent of the same stage in the two pilot plants it was noticeable that the horizontal distribution, with higher organic matter removals, achieves higher nitrification rates. As it has been mentioned above, the higher retention times applied in the horizontal distribution enhance the potential of nitrification.

This fact indicates that the greater depth of gravel bed in the horizontal distribution and so the higher retention time favor the removal of TKN and NH_4^+-N.

Ammonia nitrogen removal could be estimated by a first-order plug flow kinetic model:

$$Ne = Ni \cdot \exp(-K_N \cdot t) \qquad \text{(eq.1)}$$

where N_e and N_i (mg/L) are the ammonia nitrogen in effluent and influent, respectively, K_N (h^{-1}) is the constant rate and *t* is the hydraulic retention time.

Hydraulic retention time is calculated by the equation (Kadlec and Knight, 1996):

$$t = (n \cdot A \cdot d)/Q \qquad \text{(eq.2)}$$

where d (m) is the depth of the symbiotic bed, n is the effective porosity of the media (%) (n was estimated as 0.4), A is the cross-section of the bed (m^2) and Q is the average flow through the bed (m^3/h).

And so, the overall removal in this system can be estimated as follows:

$$Ne = Ni \cdot \exp\left(-(K_N \cdot n \cdot A \cdot d)/Q\right) \qquad \text{(eq.3)}$$

The results of the application of equation 3 to the symbiotic treatment in the two pilot plants are represented in Figures 8 and 9. The application of the model gives acceptable results ($r > 0.7$), indicating that ammonia nitrogen in effluent was proportional to ammonia nitrogen in influent and exponential to contact time. Higher values of K_N where obtained at the last stages in both pilot plants, which is in concordance with the favored conditions for nitrification in these stages. Besides, the values of constant rate in the three last stages of the horizontal distribution and the two last stages of the vertical distribution, stages where nitrification takes place predominately, are similar. It was noticeable that high ammonia nitrogen removal has been achieved with the two combinations of symbiotic systems.

CONCLUSIONS

The application of symbiotic treatment as a reliable wastewater technology may be a viable choice in order to fulfill the discharge requirements. The configuration of the symbiotic treatment guaranties the required oxygen supply for both organic matter degradation and nitrification. The system has demonstrated tolerance to the variation of organic load and the combination of symbiotic treatment was found to be very effective. High ammonia nitrogen removal has been obtained in both combinations of the symbiotic treatment and nitrification has been pointed up as the major process to remove ammonia nitrogen.

Even though comparison between the two parallel pilot plants is not direct, because of the difference in hydraulic load, bed depth and for the existence/absence of intermediate filtration, the present study provides interesting results that could be consider for the combination of symbiotic treatments. The comparison of the effluent quality in the two pilot plants demonstrates that even though the horizontal distribution is more efficient in pollutant removal than the vertical distribution, both configuration complies with the standards´ criteria set by the 91/271/EEC Directive for the disposal of treated domestic effluents. And so, the lower construction and maintenance cost as well as the lower land and power requirements for the vertical distribution as compared to the horizontal distribution balance the relatively lower pollutant removal efficiencies.

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Table 1. Details of the two pilot plants.

Pilot plant	Horizontal distribution	Vertical distribution
Bed		
Number of beds	4	4
Shape	Cylindrical	Cuboid
Sizes of tanks	Diameter: 30 cm Height: 1.30 cm	Width: 65 cm Length: 90 cm Height: 50 cm
Bed surface area	0.071 m^2	0.585 m^2
Layers of soils	For the four beds: Upper media: 20 cm of sand Lower media: 1 m of gravel	For the first bed (the top one): Upper media: 20 cm of sand Lower media: 20 cm of gravel For the other three beds: Media: 40 cm of gravel
Feeding system	2 drips in each bed (4 L/h·drip)	12 drips in the first bed (4 L/h·drip)
Characteristics of the filtering media		
Mineralogy	Carbonate gravel	
Diameter	Range between 12 mm and 30 mm Nominal mean diameter of particles, 20 mm	
Porosity	40 %	
Hydraulic		
Flow	Vertical	Vertical
Feeding	Continuous	Continuous
Hydraulic load	0.113 $m^3/m^2 \cdot h$	0.082 $m^3/m^2 \cdot h$
Raw flow	8 L/h	48 L/h
Equipment		
Filters between stages	Yes One filter for stage (Azud, 130 mesh ring filter)	No
Pumping between stages	Yes One peristaltic pump for stage	No

Table 2. Physico-chemical characterization of raw wastewater and the influent and the effluent of the two pilot plants.

			Vertical distribution		Horizontal distribution	
Parameter	RW	IC	Effluent	Average removal (%)	Effluent	Average removal (%)
pH	6.9-8.5 (7.8±0.36)	6.9-8.2 (7.4±0.36)	7.4-8.1 (7.4±0.15)	—	7.3-8.3 (7.9±0.26)	—
Conductivity (mS/cm)	1.5-3.6 (2.3±0.62)	1.7-3.0 (2.4±0.33)	1.6-2.9 (2.1±0.34)	—	1.7-2.8 (2.3±0.3)	—
$[O_2]$dissolved (mg O_2/L)	0.98-6.7 (3.0±1.7)	0.28-4.6 (1.8±1.1)	4.0-10.6 (7.2±1.9)	—	3.9-11.1 (8.4±1.9)	—
Temperature (ºC)	15.6-27.3 (21.8±4.7)	13.3-28.8 (21.7±5.3)	10.3-27.7 (18.4±5.8)	—	11.7-32.8 (20.2±6.5)	—
TSS (mg/L)	177-1706 (446±329)	36-886 (215±193)	15-74 (36.1±18.9)	74.5-96.5 (90.0±6.0)	2.5-19 (7.4±4.7)	94.2-99.7 (98.0±1.4)
COD (mg O_2/L)	470-1902 (851±353)	226-1385 (523±283)	38.6-171 (76.4±33)	78.4-95.7 (95.5±5.3)	11-68 (34±17.5)	91.4-98.4 (95.8±2.2)
BOD_5 (mg O_2/L)	100-620 (433±149)	110-400 (231±99)	3-70 (19.2±18.5)	86.5-99.1 (89.5±3.5)	1-22 (5.2±5)	95.0-99.7 (98.8±1.1)
TKN (mg N/L)	29-107 (47.4±19)	18-87 (51.0±19)	0.8-30.4 (12.8±8.5)	34.8-98.5 (69.6±17)	0.2-46.7 (4.3±10.5)	11.9-99.7 (90.4±20)
NH_4^+-N (mg N/L)	22-81.3 (38.6±15)	14.1-74.9 (43.3±16)	0.3-27.6 (11.7±8.6)	28.9-99.3 (65.6±20)	0-40.9 (4.3±10.7)	4.7-99.9 (86.4±24)
Nitrates (mg N/L)	0-1.4 (0.3±0.6)	0-0.9 (0.2±0.1)	8.9-72.0 (28.2±18.1)	—	9.2-73.6 (40.2±18)	—
TP (mg P/L)	4.2-19.7 (10.8±3.6)	4.6-19.6 (7.8±3.4)	2.8-7.8 (4.7±1.2)	-42.9-79.7 (49.7±28)	2.7-6.6 (4.5±1.1)	-26.2-80 (51.9±26)
PO_4^{3-} (mg P/L)	2.3-12.9 (4.4±2.3)	1.9-6.0 (3.9±1.1)	2.5-6.6 (3.4±1)	-20-48.9 (10.8±23)	2.1-6.61 (3.8±1)	-56.5-68.2 (3.1±35)

Figures captions.

Figure 1. Scheme of the symbiotic treatment.

Figure 2.- Layout of the pilot plant with horizontal distribution.

Figure 3.- Layout of the pilot plant with vertical distribution.

Figure 4. Evolution of the nitrogen species along the treatment in the two pilot plants.

Figure 5. Evolution of the total nitrogen along the treatment in the two pilot plants.

Figure 6. Evolution of the dissolved oxygen along the treatment in the two pilot plants.

Figure 7. Relationship between the BOD_5/TKN ratios and nitrification rate along the symbiotic beds.

Figure 8. Application of the first order plug flow model for NH_4^+-N removal in the symbiotic beds of the horizontal distribution.

Figure 9. Application of the first order plug flow model for NH_4^+-N removal in the symbiotic beds of the vertical distribution.

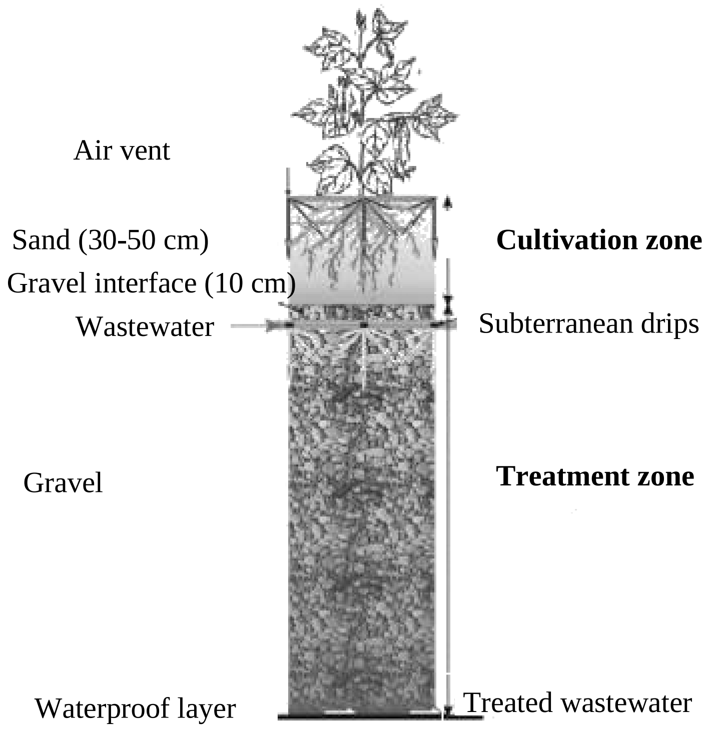

Air vent
Sand (30-50 cm)
Gravel interface (10 cm)
Wastewater
Gravel
Waterproof layer
Cultivation zone
Subterranean drips
Treatment zone
Treated wastewater

Figure 1.

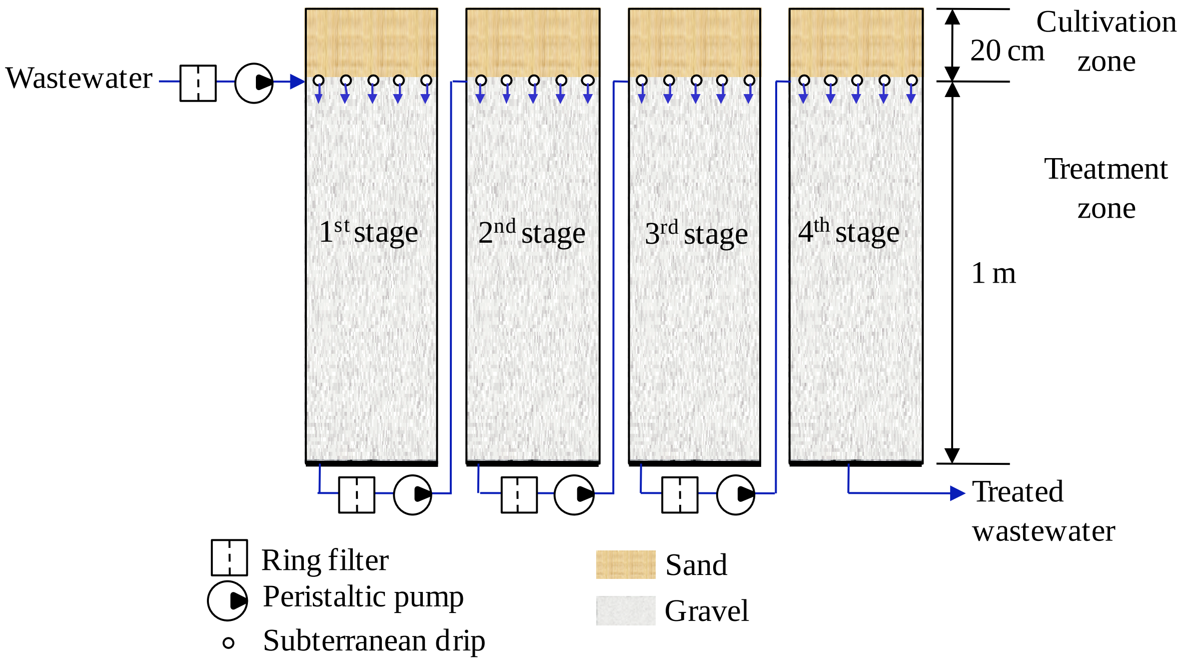

Wastewater
1st stage
2nd stage
3rd stage
4th stage
20 cm
Cultivation zone
Treatment zone
1 m
Treated wastewater
Ring filter
Peristaltic pump
Subterranean drip
Sand
Gravel

Figure 2.

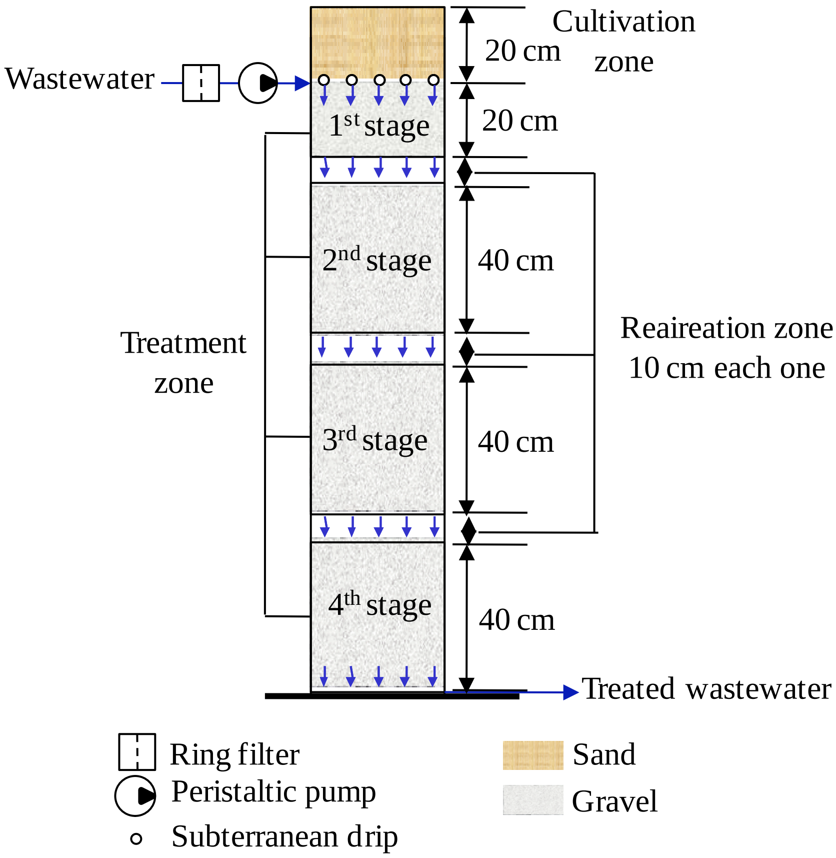

Cultivation zone
20 cm
Wastewater
1st stage
20 cm
2nd stage
40 cm
Reaireation zone
10 cm each one
Treatment zone
3rd stage
40 cm
4th stage
40 cm
Treated wastewater
Ring filter
Peristaltic pump
Subterranean drip
Sand
Gravel

Figure 3.

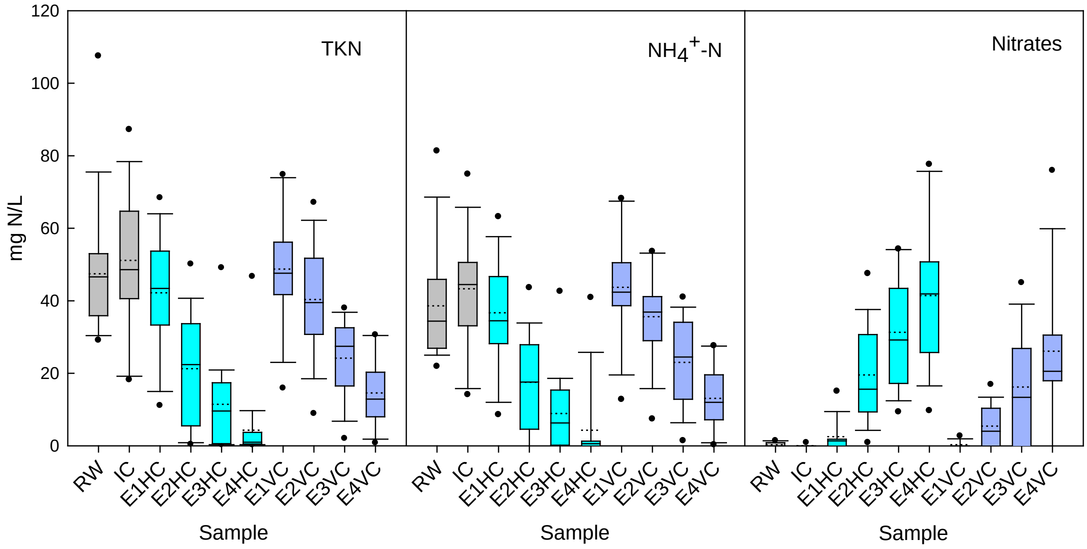

TKN
NH4+-N
Nitrates
mg N/L
Sample
RW
IC
E1HC
E2HC
E3HC
E4HC
E1VC
E2VC
E3VC
E4VC
0
20
40
60
80
100
120

Figure 4.

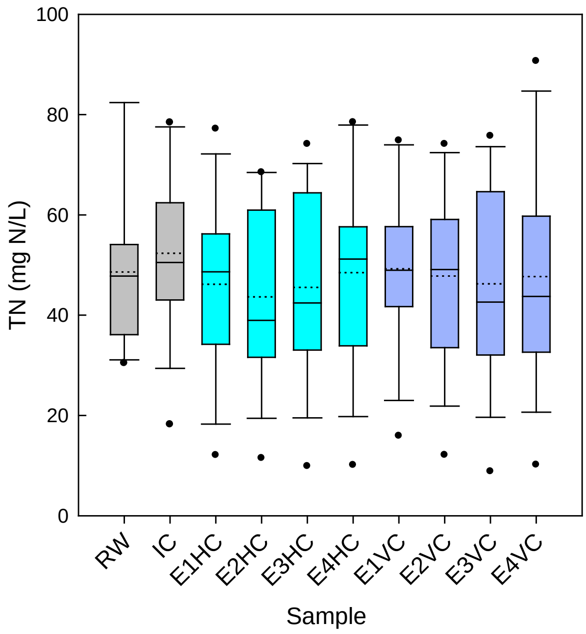

100
80
60
40
20
0
TN (mg N/L)
RW
IC
E1HC
E2HC
E3HC
E4HC
E1VC
E2VC
E3VC
E4VC
Sample

Figure 5.

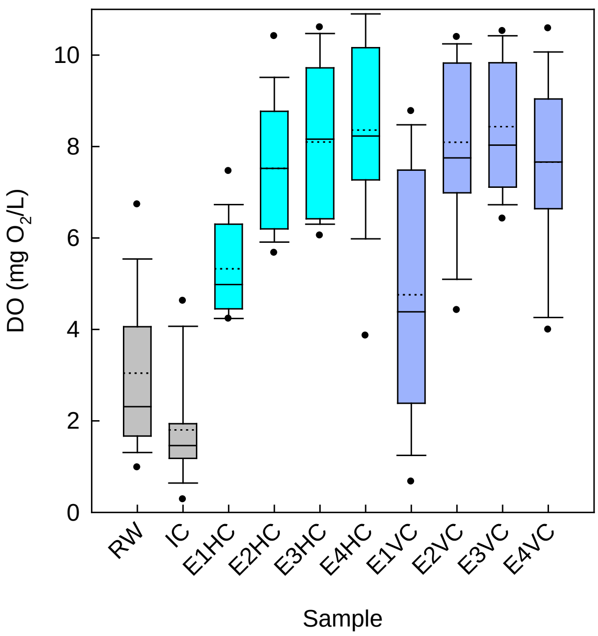
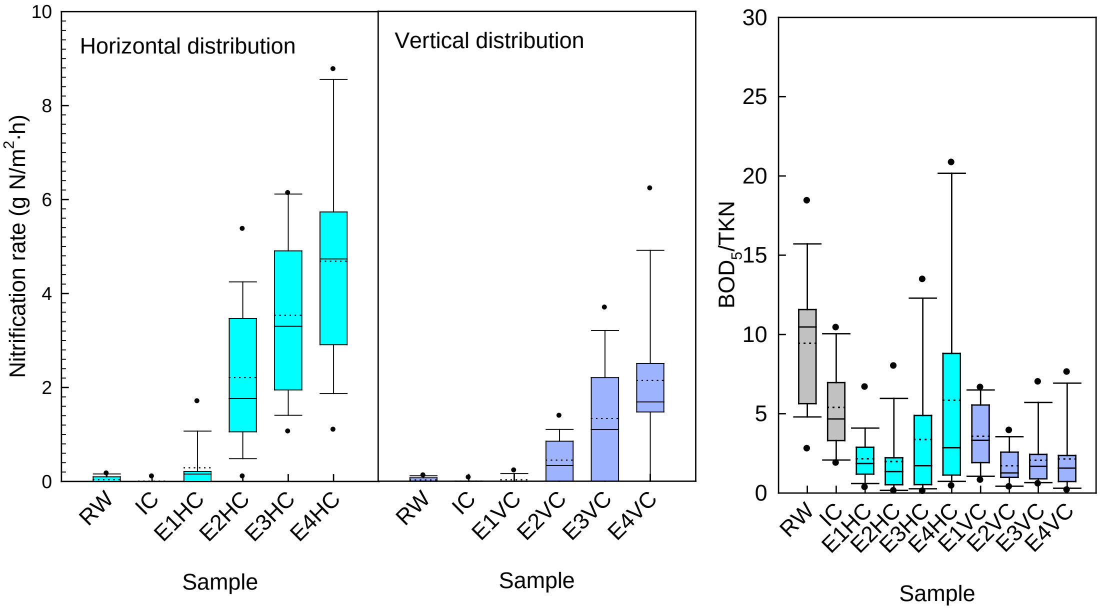

DO (mg O_2/L)
0
2
4
6
8
10
RW
IC
E1HC
E2HC
E3HC
E4HC
E1VC
E2VC
E3VC
E4VC
Sample

Figure 6.



Horizontal distribution
Vertical distribution
Nitrification rate (g N/m²·h)
10
8
6
4
2
0
RW
IC
E1HC
E2HC
E3HC
E4HC
Sample
RW
IC
E1VC
E2VC
E3VC
E4VC
Sample
BOD5/TKN
30
25
20
15
10
5
0
RW
IC
E1HC
E2HC
E3HC
E4HC
E1VC
E2VC
E3VC
E4VC
Sample

Figure 7.

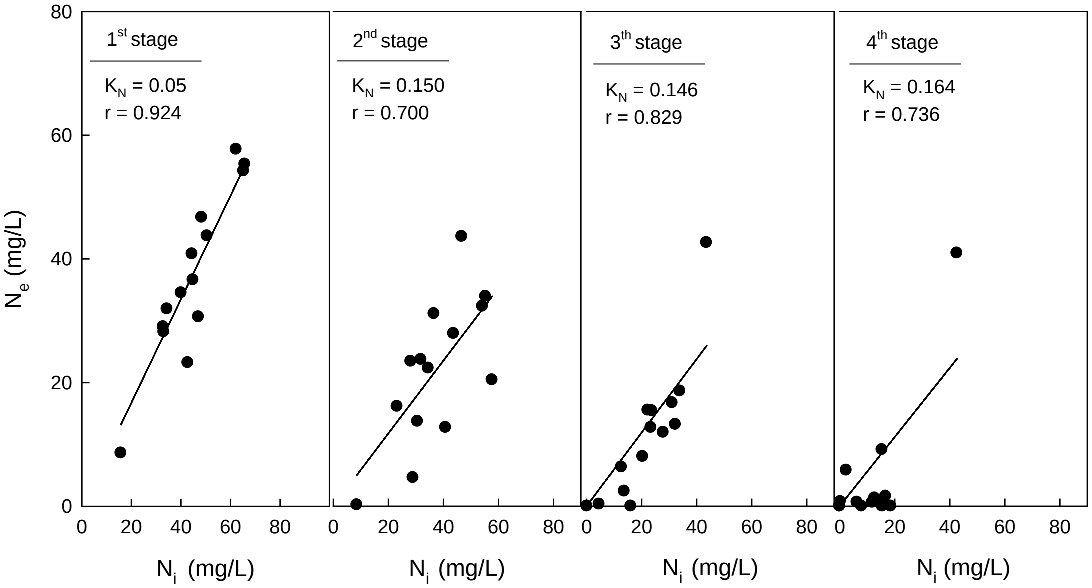

1st stage
K_N = 0.05
r = 0.924
2nd stage
K_N = 0.150
r = 0.700
3th stage
K_N = 0.146
r = 0.829
4th stage
K_N = 0.164
r = 0.736
N_e (mg/L)
N_i (mg/L)
0
20
40
60
80

Figure 8.

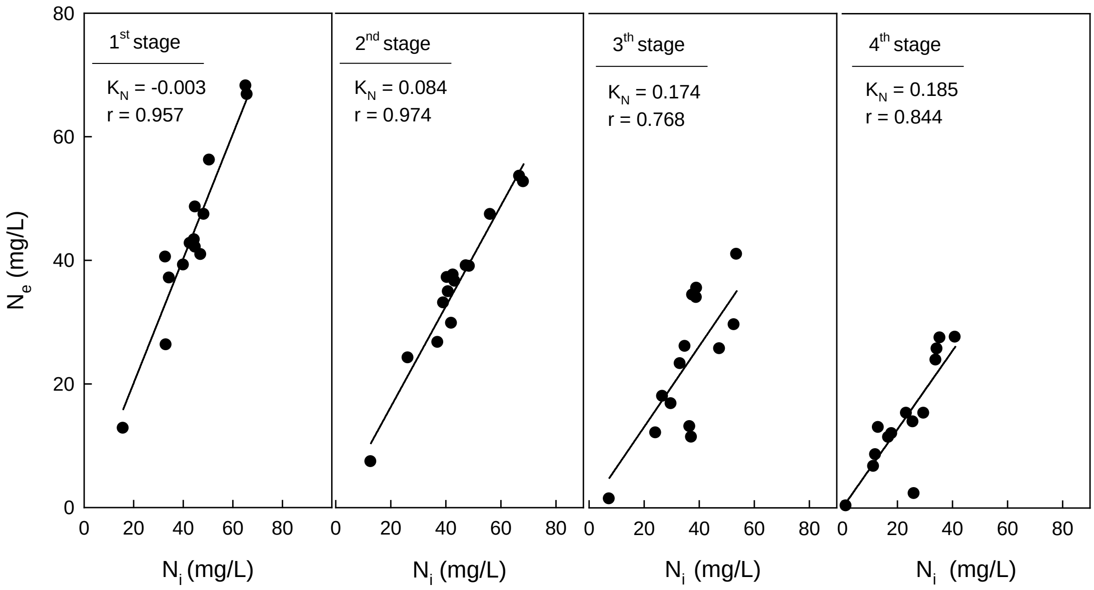

1st stage
K_N = -0.003
r = 0.957
2nd stage
K_N = 0.084
r = 0.974
3th stage
K_N = 0.174
r = 0.768
4th stage
K_N = 0.185
r = 0.844
N_e (mg/L)
N_i (mg/L)
0
20
40
60
80

Figure 9.