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Nitrification and Denitrification Process Employing Three Different Sunken Materials Types in Biological Aerated Filter (BAFs)

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***Abstract*—The overall aim of this research was to use easily obtained materials as an attached growth zone in the treatment of municipal wastewater. Where investigate their performance in the nitrification and denitrification process. were using three identical pilot-scale reactors of the biological aerated filter system BAFs, down-flow mode. Operated at ambient air temperature ranged from 8 ◦C to 29◦C with a mean 17.93 ±7.27 ˚C. While the hydraulic retention time HRT was 12-hours and the influent was 100% recirculation, with daily backwashes. As results of the experiments showed that the greatest mean removal efficiency of the NH_4^+-N was in the reactor employing activated carbon-based material bed where achieved 90.11%. And then 87.74%, 85.17% respectively for the reactor employing sand-based material bed, and the reactor employing ceramic particle-based material bed. In addition, the pilot-scale reactors of the BAFs were able to nitrify between 0.23±0.22 Kg NH_4^+-N/m^3/day to 0.24±0.21 Kg NH_4^+-N/m^3/day.**

***Index Terms*—Ammonium NH_4^+, Materials-based bed. Nitrite NO_2^-. Nitrate NO_3^-.**

I. INTRODUCTION

The term biological aerated filters systems BAFs came from the combination of air and the filtering action of the bacteria. BAFs typically consists of a medium that treats carbonaceous and nitrogenous matter using biomass fixed to the media and capturing the suspended solids in the media [1].

In a BAF system, packing media plays a significant role to meet effluent quality requirements. The granular media employed the composition of the biofilter bed for solid interception and solid-liquid separation, as well as the carrier of biofilm. The characteristics of the filter media have a great impact on the treatment efficiency, and at the same time, determine the investment of capital construction and operating costs greatly [2].

Nitrification is the term used to describe the overall process by which ammonium NH_4^+ is converted to nitrate $NO_3^{-.}$ Microorganisms involved in conventional nitrification are characterized as lithotrophic ammonia and nitrite-oxidizing bacteria [3]. The partial nitrification process is based on the fact that nitrite is an intermediary compound in both nitrification and denitrification steps: partial nitrification up to nitrite is performed followed by nitrite denitrification [4,5], biological nitrification-denitrification via nitrite pathway shown in Figure 1.

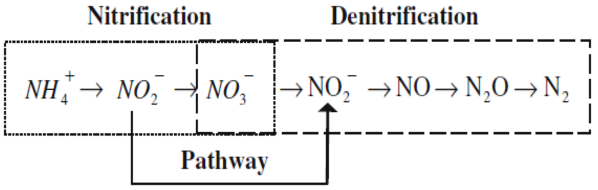

Figure 1. Biological nitrification-denitrification via nitrite pathway [6].

The common method is to remove nitrogen by nitrification which is a two-step process where ionized ammonia is oxidized first to nitrite NO_2^- and then nitrite is oxidized to nitrate NO_3^-. Nitrosomonas and Nitrosospira oxidize ionized ammonia (ammonia) to nitrite while Nitrobacter and Nitrospira do the rest [7].

$$NH_4^+ + 1.5O_2 \xrightarrow{\text{Nitrosomonas and Nitrosospira}} NO_2^- + 2H^+ + energy$$

$$NO_2^- + 0.5O_2 \xrightarrow{\text{Nitrobactor and Nitrospira}} NO_3^- + energy$$

In this process, nitrification is used as a prime method to remove ammonia by converting it to nitrate in the water. This requires a high aeration rate to supply sufficient oxygen and maintain sufficient energy needs in the system. Moreover, as nitrifying bacteria can gather very little energy from the nitrification process, their bacterial growth and reproduction are relatively low. Only 0.06 kg of nitrifying bacteria can be produced from every kg of ammonia nitrification [7]. Another limitation of this process is that nitrifying bacteria are only active and reproduce between 5°C and 40°C. The best nitrification rate occurs at 30°C but it almost stops below 5°C. Free ammonia loading in the range of 1-5 mg/d/m3 inhibits selective oxidization and the inhibition highly depends on ammonia concentration and pH, temperature, DO limit, and growth rate of ammonium oxidizers over nitrite oxidizers [8].

The second approach is simultaneous nitrification and denitrification in the system. In this case, aeration energy and chemical use can be reduced effectively as ammonium and nitrite act as electron donors and acceptors respectively [9]. Denitrifying bacteria are facultative anaerobic bacteria that use nitrite and nitrate for degradation of CBOD.

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$$6NO_3^- + 5CH_3OH \xrightarrow{\text{Facultative anaerobic bacteria}} 3N_2 + 5CO_2 + 6OH^-$$

Accidental denitrification due to an accidental anoxic condition can happen with poorly settling solids in the BAFs. This is referred to as “clumping” or “dark sludge rising” [7]. Within the sludge blanket, facultative anaerobic bacteria use nitrite ions to degrade CBOD which produces N_2 gas. Many of these gases are taken by floc particles and cause buoyancy of the solids, and thus solids rise to the surface.

In a biological aerated filter BAFs, nitrogen removal is always economical if ammonia can be nitrified to nitrite and then denitrified in one process. Oxygenation can be reduced by 25 % and electron donor requirements are 40 % less. Moreover, the denitrification rates with nitrite ions are usually 1.5-2.0 times faster than with nitrate ions [10].

Denitrification in the BAFs can be significantly affected if a high concentration of suspended solids (SS) is present in the effluent. That is why BAFs is commonly applied after primary treatment in municipal wastewater systems [11,12]. Improper treatment of SS can reduce BAFs performance by affecting the mass transfer of oxygen and substrates into the biofilm [13]. The presence of sufficient carbon accelerates denitrification during the nitrogen removal process [14].

Mainly, this research is designed to answer the question: What is the efficiency of the activated carbon-based material bed, sand-based material bed. and, the particle-based material bed in the nitrification and denitrification process in the biological aerated filters system BAFs?

II. MATERIALS AND METHODS

A. *Set-up and operation of the pilot-scale reactors of BAFs*

Three identical pilot-scale reactors of the biological aerated filters system BAFs. Where operated for 33 days including resolved operating problems. Where start-up the experiments in the laboratory of the Technical University of Civil Engineering of Bucharest at Colentina. The pilot-scale reactors of the BAFs were constructed using PVC pipe, Figure 2. Each reactor was 0.10 m internal diameter, 2.76 m height, and 0.20 m clearance at the head of the reactors to allow the influent recirculation, were 1.00 m the height of the materials-based bed as biomass support as an attached growth zone. Where the first reactor bed was contained 7.855 L of activated carbon-based material bed, the second reactor bed was contained 7.855 L of sand-based material bed, and the third reactor bed was contained 7.855 L ceramic particle-based material bed based on a working volume 65.037 L as 21.679 L in each reactor.

The pilot-scale reactors of BAFs were fed with municipal wastewater from the top which down-flow mode. Where the mean influent flow rate was 0.02859 m^3/h. And mean hydraulic loading was 0.0108 $m^3/m^2/h$ which 0.2592 $m^3/m^2/d$. The hydraulic retention time HRT was 12-hours. Where the influent was 100% recirculation. The backwashed every day for the whole experimental period. While airflow was controlled by a glass VA flowmeter at a liquid: air ratio 1:10 L min^{-1} capacity during normal operation. The pilot-scale reactors of BAFs have been operated at ambient air temperature ranged from 8 ◦C to 29◦C with a mean 17.93 ± 7.27 ˚C.

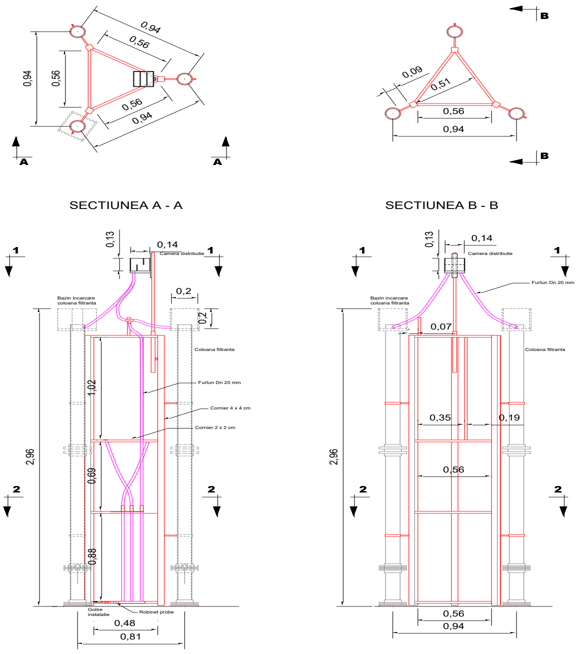

Figure 2. Schematic diagram the pilot-scale reactors of biological aerated filter system BAFs.

B. *Materials-based bed employing in the pilot-scale reactors of BAFs*

Biomass attachment is an important consideration in biological aerated filter system BAFs. From Table 1. it can be seen that the ceramic particle-based material bed has an intermediate particle size of 3.28±2.14 mm, and fine particle size of 0.78±0.60 mm, 0.95±0.58 mm, respectively for activated carbon-based material bed, and sand-based material bed.

Table 1. Properties of materials-based bed used in pilot-scale reactors of BAFs.

Parameter	Activated carbon-based material bed	Sand-based material bed	Ceramic particle-based material bed
Materials bed height	1.00 m	1.00 m	1.00 m
Particle size	0.78±0.60 mm	0.95±0.58 mm	3.28±2.14 mm
Volume bed	7.855 L	7.855 L	7.855 L

Note: particle size shown are mean ± standard deviation.

Generally, all three material-based beds employing in the pilot-scale reactors of BAFs resistant to attrition, chemically inert, had different particle sizes, It can be considered acceptable for use as biomass support as attached growth zone.

C. *Analysis of the samples*

Generally, the effluent samples were drawn at the end of the pilot-scale reactors run. during the experimental period was composite the samples of the influent and effluent took place on a daily basis, five times weekly. Where was measured the influent and effluent samples concentration included of soluble chemical oxygen demand sCOD, suspended solids SS, ammonium-nitrogen NH_4^+-N, nitrite-nitrogen NO_2^--N, nitrate-nitrogen NO_3^--N, total Kjeldahl Nitrogen TKN, dissolved oxygen DO, alkalinity as CaCO3, potential hydrogen pH, and temperature ◦C of the samples. Analyses the samples were conducted according to standard methods APHA, 2017 [15].

III. Results and Discussion

A. *Start-up of the experimental trials*

Throughout the duration of the experiments 33 days, where was the pilot-scale reactors of BAFs operated at ambient air temperature ranged from 8 ◦C to 29◦C with a mean 17.93 ±7.27 ˚C. While the hydraulic retention time HRT was 12-hours and the influent was 100% recirculation, with daily backwashes. The experiments were conducted during different influent volumetric loading applied to NH_4^+-N, Figure 4. where the mean influent was 0.001695±0.00 kg NH_4^+-N/m^3/day, and the mean influent volumetric loading applied of sCOD was 0.010758±0.00 kg/m^3/day. While the mean characteristics of the influent and effluent showed in Table 2. Start-up took time 24 days period until nitrification and denitrification were first observed, where the pilot-scale reactors of BAFs have achieved the steady-state conditions Figure 3. where the number of microorganisms increased, nitrification dominated.

Table 2. Characteristics of the effluent and efficiency of the removal during a period of testing conditions.

Parameter	Activated carbon-based material bed		Sand-based material bed		Ceramic particle-based material bed	
	Effl. mg/L	Rem. %	Effl. mg/L	Rem. %	Effl. mg/L	Rem. %
NH_4^+-N	0.31±0.37	90.11	0.38±0.44	87.74	0.46±0.46	85.17
NO_2^--N	0.24±0.31	90.10	0.25±0.32	89.84	0.28±0.34	88.32
NO_3^--N	0.16±0.24	91.84	0.19±0.27	90.28	0.21±0.29	89.03
TKN	1.42±0.95	86.37	1.58±0.97	84.82	1.70±1.00	83.69
sCOD	3.53±0.79	91.47	3.75±0.84	90.96	3.93±0.97	90.51
SS	4.00±1.92	94.24	4.62±2.50	93.34	11.62±4.62	83.27
pH	7.21±0. 20	___	7.22±0. 20	___	7.22±0. 20	___
DO	6.76±2.25	___	7.33±1.82	___	6.37±1.84	___
alkalinity as CaCO3	77.25±2.60	62.72	77.56±2.77	62.57	77.31±2.71	62.69
Sample ◦C temperature	16.48±1.68	___	16.70±1.44	___	17.12±1.37	___

Note: * Effl.= Effluent   Rem. = Removal.
* concentration shown are mean ± standard deviation
* data shown are 33-day running mean.

Nitrification is a sequencing biological oxidation process, which involved two different groups of bacteria. The first step of nitrification is the oxidation of ammonia to nitrite over hydroxylamine (NH_2OH), involving the membrane-bound ammonia mono-oxygenase (AMO) and the hydroxylamine oxidoreductase (HAO), and is carried out by ammonia-oxidizing bacteria (AOB); the second group, nitrite-oxidizing bacteria (NOB), further oxidizes nitrite to nitrate. To date, any one group of bacteria that can directly oxidize ammonia to nitrate has not been found [16, 17, 18, 19].

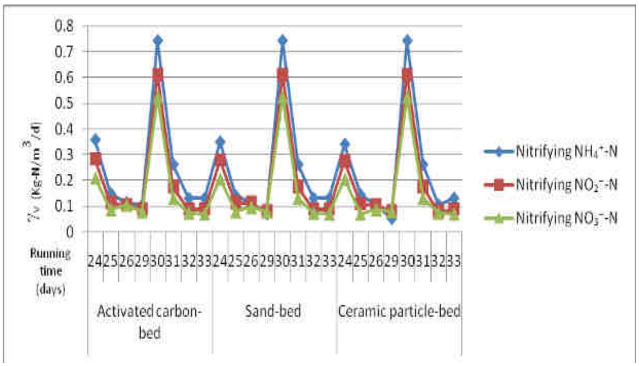

Figure 3. Nitrification and denitrification characteristics comparison between (activated carbon-bed, sand-bed, ceramic particle-bed)

B. *Ammonium-nitrogen NH_4^+-N removal pathways at three different sunken materials types*

As the results of the experiments showed that activated carbon-based material bed was able to nitrify of 0.24±0.21 Kg NH_4^+-N/m^3/day, Figure 4. The sand-based material bed was able to nitrify of 0.24±0.22 Kg NH_4^+-N/m^3/day. And the ceramic particle-based material bed was able to nitrify of 0.23 ±0.22 Kg NH_4^+-N/m^3/day. However, it can be seen in Table 2. that all three materials-based bed which employing in the pilot-scale reactors of BAFs have almost the same removal efficiency of COD and SS and there are no major differences in the nitrification efficiency mode, where the greatest mean removal efficiency of the ammonium-nitrogen NH_4^+-N was in the reactor employing activated carbon-based material bed where was achieved 90.11%. And the mean removal efficiency slightly percentage decreased where was 87.74%, 85.17%, respectively for the sand-based material bed, ceramic particle-based material bed. This results quite similar to the results of a study by Qiu et al, 2010 [2], this study was a comparison between zeolite, ceramic particle, and carbonate materials-based bed and the removal efficiency of COD and SS have almost the same and different nitrification mode.

As direct evidence of nitrification, more than 60 % of the influent alkalinity as CaCO3 was consumed. While the mean effluent of ammonium-nitrogen oxidized was 0.31±0.37, 0.38±0.44, and 0.46±0.46 mg NH_4^+-N/L, respectively for the sand-based material bed, ceramic particle-based material bed. The NH_4^+ was removed along with the COD consumption when the traditional nitrification and the middle process of denitrification (NO_2^- reduction to N_2) were inhibited [20]. The results of the removal efficiency of NH_4^+-N in this study were close to the results of a study by Rogaller et al, 1994 [21], In this investigation, the removal efficiency of NH_4^+-N was 90%. And the studied by Paffoni et al, 1990 [22], In this investigation, removal efficiency of NH_4^+-N was 95%. And the studied by Stensel et al, 1988 [23], In this investigation, removal efficiency of NH_4^+-N was between 74-80%.

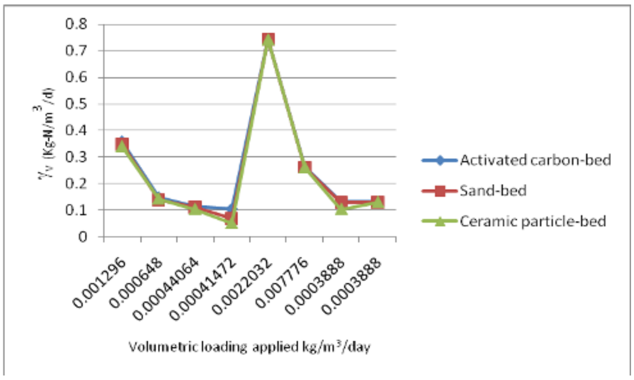

Figure 4. Nitrifying characteristics of ammonium-nitrogen NH_4^+-N comparison between (activated carbon-bed, sand-bed, ceramic particle-bed)

C. Denitrification pathways (NO_2^--N, and NO_3^--N) removal at three different sunken materials types.

Characteristics of NO_2^--N, and NO_3^--N removal at the activated carbon-based material bed. sand-based material bed. And, ceramic particle-based material bed. shown in Figure 5. and Figure 6. When the mean sCOD concentration decreased from 41.50±12.86 mg/L to 3.53±0.79 mg/L in the reactor employ the activated carbon-based material bed, the mean effluent of NO_2^--N was 0.24±0.31mg/L. and, the mean effluent of NO_3^--N was 0.16±0.24 mg/L.

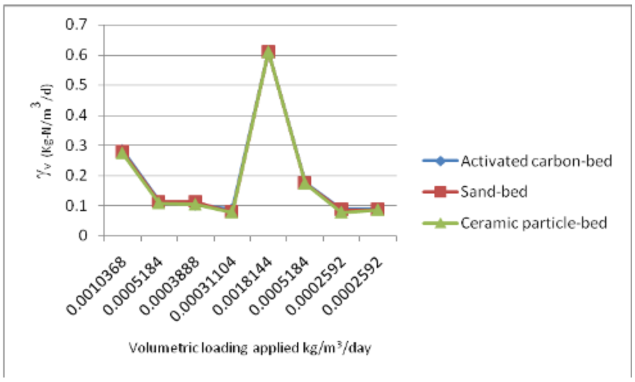

Figure 5. Nitrifying characteristics of Nitrite-nitrogen NO_2^--N comparison between (activated carbon-bed, sand-bed, ceramic particle-bed)

where the mean of TKN concentration was decreased from 10.46±6.74 mg/L to 1.42±0.95 mg/L with removal efficiency 86.379%. Furthermore, in the reactor employ the sand-based material bed the mean effluent of NO_2^--N was 0.25±0.32 mg/L with a removal efficiency of 89.847%, and the mean effluent of NO_3^--N was 0.19±0.27 mg/L with a removal efficiency of 90.284%. Likewise, they were the ceramic particle-based material bed the mean effluent of NO_2^--N was 0.28±0.34 mg/L, with a removal efficiency of 88.324%, and the mean effluent of NO_3^--N was 0.21±0.29 mg/L, with a removal efficiency of 89.030%. the mean effluent of sCOD concentration decreased where was 3.75±0.84 mg/L with a removal efficiency of 90.965% and 3.93±0.97mg/L with a removal efficiency of 90.514% respectively for reactor employ the sand-based material bed. And, reactor employs a ceramic particle-based material bed. Meanwhile, the mean effluent of TKN decreased where was 1.58±0.97 mg/L with a removal efficiency of 84.826% for reactor employ a sand-based material bed. And 1.70±1.00 mg/L with a removal efficiency of 83.692% for reactor employs a ceramic particle-based material bed.

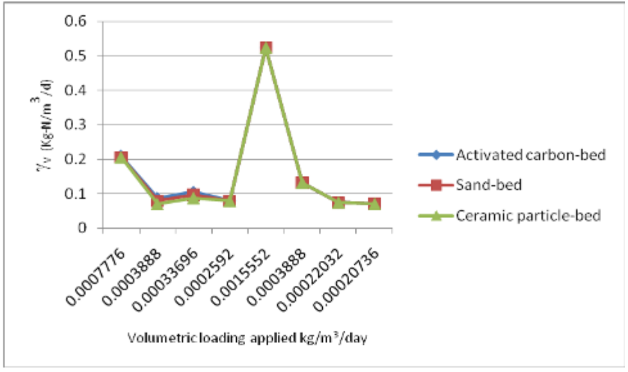

Figure 6. Nitrifying characteristics of Nitrate-nitrogen NO_3^--N comparison between (activated carbon-bed, sand-bed, ceramic particle-bed)

The results of removal efficiency of NO_3^--N in this study was close to the results of a study by Hwang et al, 1994 [24], In this investigation, the removal efficiency of NO_3^--N was 95%. And the studied by Ryhiner et al, 1994 [25], In this investigation, removal efficiency of NO_3^--N was 90%.

IV. CONCLUSION

A conclusion, To answer the research question, that activated carbon-based material bed, sand-based material bed and, the particle-based material bed as an attached growth zone proposed in this research their efficiency extremely well in the nitrification and denitrification process.

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