Technology review of the biological aerated filter systems BAFs for removal of the nitrogen in wastewater

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Abstract. The removal of nitrogen compounds in wastewater is receiving wide attention and the effluent standards will be tougher in the near future. The overall aim of this article is a review of biological aerated filter systems BAFs for removal of the nitrogen in wastewater. The BAFs technology is based on the principle of biofiltration where can be operated either in an upflow or downflow mode depending upon the position of the influent feed, where the media which attached growth zone can be either denser than water to give sunken media or less dense than water to produce floating media. The BAFs combines biological treatment and ammonia-nitrogen and solids removal in one reactor unit, where accumulated solids are removed from the BAFs through backwashing. Keywords. Bioreactor configuration; attached growth bioreactors; nitrification; denitrification.

1. Introduction
Nitrogen is an essential nutrient for plants and animals. Approximately 80 percent of the Earth’s atmosphere is composed of nitrogen, and it is a key element of proteins and cells. The major contributors of nitrogen to wastewater are human activities such as food preparation, showering, and waste excretion. The per capita contribution of nitrogen in domestic wastewater is about one-fifth of that for biochemical oxygen demand BOD. Total nitrogen in domestic wastewater typically ranges from 20 to 70 mg/L for low to high strength wastewater [1]. Factors affecting concentration include the extent of infiltration and the presence of industries. The influent concentration varies during the day and can vary significantly during rainfall events, as a result of inflow and infiltration to the collection system. The most common forms of nitrogen in wastewater are:

- Ammonia NH₃
- Ammonium ion NH₄⁺
- Nitrite NO₂⁻
- Nitrate NO₃⁻
- Organic nitrogen

Nitrogen in domestic wastewater consists of approximately 60 to 70 percent ammonia-nitrogen and 30 to 40 percent organic nitrogen [1,2]. Most of the ammonia-nitrogen is derived from urea, which breaks down rapidly to ammonia in wastewater influent. The wastewater treatment plant systems WWTPs designed for nitrification and denitrification can remove 80 to 95 percent of inorganic nitrogen (figure 1), but the removal of organic nitrogen is typically much less efficient [3]. Domestic wastewater organic nitrogen may be present in particulate, colloidal, or dissolved forms and consist of proteins,
amino acids, aliphatic N compounds, refractory natural compounds in drinking water (e.g., humic substances), or synthetic compounds (e.g., ethylene diamine tetraacetic acid EDTA and textile dyes). Organic nitrogen may be released in secondary treatment by microorganisms either through metabolism or upon death and lysis. Some nitrogen may be contained in recondensation products. Hydrolysis of particulate and colloidal material by microorganisms releases [4].

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![Figure 1. Simplified nitrogen removal](image)

1.1. Bioreactor Configuration

The biology of wastewater treatment is based on the consumption of organic matter by microorganisms which include bacteria, viruses, algae, and protozoa. An operator’s job is to regulate these micro-organisms so that they perform in an efficient and economical way [5]. Wastewater treatment bioreactors fall into two major categories, depending on the way in which microorganisms grow in them: suspended in the liquid under treatment or attached to a solid support. When suspended growth cultures are used, mixing is required to keep the biomass in suspension, and some form of physical unit operation, such as sedimentation, is used to remove the biomass from the treated effluent prior to discharge. In contrast, attached growth cultures grow as a biofilm on a solid support and the liquid being treated flows past them. However, because organisms can slough from the support, a physical unit operation is usually required before the treated effluent may be discharged [6]. The selection of the treatment process depends on various factors which include stabilization degree of the wastewater compliance to the environmental requirement, wastewater composition, and economic viability. There are several biological wastewater treatment techniques such as biological aerated filter systems BAFs, Rotating Biological Contactors RBC, Membrane Bio Reactors MBR, Moving Bed Biofilm Reactor MBBR, Upflow Anaerobic Sludge Blanket UASB, Sequencing Batch Reactors SBR and many others. These methods are sometimes employed as an anaerobic or aerobic treatment or a combination of them [1].

2. Biological aerated filter systems BAFs

The term biological aerated filter systems BAFs came from the combination of air and the filtering action of the bacteria. The BAFs typically (figure 2) consists of a medium that treats carbonaceous and nitrogenous matter using biomass fixed to the media and capturing the suspended solids in the media [7]. The BAFs technology can be used for the secondary and tertiary biological treatment of wastewater [8].

2.1. Process description

The Biological Aerated Filter BAFs is a submerged attached growth system consisting of three phases: 1. the media supporting the biofilm growth acts as the solid phase, 2. the influent settled sewage acts
as the liquid phase, and 3. the gas phase is the air supplied to the system [9,10]. The settled sewage flows through the system either in an upflow or downflow manner. Treatment of wastewater occurs due to the simultaneous physical and biological processes that take place as the sewage comes in contact with the biofilm coated media [9], [11].

![Figure 2. Typical of the BAFs for wastewater treatment [12].](image)

2.2. Development of the BAFs and the proprietary system now available

Since the late 1980s, work on the development of the BAFs has grown with a large number of the proprietary system which is now available [13]. The operating configuration depending on the design specified by the manufacturer. Where (table 1) shows some of the biological aerated filters systems BAFs commercially available are as follows:

| Process Name | Media | Liquid Flow | NH$_3$-N Loading rate (kg m$^{-2}$ d$^{-1}$) | BOD Loading rate (kg m$^{-3}$ d$^{-1}$) | Supplier |
|--------------|-------|-------------|------------------------------------------|--------------------------------------|----------|
| Biobead      | Floating | Upflow       | 0.3                                      | 3 - 5                                | Brightwater Engineering Ltd. |
| Biocarbone   | Sunken  | Downflow     | 0.3 (TKN)                                | 2.5 - 3.5                            | OTV - Burrelco |
| Biofor       | Sunken  | Upflow       | N/A                                      | 2 - 3, up to 6                       | Degremont Ltd. |
| Bioxyr       | Floating | Upflow       | 1.0                                      | N/A                                  | OTV - Burrelco |
| ColOX        | Sunken  | Up/Downflow  | 0.4 - 0.8                                | 4                                    | Capital Controls |
| SAFe         | Sunken  | Downflow     | 0.35                                     | 3 (95% rem.)                         | Paterson-Candy Ltd. |
| REBAF*       | Floating | Up/Downflow  | N/A                                      | N/A                                  | Comenco |
| Biogenerator* | Floating | Downflow     | 0.6 (design)                             | 6 (design)                           | RCL (Heerenveen, Holland) |

Table 1. Proprietary the biological aerated filters systems [13].

- Biobead: Developed by Brightwater Engineering. The media consists of buoyant plastic beads, specially designed to have a rough surface, with bed heights of 2-3 m. The majority of the plants are in the southwest of England.
- Biocarbone: Developed by the French Omnium de Traitement et de Valorisation OTV, it is the most established commercial process with >40 plants worldwide [14]. It uses expanded shale of 3-6 mm diameter as a medium for BOD/COD removal or 2-5 mm diameter media for nitrification. Media depth is approximately 2.5 m.
- Biofor: Degremont's Biofor has been used in more than 30 European sites, including a commercial unit on the south coast of England in Poole Wessex Water. It uses 1-4 mm diameter expanded clay media called ‘Biolite’ with bed depths that vary between 3 to 4 m.
- Biostyr: Devised by OTV-Birwelco, Biostyr uses floating expanded polystyrene beads of 2-4 mm diameter media called ‘Biostyrene’. In the past five years, technology has been used in over 20 installations worldwide.

- CoLOX: developed by Tetra - The Capital Controls Group, an American company specializing in infiltration. Granular sunken silica sand with a diameter of 3-7 mm is used as media with a bed depth of approximately 4 m. There is a full-scale plant in the UK, treating a mixed municipal/dairy effluent.

- SAFe: Originating from Thames Water and Process Water Technology Ltd in the mid-1980s and now marketed by Paterson Candy Ltd PCL. SAFe Uses granular Pulverised Fuel Ash (PFA) media, with a diameter of 3-5 mm and bed depths of approximately 1.9 m.

- ReBAF: Devised by Comenco, this recirculating media BAF uses small plastic floating media with a bed height of up to 4 m. There are currently no full-scale systems, with the process presently undergoing pilot-plant trials [15].

- Biogenerator: Patented by RCL (Patent WO 93/01137) the process was developed in The Netherlands [16]. The recirculating media BAF uses spherical floating media with a diameter greater than 18 mm in bed heights up to 10 m. It has been tested in domestic and industrial wastewater treatment applications [13].

2.3. Analysis of the samples

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 total chemical oxygen demand tCOD, 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 CaCO$_3$, potential hydrogen pH, and temperature °C of the samples. Analyses the samples were conducted according to standard methods APHA, 2017 [10].

3. Nitrogen removal in the BAFs

Ammonium ions can be removed from the system in several ways. 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 [17].

\[
\begin{align*}
\text{Nitrosomonas and Nitrosospira} & \\
\text{NH}_4^+ + 1.5\text{O}_2 & \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{energy}
\end{align*}
\]

\[
\begin{align*}
\text{Nitrobarctor} \text {and Nitrospira} & \\
\text{NO}_2^- + 0.5\text{O}_2 & \rightarrow \text{NO}_3^- + \text{energy}
\end{align*}
\]

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 [17]. Another limitation in 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/m$^3$ inhibits selective oxidation and the inhibition highly depends on ammonia concentration and pH, temperature, DO limit, and growth rate of ammonium oxidizers over nitrite oxidizers [18]. 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 donor and acceptor respectively [19]. Denitrifying bacteria are facultative anaerobic bacteria which use nitrite and nitrate for degradation of CBOD.

**Facultative anaerobic bacteria**

\[
6\text{NO}_3^- + 5\text{CH}_3\text{OH} \rightarrow 3\text{N}_2 + 5\text{CO}_2 + 6\text{OH}^-
\]

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” [17]. 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 [20]. 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 [21,22]. Improper treatment of SS can reduce BAFs performance by affecting the mass transfer of oxygen and substrates into the biofilm [23]. The presence of sufficient carbon accelerates denitrification during the nitrogen removal process [24]. In most of the cases, researchers proposed a nitrification-denitrification process as a two or more stage BAF system [12].

4. **Discussion**

4.1. **Nitrogen loss in the BAFs**

Nitrogen loss in the BAFs was estimated by nitrogen mass balance of NH\(_4^+\)-N, NO\(_2^\)-N, NO\(_3^\)-N, and nitrogen converted to biomass in the BAFs. The estimated nitrogen loss was negligible when the NH\(_4^+\)-N load was low. But the nitrogen loss became significant as the NH\(_4^+\)-N load was increased. Figure 3 shows the effect of NH\(_4^+\)-N load on NH\(_4^+\)-N removal and nitrogen loss. As the NH\(_4^+\)-N load increased, nitrogen loss was gradually increased while the nitrification efficiency was decreased. More than 40\% of the applied ammonium was lost at the load of 1.8 – 2.0 kg NH\(_4^+\)-N m\(^{-3}\) d\(^{-1}\).

![Figure 3](image.png)

**Figure 3.** The effect of NH\(_4^+\)-N load on nitrogen loss and nitrification efficiency at high NH\(_4^+\)-N load with 100mg dm\(^{-3}\) [25].
The conventional engineering explanation for phenomena is that simultaneous nitrification and denitrification occurs because of anoxic micro-zones in the center of sludge flocs or in the inner part of biofilms which allows heterotrophic denitrifiers to produce nitrogen gas in a conventional way. However, nitrogen loss by heterotrophic denitrification cannot explain the phenomenon because the total organic carbons from the decay of biomass could not fully serve as an electron donor to reduce \( \text{NO}_2^- \) to \( \text{N}_2 \). Stoichiometrically, denitrification of 1g of \( \text{NO}_2^- \) should consume about 0.64 g of organic carbon, corresponding to 1.3 g of VSS. Considering the average microbial yield of nitrifiers 0.1 g VSS per g \( \text{NH}_4^+ \), the influent \( \text{NH}_4^+ \) concentration 100 mg dm\(^{-3}\) and the effluent VSS concentration about 10 mg dm\(^{-3}\) in continuous operation, it can be assumed that heterotrophic denitrification was not responsible for the nitrogen loss. Nitrogen assimilation to microorganisms has a minor effect on the nitrogen loss considering the microbial yield and average composition of nitrifiers \( \text{CH}_1.7\text{O}_0.45\text{S}_0.04\text{N}_0.19 \) [26]. Ammonia stripping was also negligible under the operating conditions [25].

4.2. Combined Nitrification and Denitrification

According to Debarbadillo et al. [26], Nitrogen removal can be accomplished by either oxidizing the ammonia in a first stage followed by reducing the nitrate in a second stage where an external carbon source is added (referred to as post-denitrification), or by recycling the nitrified effluent to a denitrification stage before nitrification (pre-denitrification). In pre-denitrification, the nitrified effluent is recycled to a separate anoxic BAFs reactor located upstream of the reactor. In some upflow, floating media BAFs configurations, a portion of the nitrified effluent may be recycled to an anoxic zone in the bottom of the media [27]. If sufficient carbon is available and the anoxic zone is large enough, then nitrogen removal is proportional to the recycle but with a diminishing return. Recycle typically is limited to ratios of 3 or total nitrogen removals of 75% because of the excessive hydraulic load and oxygen recycle. The minimum nitrate concentration achievable assuming complete nitrification and denitrification and ignoring nitrogen uptake because of cell synthesis is given by:

\[
\text{NO}_3^- \text{N}_{\text{EFF}} = \frac{\text{NO}_3^- \text{N}_{\text{IFF}}}{R + 1}
\]

(1)

Where,

\( \text{NO}_3^- \text{N}_{\text{IFF}} \) = ammonia concentration in influent;
\( \text{NO}_3^- \text{N}_{\text{EFF}} \) = nitrate concentrations in effluent respectively;
\( R = (QR/Q_{\text{in}}) \) = recirculation ratio.

Recycling treated wastewater has the advantage of increasing upflow velocity in both pre-denitrification and nitrification reactors, which increases the reaction rate.

Ryhiner et al. [28], tested a pre-denitrification configuration using submerged structured media BAFs with a final polishing filter to achieve low nitrogen and suspended solids. About 60 to 70% \( \text{NO}_3^- \text{N} \) removal was achieved in the pre-denitrification reactor at loading rates ranging from 0.1 to 0.6 kg \( \text{NO}_3^- \text{N}/\text{m}^3 \cdot \text{d} \). During a one-year study, Pujol and Tarallo [29], achieved about 68% \( \text{NO}_3^- \text{N} \) removal (or 0.9 kg \( \text{NO}_3^- \text{N}/\text{m}^3 \cdot \text{d} \) with typical wastewater feed to the pre-denitrification BAFs and up to 90% removal when additional substrate (methanol) was added. A range of recycling rates (150 to 350%) and corresponding filtration velocities (9.4 to 16.9 \( \text{m}^3/\text{m}^2 \cdot \text{h} \)) also was tested. Design guidance for pre-denitrification BAF systems is provided in Table 2.
Table 2. Typical BAFs loading rates for Pre-denitrification [26].

| Type of BAFs | Applied volumetric loading, kg/m$^3$.d | Hydraulic loading, m$^3$/m$^2$.h | Removal efficiency % |
|--------------|----------------------------------------|----------------------------------|----------------------|
| Upflow, sunken media separate BAFs stages (pre-denitrification + nitrification) | NO$_3$-N: 1–1.2 | 10 – 30 | NO$_3$-N: 75% – 85% |
| Upflow, floating media combined anoxic/aerated BAFs stage | 1–1.2 | 12–21.5 | NO$_3$-N: 70% w/o supplemental carbon; 85% with supplemental carbon |

Notes: Design and performance are dependent on wastewater characteristics, upstream treatment processes, effluent goals, and readily biodegradable carbon substrate.

Many post-denitrification filters are preceded by an activated sludge biological nutrient removal process. Because some denitrification is achieved upstream, filter influent NO$_3$-N concentrations are typically less than 10 mg/L. In these cases, hydraulic considerations govern post-denitrification design and many installations are operating at mass loading rates of approximately 0.3 to 0.6 kg/m$^3$.d. The range of loading rates for upflow post-denitrification BAFs reactors tends to be higher than for post-denitrification sand filters because they are not designed for the same level of TSS removal and are not as limited by hydraulics [26]. A summary of typical volumetric and hydraulic loading criteria for different types of denitrification filters is provided in Table 3.

Table 3. Typical BAFs loading rates for Post-denitrification [26].

| Type of BAFs | Applied volumetric loading, kg/m$^3$.d | Hydraulic loading, m$^3$/m$^2$.h | Removal efficiency % |
|--------------|----------------------------------------|----------------------------------|----------------------|
| Upflow, sunken media | NO$_3$-N: 0.3 – 3.2 | 4.8 – 8.4 | NO$_3$-N: 75% – 95% |
| Upflow, sunken media | 0.8 – 5 | 10 – 35 | NO$_3$-N: 75% – 95% |
| Upflow, sunken media | 2 | | |
| Upflow, floating media | 1.2 – 1.5 | 4.8 – 5.6 | NO$_3$-N: 75% – 95% |
| Moving bed, continuous backwash | NO$_3$-N: 0.3 – 2 | | |

Notes: Design and performance are dependent on wastewater characteristics, upstream treatment processes, effluent goals, and readily biodegradable carbon substrate.

5. Conclusion
From literature review drew the following conclusions:

- The BAFs provide effective treatment and can be used for the secondary and tertiary biological treatment of wastewater, including industrial effluents.
• The BAFs combines biological treatment and ammonia-nitrogen and solids removal in one reactor unit, where small space occupied, economic and simple management.
• The BAFs has good denitrification removal effect, high handling load.
• There have been few thorough studies of removal of the nitrogen as full-scale BAFs therefore there is a need to further characterize of nitrogen conversion and removal for required to meet increasingly stringent effluent standards.

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