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BIOLOGICAL AERATED FILTERS (BAFs) FOR CARBON AND NITROGEN REMOVAL: A REVIEW

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Abstract

Biological aerated filters (BAFs) are an emerging wastewater treatment technology designed for a wide range of municipal and industrial applications. This review paper presents and discusses of the influence C/N ratio, nitrification and denitrification principle, effect of pH, DO and alkalinity on the nitrification and denitrification systems, organic and hydraulic loading of BAF reactor, etc. Results from upflow and downflow biofilter pilot at different condition, with nitrification and denitrification are reviewed. Under the optimal conditions, significant amount of COD, ammonia-nitrogen and total nitrogen were removed. Removal rates based on reactor volume for different carbonaceous COD and ammonia loading rate are reported. The BAF system for the nitrification and denitrification processes for carbon and nitrogen removal from the wastewater need to be evaluated and applied properly to protect of our environment and resources.

Keywords: Biological aerated filters (BAFs), pH, DO, Alkalinity, Nitrification, Denitrification, C/N ratio.

1. Introduction

In our increasingly urbanized and industrialized society with a rapidly expanding world population, the need for cost-effective and environmentally sound technologies for wastewater treatment is required. Therefore, all of the pollution sources; i.e., municipal, industrial, and agricultural, must be managed in order to reduce the carbon and nitrogen concentrations to improve the quality of the environment. Because nitrogen and carbon are one of the major pollution sources that contribute to environmental quality problems all over the world, especially those

Nomenclatures

COD	Organic matter, kgCOD/m^3/day
DO	Dissolved Oxygen, mg/L
N	Nitrogen, kgN/m^3/day
NH_4	Ammonium , mg/L
NO_2	Nitrite, mg/L
NO_3	Nitrate, mg/L
P	Phosphorus, mg/L
TAN	Total ammoniacal nitrogen, kgTN/m^3/day

Abbreviations

AOB	Ammonia Oxidizing Bacteria
BAF	Biological Aerated Filter
HASFF	Hybrid aerated submerged fixed film
HBR	hybrid biological reactor
HFBR	Hybrid fluidized bed reactor
HMBR	Hybrid membrane bioreactor
HRT	Hydraulic Retention Time, day
NOB	Nitrite oxidizer Bacteria
SND	simultaneously nitrification and denitrification
WWTP	Wastewater Treatment Plant

that mainly cater for treatment of wastewater. The most adverse environmental impacts associated with improper discharge of municipal wastewater havingsignificant amounts of organic matter (COD), nitrogen (N) and phosphorus (P) include promotion of eutrophication, toxicity to aquatic organisms and depletion of dissolved oxygen to receiving streams [1-3] which kills fish. So, biological nitrogen and phosphorus removal from wastewater is an effective approach for prevention of eutrophication in water bodies [4-6]. High nitrate concentration in drinking water may cause serious problems in humans and animals. Nitrate and nitrite contaminated water supplies are also related with several diseases such as methmoglobinemia infants, also called “bluebaby disease” [7, 8]. These two compounds are capable of inducing mutations of DNA, causing gastric cancer [8, 9]. Due to the adverse impacts, complete treatment of municipal wastewater before discharge has been increasingly needed.

Although conventional biological treatment processes are mostly reliable, well designed and tested, they present a number of drawbacks in terms of treatment capacity, efficiencies, and stability and space requirements. For the development of advance biological treatment process, WWTPs need to be more compact, low in operational costs and stable in operation, while at the same time minimize the noise and odour, and space requirements as well as generate high performance. However, with the continuing need to increase wastewater effluent quality with respect to the removals of nitrogen and carbon, one of the advanced biological treatment systems, the biological aerated filters (BAFs), proves to be more reliable.

The Biological aerated filters (BAFs) process is a biological treatment technology that can provide secondary treatment of municipal and industrial wastewaters. BAFs are becoming increasingly popular in Europe due to their compactness. Several wastewater treatment plants are using BAFs as secondary treatment [10, 11]. BAFs are relatively compact, easy to operate and may be more efficient in carbonaceous and ammonia removal than activated sludge system [12-14]. BAFs offer an alternative to typical biological treatment processes; however, knowledge of the process is often limited.

Several researchers have tested the BAFs for ammonia and nitrogen removal [12, 14, 15-18]. Several full scale systems have reported the operating conditions and effectiveness of BAFs. However, information on the performance of the BAFs under various operating and environmental conditions is still lacking. So, the impact of different organic and hydraulic loading rates and recircular rates on nitrification and denitrification needs further investigation.

This review study provides a brief summary of BAF, a current literature review of carbon and nitrogen removals, the biological nitrogen removal processes (nitrification and denitrification), impact of C/N ratio, pH, DO and alkalinity on nitrification and denitrification systems, hydraulic and ammonia loading, etc.

2. Biological Aerated Filters (BAFs) Reactor

2.1. Definition of BAFs

The term BAF came from the combination of air and the filtering action of the bacteria. A BAF typically consists of medium that treats carbonaceous and nitrogenous matter using biomass fixed to the media and capturing the suspended solids in the media [19]. BAF is a flexible reactor, which provides a small footprint process option at various stages of wastewater treatment. Basic operating principle of BAF is based on a conventional biofilter operating in a submerged mode. Conventionally, BAF is a submerged media wastewater treatment reactor that combines oxic biological treatment and biomass separation by depth filtration [20, 21]. The medium allows the reactor to act as a deep submerged biofilter and incorporates suspended solids removal [22]. The BAF has undergone rapid development in the last decade and is becoming a promising alternative to conventional biochemical wastewater treatment process.

2.2. Short history of BAF developments

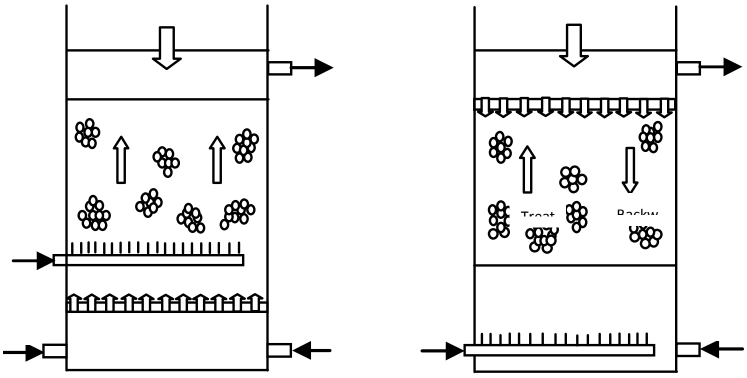
BAF have been successfully used to treat a variety of wastewater streams at both the municipal and industrial level for over thirty years. The BAF system was developed in Europe and then widely applied all over the world as a novel wastewater treatment system due to its advantage relative to other systems. Today, the BAF is increasingly being considered the preferred wastewater treatment reactor system for improving nutrient removal. The first development of a packed bed reactor for nitrification that met with widespread commercial success was the BAF [23].

2.3. Types of BAF

There are several different types of BAF units in the market today. BAF is operated either in upflow or downflow configuration depending on the design specified by the manufacturer. A list of some of the larger upflow and downflow filters commercially available are as follows: (i) Denite (ii) Biocarbone (iii) Biofor (iv) Biostyr (v) Biobead (vi) Biolest (vii) Biopur.

BAFs can be operated either in an upflow or downflow mode (Figure 1). The downflow filters were the first available commercially. Downflow systems with countercurrent air flow have the advantage of efficient mass transfer of oxygen to biofilm in the reactor. This configuration introduces wastewater at the top of the media and applies air at the bottom. Downflow BAFs are effective when carbonaceous matters and ammonia removal are required in the reactor without oxygen limitation. In downflow BAF, nitrifying microorganisms are typically found at the bottom of the reactor and therefore will not suffer oxygen limitation.

Upflow systems with co-current air and wastewater flow can handle higher influent flowrates than downflow systems. Moreover, it has longer operational cycle system, and can decrease odour problem occurring since the atmospheric air only contacts with treated effluent at the top of the BAF [24]. The upflow filters introduce wastewater at the bottom of the filter. The wastewater proceeds upwards in the same direction as the air. This upward flow ensures an even distribution of water and air and acts to reduce short-circuiting and gas entrapment. The BAF is a flexible system whereby different zones can be achieved. For example, an upflow BAF can have oxic and anoxic zones to allow for nitrification and denitrification. The anoxic zone removes soluble organic matter and nitrate, while the aerated zone oxidizes the remaining organic matter and ammonia.



Co-current Counter-current

Fig. 1. Examples of Upflow and Downflow Biological Aerated filter Designs [25].

2.4. Media types of BAF

The selection of a suitable BAF medium is critical in the design and operation of the process [22, 26]. The filter media acts as a nitrifying and denitrifying biofilms attachment, provide a large surface area per unit volume to maintain a high amount of active biofilms and variety microbial populations [24]. The ideal media should be resistant to attrition, have appropriate specific weight, high specific surface area, and chemically stable [27], more durable, easy to install and should not clog the reactor. Actually, the specific surface area of the medium is important to promote biological growth, allow maximum oxygen transfer and trap suspended solids. The surface area of the media ranges from 140 to 1500 m^2/m^3 [13]. An advantage of small granular media is the large surface area available for the growth of the bacteria and microorganisms responsible for treatment. This leads to high concentrations of attached biomass and hence much smaller reactor volumes can be used.

BAFs can be differentiated further by media type and size. The size of BAF media also affects the process performance and should be carefully selected for different applications [26]. The smaller size media offers a greater surface area per unit volume for biofilm development and minimises the required BAF volume [24]. A larger media effectuates reduction in nutrient removal due to the less surface area for biofilm growth and attachment because of the high voidage in the BAF. Farabegoli et al., evaluated the performance of four media types: glass (5 mm), plastic (6 mm), pozzolan (2-6 mm) and arlita (5-8 mm) in a pilot scale BAF in terms of organic matter and suspended solids removal [28]. The COD removal efficiency with the plastic media varied between 30% and 70% whereas 67% removal efficiency was obtained for the arlita media for the large surface area. But plastic has the lowest weight loss and it can also be considered as the most suitable media for application in the pilot scale BAF [28].Media roughness also affects the performance of the reactor. Rough surface media provides more sites for biofilm attachment than smooth media and has been found to improve solids retention.

In a pilot study by Moore et al., the BAF with 3.5 mm media had a mean depth of 1.7 m, whereas the larger media 4.5 mm had a mean depth of 2.1 m [22]. Result shows that, the smaller media gave better COD removal efficiency (83% as compared to 77%) than the larger media due to the larger surface area per unit volume. Therefore, media selection is an important factor to make strong biofilm and for good removal efficiency because no media replacement is required during the lifetime of the plant.

3. Biological Nitrogen Removal

Biological nitrogen and carbon removal wastewater treatment systems utilize a diverse microbial population to remove nitrogenous and carbonaceous compounds from wastewater. Thus, from an economical and operational point of view, biological treatment has proved to be robust and more efficient in energy use for treating biodegradable wastewaters [29].

Biological nitrogen removal can be accomplished in a two stage treatment: aerobic nitrification and anoxic denitrification. The traditional view considered the two processes to be mutually exclusive, as nitrification requires oxygen and denitrification requires the absence of oxygen. Based on this assumption, conventional wastewater treatment plants are continuous flow systems that separate nitrification and denitrification by space.

3.1. Nitrification principle

Nitrification is the term used to describe the two-step biological processing where ammonia ($N\text{-}NH_4^+$) is oxidized to nitrite ($N\text{-}NO_2^-$) and nitrite is oxidized to nitrate ($N\text{-}NO_3^-$), under aerobic conditions and using oxygen as the electron acceptor. The total ammoniacal nitrogen (TAN) in the wastewater originates from the breakdown of urea by the enzyme urease, which is present in fecal matter, and the breakdown of proteins in organic matter, which contain amine groups. The combination of the urine and faces releases a large amount of ammonia.

Aerobic autotrophic bacteria are responsible for nitrification in activated sludge and biofilm processes. Nitrification, as noted below, is a two-step process involving two groups of bacteria. In the first stage, ammonia is oxidized to nitrite, Eq. (1) by one group of autotrophic bacteria called Nitroso-bacteria or Ammonia Oxidizing Bacteria (AOB). In the second stage, nitrite is oxidized to nitrate, Eq. (2) by another group of autotrophic bacteria called Nitro-bacteria or Nitrite oxidizer Bacteria (NOB). Nitrification is aerobic oxidation of ammonia by nitrifying bacteria.

Ammonium (NH_4) is oxidised by oxygen (O_2) via the intermediate nitrite (NO_2) to nitrate (NO_3):

$$NH_4 + 1.5O_2 \rightarrow NO_2 + H_2O + 2H \tag{1}$$

$$NO_2 + 0.5O_2 \rightarrow NO_3 \tag{2}$$

Nitrogen removal involves the conversion of reduced nitrogen compounds (ammonia) to more oxidized species (nitrate), termed nitrification, followed by the conversion of the oxidized species to reduced gaseous products. The oxidation of ammonium to nitrate creates two acid equivalents (H^+) per mole of nitrogen oxidized. Oxygen is required for the oxidation of ammonium and is used as the terminal electron acceptor by the nitrifying bacteria. When sufficient oxygen was present, a drop in nitrification rate was observed due to competition from the heterotrophic organisms due to their assimilation of the ammonia. With the addition of limited oxygen as a variable, ammonia oxidation was strongly inhibited but not ceased.

3.1.1. Nitrifiers

Autotrophic nitrifying microorganisms grow relatively slow and are more sensitive toward environmental conditions than heterotroph microorganisms. As such the amount of degradable organic matter present has an impact on the growth of autotrophic nitrifying microorganisms. However, genera of microorganisms that scientists believe play roles in nitrification are *Nitrosomonas, Nitrobacter, Nitrosospira, Nitrosolobus, Nitrosovibrio*, and *Nitrosococcus* [30]. These genera of organisms are autotrophic, so their carbon source is carbon dioxide (CO_2). Ammonia Oxidizing Bacteria, such as *Nitrosomonas*, utilize the reduced nitrogen in ammonia as the electron donor, or energy source. They oxidize it to form nitrate (NO_2) using oxygen (O_2) as the terminal electron acceptor. Nitrite-oxidizing bacteria, such as *Nitrobacter*, then use the nitrite as their energy source with oxygen as the terminal electron acceptor to nitrate (NO_3) [30, 31]. Nitrite-oxidizers have a higher growth rate but are dependent on ammonia-oxidizers for a supply of nitrite. Therefore, the amount of time microbial biomass must remain in nitrifying reactors must be longer than treatment systems designed for COD removal in order to provide enough time for the nitrifying bacteria to grow.

3.1.2. pH and alkalinity

A great deal of investigation conducted has demonstrated the pH effects on nitrification. The nitrifying bacteria may be more sensitive to temperature and pH [32]. It has been reported that the pH of wastewater should be maintained between 6 and 9 to protect organisms [33]. This is important since a narrow optimal range between pH 6-9 exist for the nitrifying bacteria. The decrease in pH was caused by the reduction of alkalinity and the acid production during nitrification. After completion of nitrification, the pH started to increase. The optimum pH for nitrification was in the range of 7.2-8.6 [17, 34]. For biological nutrient removal to be accomplished, the environment must support the growth of the micro-organisms.

However, in a study on the pH effect upon the nitrification efficiency in an upflow partially-packed BAF, it is reported that the NH_3-N removal linear increasing from 81.6%-92.3% when there is a change of pH value from 4.7 to 6.4 [35]. While it is indicated that pH 6.45 to 8.95 has no effect on nitrification, a pH lower than 6.45 and over 8.95 completely inhibited the nitrification process [36].

Alkalinity concentration is also an important wastewater characteristic that affects the performance of biological nitrification process. Adequate alkalinity is needed to achieve complete nitrification. In addition, alkalinity provides the buffering capacity that is necessary to prevent pH changes due to acid production in the nitrification process. Therefore, the impact of alkalinity on the nitrification rate is also related to that of the pH. It can be seen that the nitrogen removal rate increases with an increase of alkalinity. The complete removal of ammonia indicates the end of alkalinity consumption in the wastewater, hence the end of further pH decrease. The decrease in pH is caused by the removal of ammonia form the system, as ammonia is strongly related to alkalinity of the wastewater. However, too high alkalinity is unnecessary, because when alkalinity to ammonia nitrogen ratio is more than 9, the nitrogen removal rate hardly increases even with an increase in alkalinity, while chemical dosage obviously increases, and thus the operating cost.

Alkalinity is not only important for nitrification; it can also be used to indicate the system stability [3]. During nitrification alkalinity is consumed, but alkalinity is produced during denitrification. Alkalinity was found to have a close correlation with BAF operating conditions, since different extents of nitrification (alkalinity consumption) contribute to the variation of alkalinity in the system.

3.1.3. Dissolved oxygen (DO)

The amount of oxygen that must be transferred in the aeration tank equals the amount of oxygen required by the microorganisms in the activated sludge system to oxidize the organic materials. DO concentrations have a direct effect on the growth rates of nitrifying bacteria. DO concentrations are typically maintained at or above 2 mg/L in the reactor when performing nitrification (since the growth rate of nitrifying bacteria slows dramatically when DO concentrations are below 2 mg/L). Zhu and Chen reported that it was more important to maintain sufficient DO in the fixed film process than in the suspended growth processes due to the nature of diffusion transport with fixed film [37]. Moreover, the nitrification rate is increased with increasing dissolved oxygen and it is found to be almost linearly dependent upon the oxygen concentration, up to more than 10 mg/L [38]. But values above 4 mg/L do not improve operations significantly, because it has been proven that over aeration leads to reduce the nitrification efficiency because of detachment of biofilm from the plastic media [39]. Moreover, the nitrification rate is increased with increasing dissolved oxygen in the range of 1-3 mg/L and decreased with the range of 0.3-0.5 mg/L [40]. If the problem is due to limited oxygen, simultaneous nitrification and denitrification (SND) may occur instead and it can usually be confirmed by operating the aeration equipment at full capacity or by decreasing the system SRT, if possible, to reduce the oxygen demand. Therefore, the aeration equipment should have adequate capacity to maintain at least 2.5 mg/L of dissolved oxygen in the aeration tank under normal loading conditions. If 2.5 mg/L of oxygen cannot be maintained, installation of improvements to the existing aeration system may be required.

3.1.4. Carbon to nitrogen ratio (C/N ratio)

Biological processes are often used to remove carbonaceous and nitrogenous pollutants from wastewater [41]. Carbon to nitrogen (C/N) ratio of wastewater has been found to impact the distribution of both nitrifiers and heterotrophs population in biological filters [42-44]. An understanding of the impact of C/N ratio on nitrogen removal wastewater is imperative for optimizing biofilm reactor. However, it should be noted that the pre-treatment of raw wastewater for SS removal may cause loss of organic matter and then decrease the C/N ratio of wastewater. Durmaz and Sanin [45] stated that C/N ratio also has a significant effect on the ultimate physical and chemical properties of sludge and the increase of C/N ratio from 9-21 will yield better sludge quality for an activated sludge system. From a study done by Fatihah at C/N ratio of 24:1, it showed that partial nitrogen removal occurred most probably because of very low concentration of limiting carbon source due to high TOC removal efficiency in the full and partial bed BAF [46]. Fdz-Polanco et al., also described the changes in biofilm density and specific activities of carbon within a nitrifying upflow BAF as a function of the C/N ratio in the wastewater [43].

3.2. Denitrification principle

Many studies have been conducted on nitrification, but only few have been done on denitrification. Denitrification is the conversion of nitrate or nitrite into various reduced nitrogen compounds. Microorganisms utilize the nitrate as an electron acceptor in the absence of oxygen. Denitrification consists of a sequence of enzymatic reaction leading to the evolution of nitrogen gas.

Biological denitrification involves the biological oxidation of many organic substrates in wastewater treatment using nitrate or nitrite as the electron acceptor instead of oxygen. In the absence of DO or under limited DO concentrations, the nitrate reductase enzyme in the electron transport respiratory chain is induced, and helps to transfer hydrogen and electron to the nitrate as the terminal electron acceptor. The nitrate reduction reactions involve different reduction steps from nitrate to nitrite, to nitric oxide, to nitrous oxide, and to nitrogen gas, Eq. (3).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2 \rightarrow N_2 \tag{3}$$

3.2.1. Denitrifiers

Many different species of bacteria have the capability of denitrification, including those from *Pseudomonas, Achromobacter, Bacillus, Rhizobium, Aquaspirillum, Flavobacterium, Aeromonas, Moraxella*, and even some yeasts [47, 48]. These organisms typically have a quick growth rate so they do not face the same competitive problems as the nitrifying bacteria [30]. Bacteria capable of denitrification are both heterotrophic and autotrophic. Most of these heterotrophic bacteria are facultative aerobic organism with the ability to use oxygen as well as nitrate or nitrite, and some can also carry out fermentation in the absence of nitrate or oxygen [49].

3.2.2. pH and alkalinity

Alkalinity is produced in denitrification reactions and pH is generally elevated, instead of being depressed as in nitrification reactions. In contrast to nitrifying organisms, there has been less concern about pH influences on denitrification rates. Denitrification is an alkalinity producing process. During nitrification alkalinity is consumed, but alkalinity is produced during denitrification. The optimal pH lies between 7 and 8 for denitrification with different optimums for different bacterial populations.

According to Metcalf and Eddy, a pH value near neutral is preferred and below 6.8 the methanogenic activity is inhibited [49]. Because of the high CO_2 content in the gases developed in anaerobic processes, a high alkalinity is needed to assure pH near neutrality.

3.2.3. Dissolved oxygen (DO)

Denitrification occurs when oxygen levels are depleted and nitrate becomes the primary oxygen source for microorganisms. The process is performed under anoxic conditions, when dissolved oxygen concentration is less than 0.5 mg/L, ideally less than 0.2. According to USEPA, oxygen levels must drop significantly for full denitrification to occur in the reactor environment; the USEPA suggests that levels less than 0.3 to 1.5 mg/L for activated sludge systems [50]. Many researchers have found that a good habitat for denitrification is one devoid of any oxygen, finding that oxygen levels above 0 mg/L will inhibit denitrifying microorganisms [51]. Painter also studied denitrification by activated sludge at reduced DO concentration and showed that at DO concentration of 2 mg/L, the denitrification rate was only 10% of the rate under strictly anaerobic conditions [52].

However, two factors which have an influence on the rate of denitrification are the presence of dissolved oxygen, which will inhibit denitrification and the availability of a carbon source [53]. Therefore, biological processes can be suitable for denitrification by combination of control systems with on-line sensors of nitrate and dissolved oxygen [54]. However, further investigation will be required to complete denitification by the automatic control of nitrate and dissolved oxygen in biological system.

3.2.4. Carbon to nitrogen ratio (C/N ratio)

A few studies discussed BAF system with respect to nitrogen removal by denitrification process. Nevertheless, its denitrification efficiency was quite low due to low C/N ratio of influent wastewater [12]. Sufficient carbon must be available in order to completely denitrify the nitrite formed during nitrification in nitrogen removal processes [21, 55]. It has been suggested that the ratio needs to be maintained at or above 5.0 for complete nitrogen removal to occur in wastewater activated sludge systems without any additional organic material [56].

BAF processes use methanol as an external carbon source in order to increase the C/N ratio [57, 58]. As a result of low ratio in domestic wastewater, there is a deficiency of carbon sources, which are essential for the nitrification-denitrification process. Actually, incomplete denitrification is not only due to an inadequate COD/TKN ratio; a short anoxic period would also result in high nitrogen level in the effluent. If there is sufficient organic carbon, increasing the anoxic period will allow enough time for denitrification. Therefore, further attention needs to be undertaken for the successful utilization of the BAF system in treating the low C/N ratio wastewater by additional carbon source.

4. Biological Process Systems for Nitrogen Removal

4.1. Suspended growth systems

Suspended growth processes are biological wastewater treatment systems in which the microorganisms responsible for the conversion of the organic matter, or other constituents in the wastewater, to gases and cell tissues are maintained in suspension within the liquid. Many suspended growth processes used in municipal and industrial wastewater treatment are operated with dissolved oxygen concentration, but applications exist where suspended growth anaerobic reactors are used, such as for high organic industrial wastewaters and organic sludges. The most widely used suspended growth process is the activated sludge system [59]. The activated sludge process consists of two phases, aeration and biomass separation, conventionally by means of sedimentation. The biomass converts soluble and colloidal biodegradable organic matter and some inorganic compounds into cell mass and metabolic end products.

4.2. Activated sludge system

Since its beginning in 1914, the activated sludge process developed by Arden and Lockett has increasingly gained popularity, and today it is most widely used biological treatment process for both domestic and industrial wastewaters because it is reliable and has proven to be successful. The activated sludge process is a biological process in which microrganisms oxidize and mineralize organic matter. Over the years, an activated sludge process has evolved into many kinds of wastewater treatment systems such as conventional, complete-mix, step aeration, pure oxygen, contact stabilization, extended aeration, oxidation ditch, deep tank and deep shaft systems [60].

The various types of microorganisms present enable the activated sludge process to treat various types of wastes. The typical microbiology of activated sludge consists of approximately 955 bacteria and 5% higher organisms such as protozoa, metazoan, fungi, rotifers, etc. [61]. The wastewater and the environmental conditions affect the types and the abundance of species present in the system. The principal bacteria genera found in treating municipal wastewaters are: *Achromobacter, Arthrobacter,* *Cytophaga, Falvobacterium, Alkaligenes, Pseudomonas, Vibrio, Aeromonas, Bacilus, Zoogloea, Nitrosomonas and Nitrobacter* [62].

In activated sludge systems different environment conditions (nitrification and denitrification) can be applied by regulating key process parameters such as the concentration of electron donor and electron acceptors. Different operational systems of activated sludge process have been developed to achieve high-quality treated effluent, particularly to optimize nitrogen removals. According to Pai et al., 87-98% total organic carbon and 63-75% total nitrogen was removed by biological nitrogen reactor based on the activated sludge process [63]. Bicudo and Svoboda also investigated the use of activated sludge for nutrient removal from swine wastewater [64].

An important property of the activated sludge process is the capability of growing in well formed aggregated when the composition of floc-forming and filamentous bacteria is balanced. Several researchers have suggested overcoming the difficulties about the growth and maintenance of suspended activated sludge flocs by the application of biofim BAF reactors. BAF can offer some benefits with little risk in field applications considering the results of the existing treatment process. However, conventional activated sludge processes cannot achieve a satisfactory efficiency in nitrogen removal due to washout of slow-growing autotrophic nitrifying bacteria from the reactor.

4.3. Hybrid systems

Wastewater treatment system with an activated sludge system containing both suspended and attached growth can be called hybrid biological reactor (HBR) [36]. The use of hybrid reactor systems for treating organic matter and nutrients in wastewater is an innovation that could be suitable for increasing the capacity and the efficiency of wastewater treatment plants (WWTP) [65]. Compared with a conventional activated sludge system, the removal rate of COD and ammonia-nitrogen and the nitrating rate are higher and more stable in the hybrid biological reactor. The hybrid biological reactor is also a suitable treatment system for coke plant wastewater because it can efficiently degrade COD, ammonia-nitrogen and other refractory compounds of the coke plant wastewater.

Nowadays, several hybrid system such as a hybrid moving bed biofilm reactor (HMBBR), a hybrid membrane bioreactor (HMBR), a hybrid fluidized bed reactor (HFBR) and a hybrid aerated submerged fixed film (HASFF) are being used successfully for new construction and upgrading existing wastewater treatment plants. The advantages of hybrid systems are as follows

- Increased treatment capacity
- Greater process stability
- Reduced sludge production
- High biomass concentrations and high SRT
- Reduced solids loadings on the secondary clarifier
- No increase in operation and maintenance costs.

5. Hydraulic, Organic and Ammonia Loading on BAFs Performance

BAFs also have a long history of successfully removing nitrogen and carbon in wastewater treatment plant [66-68]. BAF systems have been shown to operate successfully at higher hydraulic and organic loading rates than activated sludge systems [10, 11]. In a single unit operation of BAF, carbonaceous BOD removal, solids filtration and nitrification can be achieved [21, 69]. Some researchers have tested BAF systems with a loading rate as high as 18 kg CODm^{-3}day^{-1}. In addition, BAF systems are effective in nitrogen and COD removals for a small footprint [17, 21, 23].

According to Gilmore et al., overall nitrification efficiency for winter conditions was greater than 90% when ammonia loads were 0.6 kg Nm^{-3}day^{-1} [70]. At relatively low organic and ammonium nitrogen loadings, up to 88% nitrification was achieved [71]. The upflow aerated filters, operated under warm weather conditions (average temperature of 27° C), were able to remove about 88% of BOD, 75% of COD, and 82% of SS at an organic loading of 5.7 kg CODm^{-3}day^{-1} [72]. The influences of hydraulic retention time (HRT), air–liquid ratio (A/L) and recirculation on the removals of COD, ammonia-nitrogen and total nitrogen were investigated in BAF by Han et al. [73]. The optimum operation conditions were obtained at HRT of 2.0 h, A/L of 15:1 and 200% recirculation. Under the optimal conditions, 90% COD, more than 98% ammonia-nitrogen and approximately 70% total nitrogen were removed. It is also known that BAF adapts well to low temperature for nitrification and relieves shock load effects resulting in effectively removing organics and nitrogen with short HRT [74].

In one particular laboratory-scale study involving an upflow aerobic biofilter using floating media, COD loading resulted in reduced nitrification rates from a maximum of 1.0 kgday^{-1}m^{-3} for secondary effluent to <0.4 kgday^{-1}m^{-3} for primary effluent. A marked reduction in nitrification rate was observed when the biodegradable COD loading was 2.2 kgday^{-1}m^{-3} or greater. Under the high MLSS condition, hydraulic retention time (HRT) and sludge production are minimized and nitrification is enhanced [75-78].

A biological aerated filter with oxic and anoxic conditions for complete nitrogen removal was used by Rogalla and Burbigot [17]. They showed that the minimum BOD/N ratio needed was 3 with maximum removal of nitrogen of 75% was obtained. Moreover, denitrification can also be achieved within a short HRT (less than 6 hours) [12, 14] by the partially packed BAF system. Both biological nitrification and denitrification, a stable removal rate of 90-95% could be maintained in pilot scale fluidized-bed reactors [79]. Ong et al. [80] reported that nitrogen and COD removal efficiencies of the anoxic-oxic packed bed system were in the range of 97.5%-100% and 98.6%-99.4% respectively. Further investigation by Lee et al., showed that the highest achievable total nitrogen and COD removal rates were 47.2 g Nm^{-2}d^{-1} and 158.0 g CODm^{-2}d^{-1} and a dual-stage packed bed system was capable of achieving total nitrogen and COD removal efficiencies greater than 99% and 98%, respectively [81].

Nitrification increases with increasing ammonium loading. The nitrification may be inhibited by substrate (ammonium) concentration, so increasing the ammonium load leads to increasing the nitrification rates. According to Biplob, the removal of NH_3-N was 87.0±2.9%, 89.2±1.3% and 91.1±0.7% with a C:N of 10, 4 and 1, respectively. NH_3-N removal was relatively high over this time due to the efficient utilization of organic compounds in the aerobic process [3]. Moreover, the I-BAF system showed excellent performance in carbon and nutrients removal, which provided a cost-effective solution for the treatment of low-strength domestic wastewater by the removal rates of 82.54%, 94.83%, 51.85% and 61.49% for COD, NH_4^+-N, TN and P, respectively, and the corresponding averaged effluents could meet the first class standards of China [82]. So, BAF reactor is generally reliable and it has a better treatment capacity at different C:N ratio with less HRT.

6. Conclusion

BAF may be used as a treatment process for nitrogen and COD removal to meet discharge requirements. This literature review demonstrates that BAF systems can be operated at a low HRT and can be used as a compact system for small communities in treatment of their wastewater for carbon and nitrogen removal. High hydraulic and pollutant loading rates are possible in the biofilters and each stage in the train can be optimized for peak performance. It was also anticipated that, having the media volume in the partial-bed reactor could reduce the capital and operational costs of a BAF reactor, one of the key factors that limits the wide application of BAFs. However, such a deduction is not straightforward, since reducing the packing media in BAFs, which in turn decreases the surface area available for biofilm attachment, and specifically the masses of essential microorganisms present in the reactor, might impair the reactor performance characteristics.

Due to its compactness, the BAF could be a useful technology, not only for industrial countries like the United States, Japan and those within the European Union, but also for such developing countries as Malaysia with rapidly expanding cities and rising land costs. This is justified not only by the competitiveness of the treatment performance but also by economic considerations, as the application of the most advanced treatment processes is limited by high capital or operational costs.

In general, the nitrification and denitrification processes can be applied for the removal of nitrogen contained in the wastewater. The concentration of nitrogen in the wastewater can be from low to high contents, which require an appropriate treatment process for the removal. The application of a certain biological treatment method or process will vary, depending on the location, land availability, social and economic concerns. Thus, both traditional and innovative technologies for the nitrification and denitrification processes for nitrogen removal from the wastewater need to be evaluated and applied properly. Thus, the protection of our environment and conservation of our resources can be warranted.

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References

1. Klees, R.; and Silverstein, J. (1992). Improved biological nitrification using recirculation in rotating biological contactors. *Water Science and Technology,* 26(3-4), 545-553.
2. Moosavi, G.H.; Naddafi, K.; Mesdaghinia, A.R.; and Nabizadeh, R. (2005). Simultaneous organics and nutrients removal from municipal wastewater in an up-flow anaerobic/aerobic fixed bed reactor. *Journal of Applied Sciences*, 5(3), 503-507.
3. Biplob, K.P. (2010). *Improving nitrogen removal efficiency using a controlled partially packed biological aerated filter (BAF) system*. MSc. Thesis, Department of Civil & Structural Engineering, Universiti Kebangsaan Malaysia (UKM), Malaysia.
4. Babel, S.; Sae-Tang, J.; and Pecharaply, A. (2009). Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application. *International Journal of Environmental Science and Technology*, 6(1), 131-140.
5. Khorsandi, H.; Movahedyan, H.; Bina, B.; and Farrokhzadeh H. (2011). Innovative anaerobic upflow sludge blanket filtration combined bioreactor for nitrogen removal from municipal wastewater. *International Journal of Environmental Science and Technology*, 8(2), 417-424.
6. Lu, X.M.; and Huang, M.S. (2010). Nitrogen and phosphorus removal and physiological response in aquatic plants under aeration conditions. *International Journal of Environmental Science and Technology*, 7(4), 665-674.
7. Doyle, M.P.; Herman, J.G.; and Dykstra, R.L. (1985). Autocatalytic oxidation of hemoglobin induced by nitrite: activation and chemical inhibition. *Journal of Free Radicals Biology Medicine*, 1(2), 145-153.
8. Gálvez, J.M.; Gómez, M.A.; Hontoria, E.; and González-López, J. (2003). Influence of hydraulic loading and air flowrate on urban wastewater nitrogen removal with a submerged fixed-film reactor. *Journal of Hazardous Materials*, 101(2), 219-229.
9. Hansson, L.-E.; Nyrén, O.; Hsing, A.W.; Bergström, R.; Josefsson, S.; Chow, W.-H.; Fraumeni, J.F.; and Adami, H.-O. (1996). The risk of stomach cancer in patients with gastric or duodenal ulcer disease. *The New England Journal of Medicine*, 335(4), 242-249.
10. Belgiorno, V.; Feo, G.D.; and Napoli, R.M.A. (2003). Combined carbonaceous removal and nitrification with biological aerated filters. *Journal of Environmental Science and Health Part A*, 38(10), 2147-2156.
11. Hamoda, M.F.; Al-Ghusain, I.; and Al-Jasem, D.M. (2004). Application of granular media filtration in wastewater reclamation and reuse. *Journal of Environmental Science and Health Part A*, 39(2), 385-395.
12. Ha, J.H.; and Ong, S.K. (2007). Nitrification and denitrification in partially aerated biological aerated filter (BAF) with dual size sand media. *Water Science and Technology,* 55(1-2), 9-17.
13. Hodkinson, B.; Williams, J.B.; and Butler, J.E. (1999). Development of biological aerated filter: A review. *Journal of Chartered Institution Water Environmental Management*, 13(4), 250-254.

14. Tay, J.-H.; Chui, P.-C.; and Li, H. (2003). Influence of COD:N:P ratio on nitrogen and phosphorus removal in fixed-bed filter. *Journal of Environmental Engineering*, 129(4), 285-290.
15. Banu, J.R.; and Kaliappan S. (2007). Treatment of tannery wastewater using hybrid upflow anaerobic sludge blanket reactor. *Journal of Environmental Engineering and Science*, 6(4), 415-421.
16. Lee, J.; Kim, J.; Lee, C.; Yun, Z.; and Choi, E. (2005). Biological phosphorus and nitrogen removal with biological aerated filter using denitrifying phosphorus accumulating organism. *Water Science and Technology,* 52(10-11), 569-578.
17. Rogalla, F.; and Bourbigot, M.M. (1990). New developments in complete nitrogen removal with biological aerated filters. *Water Science and Technology,* 22(1-2), 273-280.
18. Safferman, S.I.; Mashingaidze, E.M.; and McMackin, S.A. (2003). Carbon an nutrient removal in a dual-media fluidized bed reactor. *Journal of Environmental Science and Health Part A*, 38(9), 1689-1702.
19. Ha, J.H.; Ong, S.K.; and Surampalli, R. (2010). Impact of media type and various operating parameters on nitrification in polishing biological aerated filters. *Environmental Engineering Research*, 15(2), 79-84.
20. Mendoza-Espinosa, L.; and Stephenson, T. (1999). A review of biological aerated filters (BAFs) for wastewater treatment. *Environmental Engineering Science*, 16(3), 201-216.
21. Ryu, H.-D.; Kim, D.; Lim, H.-E.; and Lee, S.-I. (2008). Nitrogen removal from low carbon-to-nitrogen wastewater in four-stage biological aerated filter system. *Process Biochemistry*, 43(7), 729-735.
22. Moore, R.; Quarmby, J.; and Stephenson, T. (2001). The effects of media size on the performance of biological aerated filters. *Water Research*, 35(10), 2514-2522.
23. Westerman, P.W.; Bicudo, J.R.; and Kantardjieff, A. (2000). Upflow biological aerated filters for the treatment of flushed swine manure. *Bioresource Technology*, 74(3), 181-190.
24. Hasan, H.A.; Abdullah, S.R.S.; Kamarudin, S.K; and Kofli N.T. (2009). A review on the design criteria of biological aerated filter for COD, Ammonia and manganese removal in drinking water treatment. *Journal - The Institution of Engineers, Malaysia*, 70(4), 25-33.
25. M'Coy, W.S. (1997). Biological aerated filters: a new alternative. *Water Environment and Technology*, 9(2), 39-43.
26. He, S.B.; Xue, G.; and Kong, H.-N. (2007). The performance of BAF using natural zeolite as filter media under conditions of low temperature and ammonium shock load. *Journal of Hazardous Materials*, 143(1-2), 291-295.
27. Kent, T.D.; Fitzpatrick, C.S.B.; and Williams, S.C. (1996). Testing of biological aerated filter media. *Water Science and Technology*, 34(3-4), 363-370.
28. Farabegoli, G.; Carucci, A.; Gandolfo, G.; Rolle, E.; and Viotti, P. (2003). Experimental study on carbon removal in biological aerated filters. *Water Science and Technology,* 48(11-12), 235-242.

29. Grady, C.P.; Daigger Jr., G.T.; and Lim, H.C. (1999). *Biological Wastewater Treatment* (2nd Ed.). Marcel Dekker, Inc., New York.
30. Madigan, M.T.; Martinko, J.M.; and Parker, J. (2000). *Brock Biology of Microorganisms* (9th Ed.). Prentice-Hall Upper Saddle River, NJ.
31. Madigan, M.T.; Martinko, J.M.; and Parker, J. (2003). *Brock Biology of Microorganisms* (10th Ed.). Prentice-Hall Upper Saddle River, NJ.
32. Hargrove, L.L.; Westerman, P.W.; and Losordo, T.M. (1996). Nitrification in three-stage and single-stage floating bead biofilters in a laboratory-scale recirculating aquaculture system. *Aquacultural Engineering*, 15(1), 67-80.
33. Akpor, O.B.; Momba, M.N.B.; and Okonkwo, J.O. (2008). The effects of pH and temperature on phosphate and nitrate uptake by wastewater protozoa. *African Journal of Biotechnology*, 7(13), 2221-2226.
34. Ahmed, M.; Idris, A.; and Adam, A. (2007). Combined anaerobic-aerobic system for treatment of textile wastewater. *Journal of Engineering Science and Technology* (*JESTEC*), 2(1), 55-69.
35. Biplob, P.; Fatihah, S.; Shahrom, Z.; and Elshafie, A. (2011). Nitrogen removal efficiency using an upflow partially packed biological aerated filter (BAF) without backwashing process. *Journal of Water Reuse and Desalination*, 1(1), 27-35.
36. Jianlong, W.; and Ning, Y. (2004) Partial nitrification under limited dissolved oxygen conditions. *Process Biochemistry*, 39(10), 1223-1229.
37. Zhu, S.; and Chen, S. (2002). The impact of temperature on nitrification rate in fixed film biofilters. *Aquaculture Engineering*, 26(4), 221-237.
38. Kermani, M.; Bina, B.; Movahedian, H.; Amin, M.M.; and Nikaeen, M. (2009). Biological phosphorus and nitrogen removal from wastewater using moving bed biofilm process. *Iranian Journal of Biotechnology*, 7(1), 19-27.
39. Peng, Y.Z.; Chen, Y.; Peng, C.Y.; Liu, M.; Wang, S.Y.; Song, X.Q.; and Cui, Y.W. (2004). Nitrite accumulation by aeration controlled in sequencing batch reactors treating domestic wastewater. *Water Science and Technology,* 50(10), 35-43.
40. Qasim, S. (1998). *Wastewater Treatment Plants, Planning, Design, and Operation* (2nd Ed.). CRC Press.
41. Fulazzaky, M.A. (2009). Carbonaceous, nitrogenous and phosphorus matters removal from domestic wastewater by an activated sludge reactor of nitrification-denitrification type. *Journal of Engineering Science and Technology* (*JESTEC*), 4(1), 69-80.
42. Carrera, J.; Vicent, T.; and Lafuente, J. (2004). Effect of influent COD/N ratio on biological nitrogen removal (BNR) from high-strength ammonium industrial wastewater. *Process Biochemistry*, 39(12), 2035-2041.
43. Fdz-Polanco, F.; Mendez, M.A.; Uruena, S.; Villaverde, S.; and Garcia, P.A. (2000). Spatial distribution of heterotrophs and nitrifiers in a submerged biofilter for nitrification. *Water Research*, 34(16), 4081-4089.
44. Ong, S.-A.; Hoo, L.-N.; Wong, Y.-S.; Dugil, D.L.; and Samad, H. (2011). Semi-batch operated constructed wetland planted with *phragmites australis* for treatment of dyeing wastewater. *Journal of Engineering Science and Technology* (*JESTEC*), 6(5), 619-627.

45. Durmaz, B.; and Sanin, F.D. (2003). Effect of carbon to nitrogen ratio on the physical and chemical properties of activated sludge. *Environmental Technology*, 24(11), 1331-1340.
46. Fatihah, S. (2004). *Effect of full and partial bed configuration on the performance characteristics of biological aerated filters*. PhD. Thesis, University of Newcastle Upon Tyne, UK.
47. Bateman, E.J.; and Baggs, E.M. (2005). Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. *Biology Fertility Soils*, 41(6), 379-388.
48. Carter, J.P.; Hsio, Y.H.; Spiro, S.; and Richardson, D. (1995). Soil and sediment capable of aerobic nitrate respiration. *Applied Environmental Microbiology*, 61(8), 2852-2858.
49. Metcalf and Eddy (2003). *Wastewater Engineering, Treatment and Reuse* (4th Ed.). McGraw Hill Inc., New York.
50. USEPA (1993). *Manual nitrogen control,* EPA/625/R-93/010, Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC.
51. Lie, E.; and Welander, T. (1994). Influence of dissolved oxygen and oxidation-reduction potential on the denitrification rate of activated sludge. *Water Science and Technology*, 30(6), 91-100.
52. Painter, H.A. (1977). Microbial transformations of inorganic nitrogen. *Progress Water Technology*, 8(4/5), 3-29.
53. Coetzee, M.A.A.; Van der Merwe, M.P.R.; and Badenhorst, J. (2011). Effect of nitrogen loading rates on nitrogen removal by using a biological filter proposed for ventilated improved pit latrines. *International Journal of Environmental Science and Technology*, 8(2), 363-372.
54. Kim, D.W.; Ryu, D.J.; Go, M.J.; Chang, D.; Han, S.B.; Hur, J.M.; Chung, B.R.; Kim, B.K.; and Jin, Y.H. (2010). Nitrogen removal in a high-efficiency denitrification/oxic filter treatment system for advanced treatment of municipal wastewater. *World Academy of Science, Engineering and Technology*, 48, 13-15.
55. Jun, B.H.; Poo, K.M.; Im, J.H.; Kim, J.R.; Woo, H.J.; and Kim, C.W. (2004). External carbon feeding strategy for enhancing nitrogen removal in SBR. *Water Science and Technology*, 49(5-6), 325-331.
56. Nagaoka, H.; and Kudo, C. (2002). Effect of loading rate and intermittent aeration cycle on nitrogen removal in membrane separation activated sludge process. *Water Science and Technology*, 46(8), 119-126.
57. Chudoba, P.; and Pujol, R. (1998). A three-stage biofiltration process: performance of a pilot plant. *Water Science and Technology*, 38(8-9), 257-265.
58. Feo, G.D. (2007). Carbon and nitrogen removal from low-strength domestic wastewater with a two-stage submerged biological filter. *Journal of Environmental Science and Health Part A,* 42(5), 641-647.
59. Quan, X.; Shi, H.; Liu, H.; Lv, P.; and Qian, Y. (2004). Enhancement of 2, 4-dichlorophenol degradation in conventional activated sludge systems bioaugmented with mixed special culture. *Water Research,* 38(1), 245-253.

60. Tchobanoglous, G.; and Burton, F.L. (1991). *Wastewater Engineering. Treatment, Disposal, Reuse.* (3rd Ed.) McGraw-Hill Inc., New York.
61. Irvine, R.L.; Wilderer, P.A.; and Flemming, H.C. (1997). Controlled unsteady state processes and technologies-an overview. *Water science and Technology*, 35(1), 1-10.
62. Reynolds, T.D.; and Richards, P. (1995). *Unit operations and processes in environmental engineering.* (2nd Ed.). CL Engineering.
63. Pai, T.Y.; Tsai, Y.P.; Chou, Y.J.; Chang, H.Y.; Leu, H.G.; and Ouyang, C.F. (2004). Microbial kinetic analysis of three different types of EBNR process. *Chemosphere,* 55(1), 109-118.
64. Bicudo, J.R.; and Svoboda, I.F. (1995). Intermittent aeration of pig slurry farm-scale experiments for carbon and nitrogen removal. *Water Science and Technology,* 32(12), 83-90.
65. M¨unch, E.V.; Lant, P.; and Keller, J. (1996). Simultaneous nitrification and denitrification in bench-scale sequencing batch reactors. *Water Research*, 30(1), 277-284.
66. Chen, J.J.; McCarty, D.; Slack, D.; and Rundle, H. (2000). Full scale case studies of a simplied aerated filter (BAF) for organics and nitrogen removal. *Water Science and Technology,* 41(4-5), 1-4.
67. Chui, P.C.; Terashima, Y.; Tay, J.H; and Ozaki, H. (2001). Wastewater treatment and nitrogen removal using submerged filter systems. *Water Science and Technology*, 43(1), 225-232.
68. Pozo, R.D.; and Diez, V. (2003). Organic matter removal in combined anaerobic-aerobic fixed-film bioreactors. *Water Research*, 37(15), 3561-3568.
69. Clark, T.; Stephenson, T.; and Pearce, P.A. (1997). Phosphorus removal by chemical precipitation in a biological aerated filter. *Water Research,* 31(10), 2557-2563.
70. Gilmore, K.R.; Husovitz, K.J.; Holst, T.; and Love, N.G. (1999). Influence of organic ammonia loading on nitrifier activity and nitrification performance for a two-stage biological aerated filter system. *Water Science and Technology*, 39(7), 227-234.
71. Stensel, H.D.; Brenner, R.C.; Lee, K.M.; Melcer, H.; and Rakness, K. (1988). Biological aerated filter evaluation. *Journal of Environmental Engineering.* 114(3), 655-671.
72. Ahmed, Z.; Lim, B.R.; Cho, J.; and Ahn, K.H. (2007). Effects of the internal recycling rate on biological nutrient removal and microbial community structure in a sequential anoxic/anaerobic membrane bioreactor. *Bioprocess and Biosystems Engineering*, 30(1), 61-69.
73. Han, S.; Yue, Q.; Yue, M.; Gao, B.; Zhao, Y.; and Cheng, W. (2009). Effect of sludge-fly ash ceramic particles (SFCP) on synthetic wastewater treatment in an A/O combined biological aerated filter. *Bioresource Technology*, 100(3), 1149-1155.
74. Kim, S.W.; Park, J.B.; and Choi, E. (2007). Possibility of sewage and combined sewer overflow reuse with biological aerated filters. *Water Science and Technology,* 55(1-2), 1-8.

75. Ahn, K.H.; Song, K.G.; Cho, E.; Choa, E.; Cho, J.;Yun, H.; Lee, S.; and Me, J. (2003). Enhanced biological phosphorus and nitrogen removal using a sequencing anoxic/anaerobic membrane bioreactor (SAM) process. *Desalination*, 157(1-3), 345-352.
76. Cho, J.; Song, K.G.; Lee, S.H.; and Ahn, K.H. (2005). Sequencing anoxic/anaerobic membrane bioreactor (SAM) pilot plant for advanced wastewater treatment. *Desalination* 178(1-3), 219-225.
77. Kim, H.S.; Choung, Y.K.; Ahn, S.; and Oh, H.S. (2008). Enhancing nitrogen removal of piggery wastewater by membrane bioreactor combined with nitrification Reactor. *Desalination*, 223(1-3), 194-204.
78. Sun, D.D.; Hay, C.T.; and Khor, S.L. (2006). Effects of hydraulic retention time on behavior of start-up submerged membrane bioreactor with prolonged sludge retention time. *Desalination*, 195(1-3), 209-225.
79. Ahmed, S.U.; and Mogens, H. (2004). Biological denitrification of fertiliser wastewater at high chloride concentration. *Water SA*, 30(2), 191-195.
80. Ong, S.L.; Hu, J.Y.; Lee, L.Y.; Ng, W.J.; and Song, L.F. (2002). Packed bed columns for high rate nitrogen and carbon removals. *Water Science and Technology*, 46(11-12), 57-62.
81. Lee, L.Y.; Ong, S.L.; and Ng, W.J. (2004). Denitrification of nitrate wastewater using packed-bed columns. *Water Environment Research*, 76(5), 388-393.
82. Chen, Q.; Qu, L.; Tong, G.; and Ni, J. (2011). Simultaneous nutrients and carbon removal from low-strength domestic wastewater with an immobilised-microorganism biological aerated filter. *Water Science and Technology*, 63(5), 886-891.