Evaluation of the Performance of a Biological Filter with and without a Cleaning Mechanism

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Abstract: A biological filter with a cleaning mechanism (BCM) was built and tested for use in rural Trinidad and Tobago. The purpose of the cleaning mechanism was to increase the ammonia removal ability of the filter which will keep the bio-media clean at all times hence influencing the various conversions in the nitrogen cycle and improving the performance of the bio-filter. The performance of the BCM was tested in two approaches to determine its effectiveness. The first approach utilised the cleaning mechanism while the second approach did not. The concentration of ammonia decreased by 88% when using the BCM and the BCM produced higher concentrations of nitrites in less time. There was also the subsequent increase in concentration rates of nitrates with the BCM. Hence, there was an increase in ammonia removal and thus improved performance. The concentrations of dissolved oxygen, pH and temperature were also monitored for both cases. There were no significant variations between the two cases and therefore were not factors in determining the performance of the bio-filter.

Keywords: Bio-filter with cleaning mechanism, Bacteria, Ammonia, Nitrogen cycle, Tilapia, Trinidad and Tobago

1. Introduction

There is the growing demand for the consumption of fresh water fish in Trinidad and Tobago especially in the area of Tilapia production (Boodan, 2007). This has led to the farming practices that are carried out today, where large ponds are man-made and the fishes are reared in a controlled environment. For this modern method of rearing fishes to be successful, research and modern science has to be implemented to achieve the ideal condition for the rearing of fresh water fish.

In their own natural environment, fishes have an unlimited supply of water to live in. The water is continuously replenished by rainfall which contributes to a clean fresh water supply. However, in commercial production systems fresh water fishes, especially cascadoria and tilapia are reared in an enclosed environment. These enclosed environments are man-made, fresh water ponds having surface areas ranging from 100 m\textsuperscript{2} to 2,000 m\textsuperscript{2} with depths of approximately 1 m. These ponds can produce a maximum of approximately 100,000 tonnes of fish annually (Boodan, 2007). Rearing of the fish at this high density by this method introduces problems due to the accumulation of toxic metabolites (Avnimelech, 2006). As there is a limited supply of water in the systems all the excess food and subsequent waste produced by the fishes coupled with the decaying plant material contribute to the pollution of the water and reduce water quality. The water is polluted with various substances but is most significantly affected by ammonia and nitrite (Avnimelech, 2006; Kuhn et al., 2010).

The ammonia is present in the pond through various sources such as the wastes from fishes, the decomposition of plant tissues and excess feed and metabolic ammonia that is excreted from their gills as waste products (Hargreaves and Tucker, 2004). Since these ponds are specifically used for rearing fish, the number of fish per pond is high and the amount of ammonia they release is significant. The uneaten food and plant material are broken down by bacteria called heterotrophic bacteria. These heterotrophic bacteria have a healthy appetite and are always eating. As they do this, they release ammonia as a by-product. Since ammonia is continuously being released in the pond and clean water is not constantly entering the pond, the concentration of ammonia steadily increases. As a result, the fishes start showing signs of stress. As more ammonia is being released and the concentration increases, the ammonia will start to inflame the gills of the fishes leading to breathing problems making the fishes more vulnerable to diseases and even
death (Kuhn et al., 2010).

One approach in getting rid of the toxic ammonia in the pond is through the process of biological filtration (Avnimelech, 2006). Biological filtration is the process by which toxic organic substances are removed from an aquatic system by being consumed by beneficial bacteria that uses them as a natural food source (Warahomshi et al., 2004). The biological filter (bio-filter) incorporates the nitrogen cycle and provides a control environment for beneficial bacteria to accumulate which will convert ammonia into nitrites (NO$_2$) and then into nitrates (NO$_3$), by the production of beneficial bacteria (De Feo, 2007). The bacteria that consume the ammonia are called nitrosomonas. However, it releases a second toxic substance called nitrite. The nitrite in the pond is then consumed by the second bacteria called nitrobacteria. This specific bacterium converts the nitrites to nitrates which are not harmful to fishes even at high concentrations (Kuhn et al., 2010). This bacterium accumulates on to the surface of the media to form a biofilm (Tseng and Wu, 2004). The biofilm formation on the surface of the filter media is called the zoogloal film. It is composed of nitrifying bacteria, fungi algae protozoa and other life forms. Tseng and Wu (2004) identified that this bio-film grows thicker overtime as a result of microbial population build-up on the medium.

One measure of performance for bio-filters is the ammonia removal efficiency (Colt et al., 2006). Tseng and Wu (2004) identified that the specific ammonia rate (i.e. ammonia removal rate per unit medium surface area, SNR, mg/ m$^2$-h) increases until a maximum SNR is achieved and remains constant despite further growth of the bio-film. Tseng and Wu (2004) have also indicated that for a temperature between 22$^\circ$C to 32$^\circ$C this maximum SNR can occur between 10 to 15 days. A situation then arises where this excessive growth creates an anaerobic environment that eventually results in death of cells and detachment of the bio-film to the medium surface and hence the bio-filter shows a sharp decrease in ammonia removal efficiency (Tseng and Wu, 2004).

To achieve a successful pond for rearing fishes, it is important that the biological filter be incorporated in the pond to assist in establishing the nitrogen cycle which entails the various conversion processes (Avnimelech, 2006). An effective operational biological filter must support the life of these bacteria which converts the ammonia to the nitrates. These bacteria are aerobic which require a sufficient amount of oxygen to obtain a successfully population growth. Also, an important factor to obtain a successful bacterial growth would be the fact that they require a periodically clean hard surface on which the bacteria can colonise.

There exist commercial bio-filters and these include the following:

a) Bio foam bio-filters (Zimmer, 2009). These filters use a “moving-bed” media which is suspended in the biological filter system. The “moving-bed” bio-filter utilises suspended media which eliminates the possibility of a channeling media bed.

b) Fluidised bed bio-filters (Zimmer, 2009). These filters have unique shapes that are designed for concise space with a high surface area. The fluidised bed filters use a 1 mm silica sand, or garnet, that offers a large surface area for colonising the bacteria.

c) The Oase biological filters have a simple design (ERK, 2009). The biological media (Zeolite aggregate) are placed in a proffered netting bag which is then placed in a plastic container.

d) The Hozelock bio-force filter (Hozelock, 2009) is manufactured by Hozelock Limited, which specialises in all pond equipment. The water enters at an angle, creating a vortex to settle out solids. The water then enters the dark chamber containing superior Kaldnes K3 biomedia which encourages the growth of large numbers of beneficial bacteria.

Although these filters are commercially available, they are costly and therefore inappropriate for rural communities in Trinidad and Tobago. Hence the objective of this project was to design and build a cost effective bio-filter with a cleaning mechanism (BCM) that will be appropriate for use in rural communities in Trinidad and Tobago and elsewhere.

2. The Fabrication of the Bio-Filter with Cleaning Mechanism (BCM) Assembly

The biological media is made from a polyethylene mesh wound in a cylindrical shape of surface area 54 m$^2$. The framework (see Figure 1) is made from stainless steel and is aligned with three different types of bushing. The rotary bushing supports the rotational motion of the central rod, while the linear rotary bushing supports its vertical motions. The tapered bushing is placed at the bottom of each media where it supports the weight of the media and also the radial motion of the stainless steel rod when the cleaning operation is being undertaken.

Figure 1. The bio-filter (BCM)
Twelve (12) media are placed in a case and are supported by a steel stand, hence it is held fixed at a height above the ground. At the bottom of the filter, there is a water-sealed cover, which is screwed onto the plastic case (see Figure 2).

**Figure 2. Cross-sectional sketch of the filter**

The cleaning process entails a screwing and lifting motion. This is simple and highly effective, since the cleaning mechanism involves two parts: the lower part (scraper) which is used to remove heavy debris and an upper part (brush bristles) used to gently remove all the smaller colloidal particles. The scraper does not come in direct contact with the media so as not to cause exfoliation of the existing bacteria. So as to ensure that it passes close enough in order to remove unwanted accumulation, the brush bristles are strategically placed behind the scraper to remove the substances that the scraper has allowed to pass through. The bristles are in contact with the media so as to remove all the particles. However, it is made from a soft polyethylene material that does not cause any removal of bacteria that has already colonised on the media’s surface.

With a cleaning system of this design it can be ensured that all the unwanted particles that have accumulated on the media can be removed regardless of the physical geometry or nature of the particles. That is it is designed to remove particles usually found in a typical fish pond such as sand, silt, dirt, excess food, fish facieses and even smaller colloidal particles. The design of the biological filter ensures that the cleaning process is less complicated and time efficient, i.e. a simple unscrewing of the media and lifting it to a maximum height of one (1) meter then lowering it back and screwing it down, then all the removed substances is allowed to exit the filter via the bottom cover.

### 3. Performance Testing of the BCM

#### 3.1 Purpose of the Tests

Tests were conducted to:

a) Ensure that the biological filter was performing its purpose, which was to house the respected bacteria so that it could remove the ammonia.

b) Analyse how well the cleaning mechanism is functioning and a result having an impact on the filters performance hence affecting the rate at which the ammonia was removed.

#### 3.2 Testing the BCM

The biological filter was tested using two approaches:

a) The BCM filter in full operation placed as the only biological unit in the pond for a period of twelve days using the cleaning mechanism every consecutive day. Twelve days were chosen based on the results of Tseng and Wu (2004).

b) The BCM filter in full operation placed as the only biological unit in the pond for a period of twelve days without cleaning it.

#### 3.3 Testing Procedure

The pond that was used had a volume of 9 m³ and was made from concrete blocks which had a depth of 0.9 m. The water that was used in the pond was untreated rain water, which was collected prior to the testing processes. The fishes that were used were tilapia. The pond contained approximately 100 kg of fishes and each fish weighed approximately (0.5 - 0.8) kg.

The water samples were taken in an acid wash container to the research laboratory every two days to determine the concentrations of ammonia, nitrite and nitrates. Hach method 8155 (Hach Co., 2008) also called salicylate method which uses nitrogen-ammonia reagent Se, was used to measure the concentration of ammonia. This method was used because of its range (0.01-0.5) mg/L, which is ideal for this application. Hach method 8507 (Hach Co., 1999) also called diazotization method was used to determine the concentration of nitrite. It uses NitraVer 3 nitrite reagent, which has a measuring range of (0.002- 0.3) mg/L. Hach method 8039, also called cadmium reduction method (Hach Co., 1999) was used for measuring the concentration of the nitrates over a range of (0.0- 30.0) mg/L. It uses NitraVer 5 nitrate reagents. Dissolved oxygen concentration, pH and temperature were also monitored on site using various meters.

### 4. Results and Discussion

In Table 1, it can be seen initially, between days 0 and day 2 that there were little chemical changes occurring in the pond. This was evident because of the small variations in all the concentrations of ammonia, nitrates and nitrites.

As time progressed, and the nitrogen cycle was being enforced and gradual changes started to occur, the nitrosomonas bacteria population began to increase
because of the ammonia enriched water that was available to it. At the early stages in the operation, the nitrobacteria population was insignificant as evident by the very small concentration of nitrates. This was as a result of the lack of nitrite in the water initially, hence little food was available for the nitrobacteria to consume and multiply and as a result enforce the conversion processes of nitrite to nitrate. Figure 3 identifies the order of the conversion process. It shows that ammonia was converted to nitrites and then the nitrites were converted to the nitrates respectively. This happened in both approaches.

Further examination of Figure 3 showed that the conversion of ammonia to nitrites and then into nitrates occurred at a faster rate for BCM when operating the cleaning mechanism. In the first approach the BCM was periodically cleaned using the cleaning mechanism and it is shown in Table 1 that the initial concentration of ammonia was 0.56 mg/L and this was reduced to 0.06 mg/L on the day 12 compared with the reduction from 0.48 to 0.19 mg/L for the BCM when not using the cleaning mechanism for the same duration. This is a 0.19mg/L difference between the two approaches and results in 88% decrease in ammonia concentration for the BCM when operating the cleaning mechanism.

The performance of the filter was also evident when considering the rate of formation of nitrites. This faster increase in the nitrite concentration relates to the rate of the conversion, which in turn is determined by the bacteria’s population density. Examination of the line plots for ammonia and nitrite with cleaning, would reveal that it was only when the ammonia concentration started to decrease that the nitrite concentration increased. Examination of the nitrite plots showed that the concentration of nitrites increased from 0.003 to 0.6 (max.) mg/L in 8 days for BCM when using the cleaning mechanism while it increased from 0.002 to 0.56 (max.) mg/L in 10 days for BCM when the cleaning mechanism was not employed.

The conversion of nitrites into nitrates is important since it is the last stage of the nitrogen cycle that the filter could influence. Examining the nitrite and nitrate line plots revealed that it was only when the concentration of nitrites decreased that the concentration of nitrates increased which was evident of the conversion process. In the first approach, the concentration of nitrates increased more rapidly in comparison to the second approach when the BCM was not clean. Since the nitrite concentration decreased more rapidly in the cleaned filter, the nitrate concentration increased at a faster rate in comparison to the uncleaned filter. This demonstrated that the nitrobacteria which were responsible for this conversion were consuming the nitrite and releasing nitrates at a faster rate when the filter was cleaned. This was evident by the greater population density of the nitrobacteria in the cleaned filter in comparison to the unclean one.

The data collected onsite during the testing (see Table 2) showed that variations in dissolved oxygen concentration, temperature of water in the pond as well as

<table>
<thead>
<tr>
<th>Days after testing</th>
<th>Ammonia mg/L</th>
<th>Nitrite mg/L</th>
<th>Nitrate mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>of the filter began</td>
<td>Without Cleaning</td>
<td>With Cleaning</td>
<td>Without Cleaning</td>
</tr>
<tr>
<td>0</td>
<td>0.480</td>
<td>0.540</td>
<td>0.002</td>
</tr>
<tr>
<td>2</td>
<td>0.470</td>
<td>0.530</td>
<td>0.006</td>
</tr>
<tr>
<td>4</td>
<td>0.450</td>
<td>0.440</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>0.400</td>
<td>0.340</td>
<td>0.14</td>
</tr>
<tr>
<td>8</td>
<td>0.320</td>
<td>0.240</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>0.200</td>
<td>0.120</td>
<td>0.56</td>
</tr>
<tr>
<td>12</td>
<td>0.190</td>
<td>0.060</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Figure 3. The concentration of ammonia, nitrite and nitrates days after the testing (operation) of BCM began

Hence there was a higher ammonia removal rate with the BCM in the first approach. Since the only mode that ammonia could be removed from the system was via the nitrosomas bacteria, this implied that when the filter was cleaned periodically, the nitrosomas bacteria population was greater and resulted in a subsequent increase in performance in the bio-filter. This is similar to the results of Tseng and Wu (2004).
the pH were minimal with respect to time throughout the entire test period. Thus, these factors did not affect the growth of bacteria during the test period nor did they affect the performance of the filter. For instance, dissolved oxygen only varied in concentration between 2.50 mg/L and 2.55 mg/L.

Table 2. Dissolved oxygen (DO) concentration, temperature and pH

<table>
<thead>
<tr>
<th>Days</th>
<th>DO, mg/L</th>
<th>Temperature °C</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.54</td>
<td>26.7</td>
<td>7.67</td>
</tr>
<tr>
<td>2</td>
<td>2.50</td>
<td>27.1</td>
<td>7.69</td>
</tr>
<tr>
<td>4</td>
<td>2.53</td>
<td>26.9</td>
<td>8.05</td>
</tr>
<tr>
<td>6</td>
<td>2.52</td>
<td>26.0</td>
<td>7.65</td>
</tr>
<tr>
<td>8</td>
<td>2.54</td>
<td>26.5</td>
<td>7.67</td>
</tr>
<tr>
<td>10</td>
<td>2.55</td>
<td>26.6</td>
<td>7.66</td>
</tr>
<tr>
<td>12</td>
<td>2.50</td>
<td>26.2</td>
<td>7.65</td>
</tr>
</tbody>
</table>

In relation to the performance of the cleaning mechanism in terms of removing the accumulated unwanted substances on the biological media, a physical analysis was done on the media before and after the cleaning of the media. Before the cleaning of the filter, it was observed that on the surface of the media, there were sand and silt accompanied with fine debris, which had accumulated because of the incoming water. However, after utilising the cleaning mechanism, these substances were removed. It was also observed that during the cleaning processes, the brush compartment was highly effective in removing all the unwanted substances. However, the scraper was not as effective because it was designed for heavy and large debris which were absent on the media.

During the operation of the filter in both cases, both bacteria had accumulated on the surface of the media, hence there were various conversions occurring. In case one, when the filter was not cleaned periodically, the population of the nitrobacteria grew at a fairly constant rate initially. This was evident because the rate at which ammonia was being removed was fairly constant. However, after day 10, it was observed that the rate of ammonia removal decreased. This gave rise to the evidence that the rate at which the bacteria colonised the media decreased. This phenomena is known as the retard growth phase and was reported by Tseng and Wu (2004).

During the testing all variable parameters were constant. However, in the first case, the major difference was that the media was not cleaned, therefore as the water flowed through the media it brought with it insoluble substances such as sand and dirt. These insoluble substances attached themselves onto the media and over a period of time developed into an insoluble film. As a result, the existing bacteria that had already accumulated had difficulty in consuming the ammonia from the water because the insoluble film prevented the bacteria from coming in contact with the income water. Since the bacteria was not consuming the ammonia as efficiently, the growth rate started to decrease. The existing bacteria were unable to consume the ammonia since it was not in direct contact anymore. For this reason the ammonia removal rate started to decrease. This occurred approximately after day 10 as illustrated in the results. In the second approach this insoluble film was not able to form since the media was cleaned periodically. Therefore the bacteria were able to consume the ammonia without any disruption throughout the entire testing period as illustrated in the results. The filter was able to remove ammonia more effectively when the cleaning mechanism was utilised.

It was also observed that in both situations the concentration of ammonia did not reach below the suggested safe level of 0.05 mg/L. However during the operation of the first approach, the concentration was reduced to 0.06 mg/L in comparison to the second approach where the concentration was reduced to only 0.19 mg/L. Hence, the filter was more effective in removing ammonia when the media was periodically cleaned. This further illustrates that the cleaning mechanism within the biological filter is highly effective, simple to use and maintain. It is therefore quite suitable for use in rural communities.

5. Conclusion

The bio-filter with a cleaning mechanism (BCM) was successfully built and tested. It was simple to assemble and easy to operate, and was thus very effective and appropriate for rural communities in Trinidad and Tobago. The cost of fabricating one unit for a 9m³ pond containing 100kg of fish is 600.00 US dollars.

The performance of the device was tested using two approaches. The first approach used the cleaning mechanism periodically and the second approach did not use the cleaning mechanism at all. It was observed that the cleaning mechanism was highly effective in cleaning the filter and resulted in a higher removal rate of ammonia because of the greater bacteria population. Therefore the conversion of ammonia to nitrite via nitrosomonas and nitrite to nitrate via nitobacteria were occurring at a faster rate. Therefore, the BCM when using the cleaning mechanism showed higher ammonia removal rate efficiency and therefore an improved performance.

References:


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Robert A. Birch is a Lecturer of the Department of Mechanical and Manufacturing Engineering at the University of the West Indies (UWI), St Augustine, Trinidad and Tobago. He is a registered professional engineer (R.Eng) and project management professional (PMP) with over sixteen years industrial and teaching experience. He is presently pursuing a PhD in mechanical engineering. Mr. Birch is also a member of Latin American and Caribbean Association of Agricultural Engineers (ALIA) and the International Commission of Agricultural and Bio-systems Engineering (CIGR).

Kumar Narine graduated with a BSc. (Eng) in Mechanical Engineering (minor in Biosystems) from the University of the West Indies. He was awarded “best final year student project” in the area of biosystems engineering in 2010. He is presently employed as an engineering trainee with the Petroleum Company of Trinidad and Tobago (Petrotrin). His areas of interest are in environmental engineering and engineering design.

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