Review

The Need of Biofilter for Ammonia Removal in Recirculating Aquaculture System

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Abstract With the world's population increase, demands of fish production increased rapidly. Because of the demand increase, methods of aquaculture also become more intense. With the increasing intensity of aquaculture, more metabolites in the system are accumulated. The metabolites accumulated in the system turn to the causatives of water quality deterioration and become limiting factors for fish growth. Due to the toxicity of ammonia, ammonia removal is needed in aquaculture system. Biofilters, often referred as biological filter or nitrification filter are commonly used in recirculating aquaculture system to remove ammonia and convert it to nitrite, and then to nitrate.

Key words : ammonia, recirculating aquaculture systems, biofilter.

Introduction

The enormous population pressure effects and exploits the natural resources availability, especially fisheries and agriculture. Fish becomes progressively significant as main source of diet. Aquaculture's increasing contribution to global food security, poverty alleviation, rural livelihoods, employment and income generation has been duly recognized over the past decade [5]. The aquaculture industries try to fulfil human need of fish. Hence, there have been some efforts to obtain the bigger fish product, one of them through increasing biomass intensively. The need to increase aquacultural production is driving the industry toward more intensive practices [7].

However, intensification system requires large amount of high quality water supply, in order to control water quality. Yet, limitations in quality and quantity of water become the critical issues in this system. In some areas noted that there is lack of water sources for aquaculture. In Israel water cost is approximately US \$ 0.4/m^3 [3]. In Kuwait aquaculture utilizes limited resource of low-salinity underground water (2-5 ppt) [19]. In Saudi Arabia, fresh water aquaculture is obstructed by many factors, i.e. limitation of fresh water supply, the extreme hot and dry climate, irregular and low intensity of rainfall and number of evaporation. [1]. In Hawaii, ornamental fish aquaculture, with low density, requires 4 times water exchange per day. Predictably, in 2010 the aquaculture of ornamental fish in Hawaii will be forbidden if the system is held unchanged [2].

In other side, such intensification system may cause water quality limitation. Biomass increasing placed water quality as limiting factor. It is determined by accumulation of toxic metabolite [3]. In addition, untreated wastewater usually contents numerous pathogenic, or disease causing. Wastewater also contains nutrients, which can stimulate the growth of aquatic plants, and it may contain toxic compounds [15].

According to that mentioned above, intensification system needs efforts to minimize water requirement and to control water quality within tolerant limit.

Biofilter in Recirculating Aquaculture System

Recirculating technologies offers solution for intensification to solve those problems. This technology allows water to be cleaned and reused several times

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prior to discharge. Thus, a recirculating aquaculture facility capable to reduces water demands and discharges by reconditioning of water. Under certain circumstances, recirculating technology also present the only reasonable approach to economical aquaculture, for example in urban area where space is at a premium [21, 22].

In addition to water conservation, recirculating systems allow large fish yield to be obtained in a small area, enhance environmental control, and increase growth on a year around production schedule, thereby avoiding the seasonal limitations suffered in outdoor system [25].

The forms of aquaculture wastewater treatment systems may vary, but generally they can classify into two categories, i.e. biofilters and constructed wetland [17]. Of the two, biofilters are most commonly used. Generally, biological filtration is including in a filtration technique, which can utilize living organism to throw impurity away from water [26]. Biological filter encompasses living plant filter, nitrification, denitrification, extended aeration system and host from many kinds of filter types or unit processes.

In aquaculture, biofiltration is an important process in water recirculating system. Ammonia is a product from animal metabolism, which is released into water body. Due to the toxicity of ammonia, ammonia removal is needed to keep the clean environment. The efficient way is by water recycling through external unit or biofilter, which can treat and purify water in closed recirculation water system [3]. Biofilters, often referred as biological filter or nitrification filter are commonly used in recirculating aquaculture system to remove ammonia and convert it to nitrite, and then to nitrate.

Many researches have proved that biofilter system in closed recirculation water system could control water quality within tolerant limit and reduces water requirement. Wastewater treatment using biological filters and development of practical systems have progressed rapidly since the late 1980s [27]. However, the disadvantages of biofilters are also obvious, including excessive sludge production, unstable performance, and nitrate accumulation [12].

Biofilter contains nitrifying bacteria and heterotroph microorganisms [23]. These organisms metabolize TAN and organic material, which entered biofilter. Biological growth occurs on the surface of media and furthermore attached film of microorganisms will oxidize dissolved ammonia. This transformation process is termed as nitrification.

Nitrification Kinetic

Decomposition of nitrogenous compound is one of the most important things in aquaculture, because ammonia, nitrite, and nitrate (in higher concentration) can be poisonous to aquaculture organisms. Among toxic metabolites which accumulated in aquaculture system, ammonia and nitrite are the most poisonous [3], therefore removal ammonia, nitrite and nitrate from wastewater become the aims of biological wastewater treatment, especially through nitrification and denitrification [6].

Complex organic nitrogen compounds are converted to simpler organic compound and then to ammonia (the direct inorganic product) by heterotrophic bacteria. Ammonia will be oxidized by some genera from autotroph bacteria. The oxidation of ammonia into nitrite and the subsequent oxidation to nitrate are performed by two different bacteria. The first step, the oxidation of ammonia into nitrite (NO_2) is done by some bacteria mostly from Nitrosomonas. The second step, the oxidation of nitrite into Nitrate (NO_3) is done by bacteria of the genus Nitrobacter.

Heterotrophic bacteria rely on organic compounds as their energy resources, on the other hand autotrophic bacteria depend on inorganic compounds as their energy resources. Heterotrophic bacteria are growing significantly rather than Nitrosomonas and Nirobacter. Thus, attempting to combine the conversion of organic compound and the inorganic forms of nitrogen in the same biological filter induces the competition for growing space between heterotrophs and autotrophs bacteria [26].

Moreover, the presence of organic material will disturb nitrification rate of biofilter [29]. Easily biodegradable organic matter in wastewater induced growth of heterotrophic bacteria, and then these bacteria became competitor for autotrophic bacteria in film making process, oxygen utilization, nutrient and space.

That is strong relationship between C/N ratio and heterotrophic abundance in biological filter [13]. Nitrification efficiency was negatively affected by the increase in the C/N ratio, suggesting that the fast growing heterotrophs, found in the outer layers of a biofilm, reduced the availability of oxygen and the diffusion of ammonia to the deeper layers where the slow growing nitrifiers were probably found.

In addition, heterotrophic populations produce significant quantities of bacterial biomass, which may contribute to the clogging of a filter and reduce nitrification capacity. On the other hand, the heterotrophic layer could also have a positive effect on nitrification by protecting nitrifiers from detachment and grazing [16].

In experimental condition, when a synthetic medium is mixotrophic (i.e. contains both ammonia and organic matter), the biofilm will segregate into distinct layer [8]. Competition between bacteria would be lessened when series of biofilter were used [9].

Denitrification conversion from NO_3 to NO_2 (nitrate to nitrite), NO_3 to N_2O or N_2 (nitrate to dinitrogen oxide or nitrogen gas, respectively), and N_2O to N_2 occur only under anaerobic conditions. This reaction is not expected in well-aerated filter condition.

Equation 1 and 2 shows basic chemistry conversion happen in nitrification filter:

$$NH_4^+ + 1.5\ O_2 \Rightarrow 2H^+ + H_2O + NO_2^- \quad (1)$$

$$NO_2^- + 0.5\ O_2 \Rightarrow NO_3^- \quad (2)$$

Reaction 1 and 2 released energy for Nitrosomonas and Nitrobacter. This energy is used to conduct their life cycle. Those reactions need oxygen and produce hydrogen ion (lowering pH) and also produce nitrite as intermediate product [26].

Some Factors Affecting Biofilter Performance

pH

The optimum pH range in nitrification is 6-9, but for the specific filter, the optimum range is narrower [26]. Biofilter bacteria which are important in decomposing waste products are not efficient over a wide pH range [14]. The optimum pH range for biofilter bacteria is 7 to 8. However, pH < 6 did not inhibit activity of the NH_3-oxidizers [4]. Specific range is being a function of adaptation of the bacteria in the filter to pH. The pH usually is managed in lower optimum limit because unionized ammonia percentage will increase concurrently with pH increasing. By adjusting pH in lower optimum limit, ammonia stress in nitrification can be minimalized.

In addition, in water at pH 7.0, less than 1% of any ammonia will be present as NH_3, and NH_3 excreted by the fish into water of this pH will be converted to $NH4^+$ [10]. Dramatic pH change, for instance within few minutes pH is changing over than 0.5-1.0 unit, will diminish filter efficiency of bacteria [11]. Efficiency of bacteria will be normal after bacteria can adopt the new condition.

Oxygen

Nitrification rate will decrease when oxygen content is not adequate for the activity of nitrification bacteria, even certain bacteria are capable to simultaneous ammonia and nitrite removal under anoxic condition [20]. Limiting concentration of oxygen is a function of some variables, including temperature; organic concentration in filter feed water, and bacteria biomass.

Applicably, filter contains heterotrophs as well as nitrifiers, therefore filter which receives culture water must contain high percentage of heterotrophs bacteria in first phase, because nitrogen cycle is starting from changing of organic compound to ammonia [25]. Then, Nitrosomonas population will develop in filter and they will remove ammonia. Subsequently, still in biofilter, Nitrobacter will grow concurrently with the increasing of nitrite. Position of bacterial strains in the filter dictates that oxygen is used first by heterotrophics, then by Nirosomonas, and then by Nitrobacter.

Managing oxygen concentration at least 2 mg/L will be safer in wastewater nitrification filter operation and in aquaculture operation as well [26]. Thus, aquacultural nitrification filters are often ammonia or nitrite limited, rather than oxygen limited. In this case, oxygen increasing will give small impact on filter performance, until oxygen reach limiting factor.

Ammonia/nitrite concentration

Over concentration of ammonia and/or nitrite will become poisonous for nitrification filter operation [26]. Un-ionized ammonia inhibits Nitrosomonas in higher concentration compare with the inhibiting concentration for Nitrobacter (10-150 mg/L compare with 0.1-1.0 mg/L).

In a recirculating system with a mature biofilter, nitrite-nitrogen concentrations should not exceed 10 mg/L long periods of time and in most cases should remain below 1 mg/L [14].

Furthermore, nitrification aquaculture work on lower ammonia and nitrite concentration rather than filter nitrification in municipal wastewater [26]. Presence of ammonia and/or nitrite can reveal nitrification rate in aquaculture nitrification filter.

Temperature

There are some different opinions concerning with specific effect in nitrification. Those different opinions revealed that nitrification bacteria would adjust to many temperature conditions, which are applied in filter [26].

The impact of temperature was insignificant on nitrification rates of fixed-film filters with temperatures ranging from 14 to 27 ^{0}C under a limitation of dissolved oxygen [30]. As saturation D.O. concentration decreases with an increase of temperature, it reduces the temperature effect on the nitrification rate due to the improvement in biofilm bacteria growth.

Type of Filter Media

Filter media is solid material, which is placed inside the filter, supplying surface area for bacteria growth. Biofilter necessitates suitable media which can provide appropriate environment for growth of autotroph nitrifying bacteria [18].

There are thousand types of media which used for nitrification system, including sand and stone or plastic media. Selection of media types usually based on some considerations. Specific surface area usually becomes one of the most considerations in media type's selection. SSA is surface area media per unit volume. The higher SSA of a media, the more bacteria can grow per unit volume media, and also total ammonia removal per unit volume filter will be higher. Filter media with surface and structural characteristic are conductive to the development of biofilms and the capture of organic suspended matter are desirable to ensure good and consistent biofilter performance [28].

The others consideration for choosing biofilter media type are media must have low void ratio to allow longer interaction between water and media, therefore bacteria can grow easily; media must have low weight to get simply treatment; media must have reasonable economic value; and media must have high homogeneous water flow possibility to avoid dead zone and channel, which can decrease nitrification rate [12]. Media size, void ratio, and specific surface area are related each others. Media with small diameter usually has wider specific area and has lower void ratio, compare with bigger diameter from the same media [26].

Operational Characteristic of Biofilter

A perfect biofilter will be able to remove all ammonia which enters the system, and will not produce nitrite. Even in cheap material, biofilter will not restrain solid and can grow large number of microbial as well and need a simply treatment [24]. Unfortunately, there have not been biofilter that fulfil all of the criteria.

Type of biofilter varies in different ways. Some of them are submerged filter [6, 13, 16], fluidized reactor [23, 13, 24], floating bead reactor [9, 28, 19], and trickling filter [12]. Many biofilters have been developed concerning with their functions. In aquaculture industry, every biofilter have their owns design and operational character. Instead of that, biofilter selected based on each system requirements [24]. There have many research done to get information about biofilter performance maintaining water quality in aquaculture. Yet many efforts to find out the most effective and efficient media is still going on.

References

1. Al-Hafedh, Y.S., Alam, A., Alam, M.A., 2003. Performance of plastic biofilter media with different configuration in a water recirculation system for the culture of Nile tilapia (*Oreochromis niloticus*). Aquacultural Engineering 29, 139-154.
2. Asano, L., Ako, H., Shimizu, E., Tamaru, C.S., 2003. Limited water exchange production systems for freshwater ornamental fish. Aquaculture Research 34, 937-941.
3. Avnimelech, Y., 2006. Bio-filters: The need for an new comprehensive approach. Aquacultural Engineering 3, 172-178.
4. Chen, Y.X., Yin, J., Wang, K.X., 2005. Long-term operation of biofilter for biological removal of ammonia. Chemosphere 58, 1023-1030.
5. FAO, 2003. Review of the state of world aquaculture. FAO Fisheries Circular No. 886, Rev. 2, Rome, 95 p.
6. Fdz-Polanco, F., Mendez, E., Uruena, M.A., Villaverde, S., Garcia, P.A., 2000. Spatial distibution of heterotrophs and nitrifiers in a submerged biofilter for nitrification. Water Research 34, 4081-4089.
7. Guiterrez-Wing, M.T. and Malone, R., 2006. Biological filters in aquaculture: Trend and research direction for freshwater and marine applications. Aquacultural Engineering 34, 163-171.
8. Hagopian, D.S. and Riley, J.G., 1998. A closer look at the bacteriology of nitrification. Aquacultural Engineering 18, 223-244.
9. Hargrove, L.L., Westerman, P.W., Losordo, T.M., 1996. Nitrification in three-stage floating bead biofilters in a laboratory-scale recirculating aquaculture system.

Aquacultural Engineering 15, 67-80.
10. Ip, Y.K., Chew, S.F., Randall, D.J., 2001. Ammonia toxicity, tolerance, and excretion. In: Wright, P.A., Anderson, P.M. (Eds.), Nitrogen Excretion. Academic Press, pp. 109-148.
11. Lawson, T.B., 1995. Fundamentals of Aquaculture Engineering. Chapman and Hall, New York, USA.
12. Lekang, O. and Kleppe, H., 2000. Efficiency of nitrification in trickling filters using different filter media. Aquacultural Engineering 21, 181-199.
13. Ling, J. and Chen, S., 2005. Impact of organic carbon on nitrification performance of different biofilters. Aquacultural Engineering 33, 150-162.
14. Losordo., T.M., Masser, M.P., Rakocy, J., 1998. Recirculating Aquaculture Tank Production Systems; An Overview of Critical Considerations. Rev. Southern Regional Aquaculture Center Publication No. 451.
15. Metcalf and Edy, Inc., 1991. Wastewater engineering, treatment, disposal, and reuse. 3rd eds. McGraw-Hill, New York.USA.
16. Michaud, L., Blancheton, J.P., Bruni, V., Piedrahita, R., 2006. Effect of particulate organic carbon on heterotrophic bacterial populations and nitrification efficiency in biological filter. Aquacultural Engineering 34, 224-233.
17. Qin, G., Liu, C.C.K., Richman, N.H., Moncur, J.E.T., 2005. Aquaculture wastewater treatment and reuse by wind-driven reverse osmosis membrane technology: a pilot study on Coconut Island, Hawaii. Aquacultural Engineering 32, 365-378.
18. Ridha, M.T. and Cruz, E.M., 2001. Effect of biofilter media on water quality and biological performance of the Nile tilapia *Oreochromis niloticus* L. reared in a simple recirculating system. Aquacultural Engineering 24, 157-166.
19. Rusten, B., Eikebrokk, B., Ulgenes, Y., Lygren, E., 2006. Design and operation of the Kaldnes moving bed biofilm reactors. Aquacultural Engineering 34, 322-331.
20. Sliekers, A.O., Derwort, N., Gomez, J.L.C., Strous, M., Kuenen, J.G., Jetten, M.S.M., 2002. Completely autrotophic nitrogen removal over nitrite in one single reactor. Water Research 36, 2475-2482.
21. Stickney, R.R., 1979. Principles of warmwater aquaculture. John Wiley and Sons, New York, USA.
22. Stickney, R.R., 1994. Principles of aquaculture. John Wiley and Sons, New York, USA.
23. Summerfelt, S.T. and Sharrer, M.J., 2004. Design implication of carbon dioxide production within biofilters contained in recirculating salmonid culture systems. Aquacultural Engineering 32,171-182.
24. Summerfelt, S.T., 2006. Design and management of conventional fluidized-sand biofilters. Aquacultural Engineering 34, 275-302.
25. Van Gorder, S.D., 1994. Operating and managing water reuse systems. In: Timmons, M.B., Losordo, T.M. (Eds.), Aquaculture Water Reuse Systems: Engineering Design and Management. Development in Aquaculture and Fisheries Science, vol. 27. Elsevier, Amsterdam, pp. 281-306.
26. Wheaton, F.W., Hochheimer, J.N., Kaiser, G.E., Malone, R.F., Krones, M.J., Libey, G.S., Easter, C.C., 1994. Nitrification filter principles. In: Timmons, M.B., Losordo, T.M. (Eds.), Aquaculture Water Reuse Systems: Engineering Design and Management. Development in Aquaculture and Fisheries Science, vol. 27. Elsevier, Amsterdam, pp. 101-126.
27. Xie, W., Wang, Q., Song, G., Kondo, M., Teraoka, M., Ohsumi, Y., Ogawa, H.I., 2004. Upflow biological filtration with floating filter media. Process Biochemistry 39, 765-770.
28. Yang, L., Chou, L.S., Shieh, W.K., 2001. Biofilter Treatment of Aquaculture Water for Reuse Applications. Water Research 35, 3097-3108.
29. Zhu, S. and Chen, S., 2001. Effect of organic carbon on nitrification rate in fixed film biofilters. Aquacultural Engineering 25, 1-11.
30. Zhu, S. and Chen, S., 2002. The impact of temperature on nitrification rate in fixed film biofilters. Aquacultural Engineering 26, 221-237.