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Recirculating Systems for Pollution Prevention in Aquaculture Facilities

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ABSTRACT

As all other forms of livestock production, fish farming has numerous environmental impacts. Water pollution is one of the most significant outcomes, since aquaculture effluents contain non-ingested food and fish dregs that affect the receiving water bodies when discharged without any treatment. Conventional pollutants (suspended solids, dissolved organic matter and nutrients), as well as pesticides, heavy metals and emerging pollutants (as antibiotics and hormones), are commonly found in these effluents. Recirculating aquaculture systems (RAS, systems that integrate the treatment and the reuse of water in the process) are an invaluable alternative for preventing water pollution by diminishing both the volume and the eutrophication potential of the effluents. Based on our review of the extant literature in the field, we conclude that activated carbon-based biofilters are a favorable technology to achieve a level of water quality that is compatible with environmentally-sound aquaculture practices.

Keywords: Fresh Water Production; Biofilter; Nitrogen Removal; Biological Activated Carbon

1. Introduction

Fish is an exceptional source of good-quality proteins, lipids and a wide variety of essential nutrients. Production of farmed fish, or aquaculture, is probably the fastest growing food sector worldwide, as now it accounts for nearly 40% of the world fish production [1]. Aquaculture production has expanded 12-fold in the last three decades (1980-2010) [1], and the reliance on farmed fish will certainly increase alongside with world population [2].

Until two decades ago, when extensive technologies prevailed, aquaculture was considered an environmentally-sound activity. Several traditional techniques even functioned as efficient water treatment systems, thereby contributing to the abatement of pollution [3]. But recently, with the adoption of more intensive production systems, the sustainability of aquaculture has been questioned. Environmental concerns arise from both the increased use of resources (as land, water, feed and energy) and the concomitant waterborne and airborne emissions of the farms. The risks inherent to aquaculture [4,5] can be summarized as in the following list.

- Habitat alteration or destruction
- Generation of organic-rich sediments
- Excessive freshwater consumption
- Modification of water temperature and flow rate profiles
- Water pollution
- Modification of the biotic index
- Transmission of infections from farmed organisms to wild stock
- Emergence and spread of antibiotic resistance
- Genetic risk of escaped culture animals
- Introduction of exotic species
- Diminution of wild fish stock for farming carnivorous species
- Multi-use conflicts for resources

However, for some authors, even larger-scope impacts of aquaculture should be taken into account, such as greenhouse gases originating from energy consumption and their contribution to global warming, ocean acidification and ozone layer depletion [6].

Here we examine the effects of aquaculture on the quality of receiving water bodies, with emphasis on the impacts of freshwater fish production in ponds. This review examines the water quality requirements of the in-

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dustry and summarizes the extant literature concerning the pollutants expected to be presented in the effluents from intensive aquaculture facilities. We present also the recycling aquaculture systems (RAS) as an efficient alternative for pollution prevention in these facilities.

2. Farmed Fish Production and Water Quality

An aquatic farm (**Figure 1**) has water quality levels to maintain, which are very dependent on the species cultivated. The main requirements concern dissolved oxygen, pH, ammonia and nitrites [3]. In salmonid culture, dissolved oxygen levels are not allowed to be less than 5 mg/L for more than a few hours. Although carp and tilapia in farms can tolerate lower concentrations (ranging from 3 to 4 mg/L), the optimum levels of dissolved oxygen are higher, and so the desirable range is usually above 5 mg/L. For pH values, the desirable range for fish production is 6.5 - 9.0 [3].

Toxicity of ammonia is generally attributed to the concentration of the unionized ammonia molecule (NH_3), due to its ability to move across cell membranes [7]. Median lethal concentrations (LC_{50}) over a 96-hour period of exposure to unionized ammonia have been established for rainbow trout (0.32 mg/L), bluegill (0.4 - 1.3 mg/L) and channel catfish (1.5 - 3.1 mg/L) [8]. Since chronic exposure to low concentrations of ammonia may reduce growth and also increase the susceptibility to diseases, some authors consider the maximum tolerable concentration to be 0.1 mg/L, although the preferred level is lower (the EPA standard for rainbow trout is 0.02 mg/L) [8]. The content of unionized ammonia is determined by the concentration of total ammonia nitrogen (TAN), pH and temperature. In this way, at a TAN of 5 mg/L and pH of 9.0, typical fish would be dead in hours, while with pH less than 6.0, ammonia would have negligible impacts at the same TAN concentration [7]. Concerning nitrites, the suggested maximum level for prolonged exposure in hard freshwater is 0.1 mg/L [3]. The main mechanism of nitrite toxicity relies on the transformation of hemoglobin to meta-hemoglobin, which lacks the capacity to bind oxygen irreversibly [9].

Figure 1. Farmed carp production.

3. Pollution Caused by Freshwater Aquaculture Effluents

Modern aquaculture depends upon the supply of nutrient inputs. However, for some species, a large fraction of the food ration can remain uneaten (e.g., European eels and tilapias spill around 1% - 10% and 10% - 30% of the ration, respectively [4]). Thus, on the one hand, the rates of supply and assimilation of nutrient inputs are decisive factors of the farm outputs, in particular for intensive operations in open aquaculture systems [10]; on the other hand, overfeeding should be avoided due to its large impact on water quality.

Aquacultural wastes include all materials used in the process which are not removed from the system during harvesting [11]. These wastes are mainly associated to uneaten feed or excreta, chemicals and therapeutants added to the ponds, and can be discharged either in the sediments or in the farm effluents. Sediments are usually collected intermittently or at the end of the production cycle and consist of inorganic and organic particulate material. By contrast, effluents are commonly discharged on a continuous basis over the production cycle and contain both dissolved and particulate pollutants (inorganic and organic) [10].

Although the characteristics of aquaculture effluents are highly variable following the cultivated species, the type of production facility and the feed quality and management, some general features can be drawn (**Table 1**). In a general way, the quality of aquaculture effluents is rather comparable to raw surface water than to domestic or secondary effluents, with low contents of total suspended solids (TSS), organic matter, and total and ammonium nitrogen. However, these low levels of pollution are not conducive to easy treatment, at least concerning solids. In fact, it has been reported that the efficiency of sedimentation increases with higher concentrations of solids [11].

Table 1. Comparison between aquaculture effluents and other types of water.

Parameter	Domestic effluent	Domestic secondary effluent	Aquaculture effluent	Raw surface water*
TSS [mg/L]	400 - 500	30	5 - 50	50 - 400
TKN [mg/L]	300 - 400	20	3 - 20	7
N-NH_4^+ mg/L]	40 - 75	5	0.5 - 4.0	0.05 - 0.50
BOD_5 [mg/L]	300	20	0.2 - 0.5	2 - 4

*That requires treatment. Sources: [3,13].

3.1. Conventional Pollutants

Conventional pollutants (TSS, BOD_5 and nutrients) are mainly derived from feed, excreta and fertilizers. The main purpose of the addition of fertilizers is the stimulation of both phytoplankton growth and fish production. Inorganic compounds of N and P are among the most usual fertilizers, but K, trace metals, and silicates may also be presented [12]. Since fertilizers increase the concentrations of nutrients in pond water, they may cause eutrophication in receiving water bodies.

Even though the concentrations of conventional pollutants are usually low, pond cleaning can increase them considerably. In a study examining the quality of effluents from a hatchery, TSS, BOD_5 and total phosphorus increased during cleaning from 1 to 88 mg/L, 3 to 32 mg/L and from 0.22 to 4.00 mg P/L, respectively [14].

Due to their content of nutrients, aquaculture effluents are well-suited for biological treatments (e.g., wetlands, biofilters or algae-based systems) and agricultural reuse (as in hydroponics and crop production). In the first case, it must be noticed that aquaculture discharges have nitrogen levels disproportionately high regarding carbon contents [4]. As balanced microbial growth requires a C:N ratio of about 100:10, biological treatment of aquaculture effluents is likely to involve the addition of exogenous carbon substrates.

3.2. Pesticides, Heavy Metals and Emerging Pollutants

Intensive aquaculture often relies on chemical additives for health management, manipulation of reproduction or growth promotion, among other purposes. Some pesticides commonly used are rotenone, simazine, 2,4-D, diquat and diuron [3,10], essentially for weed control. Organophosphate compounds (as malathion and dichlorvos), carbamates and pyrethroids are also employed as parasiticides. A concern arises from their non-selective action and their long-term effects on pond productivity [3]. However, the concentration of pesticides in aquaculture effluents is scarcely reported, and there is a lack of information about their effects on non-target organisms.

Heavy metals can also be found in pond effluents because they are common constituents of proteinates and vitamin/mineral premixes (e.g., Cu and Zn [15]). But mainly, they can be added to ponds as oxidizing agents for controlling phytoplankton and pathogenic organisms (e.g., $KMnO_4$ [12]) or as algicides (e.g., $CuSO_4$ [12]). Although these metals tend to precipitate as bottom sediments, the applied doses should be surveyed to avoid any toxic effect on fish. For instance, $CuSO_4$ is frequently used for eradicating submerged weeds, but the safe Cu levels have not been fully established for chronic exposure [15]. In fact, sublethal effects of Cu such as reduced swimming speed, reduced feeding and growth inhibition have been widely reported in salmonids [15].

Nowadays, one of the main environmental concerns about aquaculture is the release of bactericides (glutaraldehyde, formalin), therapeutants (as malachite green and dipterex) and antibiotics (mainly tetracyclines, quinolones and β-lactams) to the aquatic media. Some of these compounds are added in appreciable amounts; for instance, glutaraldehyde and formalin are regularly added at concentrations of 1 - 10 mg/L to avoid the proliferation of pathogens [12]. In a survey of fish farms in England, contents as high as 15.20 and 0.61 mg/L of formalin and malachite green, respectively, were found [3]. It is worth noting that malachite green is environmentally persistent, mutagenic in rats and mice, cytotoxic to mammalian cells and carcinogenic to experimental animals [16]. Even though malachite green has been banned in several countries, it is still used in others due to its efficiency and low cost [16]. Antibiotics are found in the water of intensive farms rather than in extensive ones [17], most likely because in an intensive hatchery fish are subject to more stressors that decrease the ability of their immune system to deal with infections [18]. The concentrations measured for antibiotics are usually low (e.g., from 0.17 to 10 μg/L for oxytetracycline [19]), although they rise noticeably through prophylactic treatments. Ormetoprim content has been measured at 0.69 μg/L, but it can be found at levels as high as 12 μg/L during fish treatment [20]. The main consequence of the reliance of aquaculture on antibiotics is probably the augmented antibiotic resistance in fish pathogens, which raises the possibility for passage of their antibiotic resistance determinants to bacteria of land animals and human beings via the food chain.

Intensive fish farming is also a source of steroid hormones such as estrone, testosterone and androstenedione [21]. In fact, estrone has been pointed out as the most important natural endocrine disrupting compound found in natural water due to its ubiquity and estrogenic potency (higher than that of nonylphenol) [22]. Steroids are presented in the blood plasma of fish and can be excreted via urine or bile, mainly during periods of reproduction [21]. The contents detected (of about 1 ng/L) of these emerging pollutants in aquaculture effluents are similar to those found in domestic secondary effluents and high enough to lead to adverse reproductive effects on aquatic species as trouts [21,22]. However, the removal and the effects of hormones in the usual treatment systems of aquaculture effluents have not been studied thoroughly yet.

4. Recirculating Aquaculture Systems (RAS)

The reduction of the wastewater volume is essential for enhancing the sustainability of fish farming, and recirculating aquaculture systems (RAS) have been proposed with this purpose. In these systems, water is partially reused in the process after undergoing a proper treatment, thereby reducing water usage and improving effluent quality. By means of the life cycle analysis methodology, RAS have been compared against a conventional flow-through system [23]; it has been found that RAS reduce water dependence by 93% in comparison to conventional systems. Moreover, RAS eutrophication potential resulted to be 26% - 38% lower than that of traditional systems.

RAS technology relies considerably on biological filtration as the mechanism for removing critical pollutants [24]. In a study following the oxytetracycline content in water of a sand biofilter-based RAS, peak concentrations of 0.39 - 0.72 ng/L were detected in the water both entering and leaving the biofilter only during the 10-day treatment of fish [25]. All through the therapeutic period, the amount of oxytetracycline discharged by RAS was considerably lower than that discharged by a conventional flow-through system [25].

In addition, through nitrification, biofilters are able to make recycled water suitable for fish production by oxidizing TAN to nitrates. In first generation-RAS, the maximum allowed concentration of nitrates steers the external water exchange rate [23]. But recent technological developments include a denitrification reactor for full nitrogen removal. As a result, last generation-RAS reduce water consumption, as well as the concentrations of nitrates and BOD_5 in the final discharge [23]. Although RAS are intended to reduce the water volume used, a minimum water exchange ratio must be maintained. By lowering the make-up water volume, an accumulation of growth inhibiting factors (e.g. fish-produced cortisol, bacterial metabolites and metals) is likely to occur. In a low water exchange RAS, the accumulation of phosphate, As and Cu led to higher mortality and reduced larvae length and body weight in the culture of carp [26].

Activated carbon-based biofilters are well-suited for RAS, because they offer the possibility of removing pollutants either by adsorption or by biological mechanisms such as biodegradation, nitrification or denitrification. It has been demonstrated that biological activated carbon filters (*i.e.*, fixed beds of granular activated carbon supporting bacterial growth) can effectively remove (>90%) emerging pollutants such as pesticides, steroids, antibiotics and other persistent chemicals from water [27] and wastewater [28]. In this way, the accumulation of growth inhibiting factors in RAS could be avoided.

5. Conclusion

Aquaculture effluents contain low concentrations of conventional pollutants (TSS, organic matter and nutrients), pesticides, heavy metals and emerging pollutants. Biological treatments are environmentally-friendly alternatives for removing these pollutants in RAS and hence for preventing the pollution originated by this industry. To this end, activated carbon-based biofilters seem appropriate for minimizing water exchange ratios in RAS without compromising the quality of fish production by the accumulation of growth inhibitors. However, the typical unbalance between the contents of organic matter and nitrogen could require the addition of easily assimilable carbonaceous sources for achieving full nitrogen removal.

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