The management of undesirable cyanobacteria blooms in channel catfish ponds using a constructed wetland: Contribution to the control of off-flavor occurrences

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Abstract

An exploratory study on the management of undesirable cyanobacteria blooms with respect to off-flavor problems using an integrated vertical-flow constructed wetland (CW) was performed at a small commercial-scale channel catfish farm from 2004 to 2007. The results of the three-year experiment indicated that water treatment by the CW could reduce the possibility of dominance by undesirable cyanobacteria species that often cause off-flavor problems. A detailed investigation in 2007, showed that the concentrations of geosmin, MIB (2-methylisoborneol), and β-cyclocitrinal in the water of the recirculating pond (4.3 ng L⁻¹, U.D. (undetected) and 0.2 ng L⁻¹, respectively) treated by the CW were significantly lower than those in the control pond (152.6 ng L⁻¹, 63.3 ng L⁻¹ and 254.8 ng L⁻¹, respectively). In addition, the relationships among the cyanobacteria species, the off-flavor compounds and ten environmental variables were explored by canonical correspondence analysis (CCA). The results showed that Oscillatoria sp., Oscillatoria kawamurae and Microcystis aeruginosa were the main sources of off-flavor compounds in the catfish ponds. The successful manipulation of undesirable cyanobacteria species potentially resulted in lower concentrations of odorous compounds in the water of the recirculating pond. An investigation of the concentrations of geosmin and MIB in catfish fillets showed that the levels of odorous compounds were below the OTC (odor threshold concentration) values in the recirculating pond but were above the OTC values from July to October in the control pond. Water recycling by the CW could potentially be one of the best management practices to control off-flavor occurrences in aquaculture.

1. Introduction

Static-style pond culture is the dominant practice of the aquaculture industry in China and has a centuries-old history. The urgent call for increasing yield in past decades has been driving this traditional culture toward an intensive practice without optimization of the structure of the pond system or integration of water treatment facilities, thereby hindering sustainable development for the aquaculture industry in China.
High fish stocking densities (>10,000 fish ha⁻¹) and feeding rates (exceeding 70 kg ha⁻¹ d⁻¹) resulted in high waste loading rates that often caused excessive eutrophication in fish ponds, leading to the dominance of phytoplankton communities by cyanobacteria (Zimba and Grimm, 2003). Certain species of cyanobacteria are known to be responsible for the occurrence of off-flavor compounds (2-methylisoborneol (MIB), geosmin, and β-cycloclotrial) in water bodies, including species from the genera Oscillatoria (Matsumoto and Tsuchiya, 1988), Anaabaena (Rosen et al., 1992), Microcystis Jütterm et al., 2010), Phormidium (Izaguirre, 1992), Lyngbya (Schrader and Blevins, 1993), and Pseudanabaena (Izaguirre and Taylor, 1998), imparting an undesirable earthy, musty, or muddy flavor to the fish.

Off-flavors represent one of the most significant economic problems in aquaculture. Off-flavor problems can cause inconsistent product quality and lead to a major reduction in the consumption of the products or make them unsuitable for sale, decreasing profits for producers and processors. Off-flavor problems can cost catfish producers as much as $60 million annually because of additional feeding, interruption of cash flow, forfeit of income from foregone sales, and the possible loss of market-sized catfish during the depuration process (Engle et al., 1995; Tucker, 2000). How to produce fish free of off-flavor has gradually become a major challenge for today’s aquaculture industry.

Because the off-flavors most frequently encountered in aquaculture have been linked to the presence of odor-producing cyanobacteria (Matsumoto and Tsuchiya, 1988; Jütterm, 1995; Tucker, 2000), such preventive measures as the application of algaecides (Schrader et al., 2005), bio-manipulation using filter-feeding fish (Tucker, 2006) and other preventive measures have been taken to control or eliminate such groups of organisms.

Among algaecides, a low dose of copper sulfate applied weekly was found to be beneficial in mitigating off-flavor problems in commercial-sized catfish ponds (Schrader et al., 2005). However, only a small acceptable range exists for the appropriate doses for copper treatments (i.e., the range of doses that are safe for the fish but toxic to the algae). Moreover, the toxicity of copper in aquatic organisms is strongly influenced by complex interactions with environmental variables such as pH, water temperature, and the concentrations of calcium and dissolved organic matter (Schrader et al., 2005; Hyne et al., 2005). These complex interactions are mostly not understood, making consistency in safe and effective copper treatments for algae control almost impossible. In addition, the prolonged use of copper sulfate may be related to the development and growth of copper-tolerant cyanobacteria (Tucker, 2000).

Bio-manipulation by filter-feeding organisms, such as silver carp, can effectively filter phytoplankton larger than 10 μm, especially colony-forming Microcystis (Ma et al., 2010; Xie and Liu, 2001). However, some limitations have emerged on the application of bio-manipulation to aquaculture systems. For example, hypertrophic conditions in fish ponds may overwhelm the effect of silver carp grazing at lower densities, and odor-producing cyanobacteria cannot be eliminated (Tucker, 2006). At higher densities, even if silver carp could reduce the prevalence of off-flavor problems, a large quantity of them might greatly decrease profits because of the low value of the silver carp.

Off-flavors in fish have also been reported to correlate with odorous compounds in water through absorption via the gills (From and Hurlyck, 1984). The adsorption process was found to be rapid (Johnsen et al., 1996; Robertson et al., 2005), whereas the depuration of off-flavors in fish was much slower (Tucker, 2000). Although fish can be purged of off-flavors if exposed to taint-free water, the timely provision of taint-free water is a great challenge in the current pond system (Robertson et al., 2005).

Many studies reported the successful removal of off-flavor compounds from water by oxidation (Kutschera et al., 2009), filtration (Kim and Bae, 2007), isolated bacteria (Lauderdale et al., 2004) and other processes such as ultrasonic degradation (Song and O’Shea, 2007) or membrane separation (Dixon et al., 2011). However, few of these methods have found practical application in aquaculture systems.

2. Material and methods

2.1. Constructed wetland and ponds

An integrated vertical-flow constructed wetland (CW) (with an area of 160 m²) was built beside four channel catfish ponds located on the side of the East Lake, Wuhan, China (Fig. 1). The CW was divided into two equal chambers: a down-flow chamber and an up-flow chamber. The influent and the effluent pipes were distributed into the down-flow chamber and send water to the up-flow chamber. In particular, small holes (5-mm diameter) were designed on the underside of the influent and the effluent pipes for an even distribution and collection of water. In the down-flow and up-flow chambers, canna (Canna indica) and cumbungi (Typha orientalis) were planted, respectively. The CW was operated under intermittent flow with a hydraulic loading rate (H LR) of 0.2–0.4 m d⁻¹ to treat water from the recirculating pond.

The catfish ponds with a historic earthy taint problem had a water surface of 200 m² and average depths of 1.5 m. Because the application of CWs to an aquaculture system is
still under evaluation, it is impractical to construct and operate several commercial-scale experimental systems simultaneously. Time replication was, therefore, used instead of number replication. Two ponds were selected randomly for the experiments in each year (2004, 2006 and 2007). The water in one pond (10–20%) was recycled by the CW, whereas the water in the other pond was not treated to simulate the traditional culture. No water discharge or importing of water occurred during the entire period of the experiment, except for the supply of water because of water lost through evaporation (0.57–0.70 m³ d⁻¹ per pond).

Fish were stocked in the recirculating pond and the control pond at the same density each year. The fish were fed to satiation with a commercial floating feed in the same manner in both ponds. Tube diffusers were installed in both ponds to supply oxygen when the oxygen concentration was below 3.0 mg L⁻¹. The fish were harvested at the end of each year, and the sediment in each pond was removed. No algicide was used in either of the ponds.

2.2. Physicochemical and biological analysis

Water samples from the recirculating pond and the control pond, as well as the influent and the effluent of the CW, were collected periodically (monthly in 2004 and biweekly in 2006 and 2007) between 9:00 a.m. and 10:00 a.m. In the ponds, water samples were obtained by mixing the equal volume of water taken 50 cm below the water surface from each corner of the pond for physicochemical and phytoplankton composition analysis. In the influent and effluent of the CW, water samples were obtained by mixing the equal volume of water sampled three times every ten minutes for physicochemical analysis.

Water samples were analyzed for chemical oxygen demand (COD₉), 5-day biochemical oxygen demand (BOD₅), total nitrogen (TN), total phosphorus (TP), soluble reactive phosphorus (SRP), and total suspended solids (TSS) within 24 h in the laboratory according to standard methods (State Environmental Protection Administration of China, 2002). Light intensity was measured with a ZDS-10 digital luxmeter (Shanghai Jiading Xuelian Meter Factory). Dissolved oxygen (DO), pH, conductivity (Cond) and water temperature (T) were measured with the Thermo Orion 5 Star portable meter.

With regard to phytoplankton composition analysis, water samples (1 liter) from both ponds were preserved immediately with 1% Lugol’s preservative solution for quantitative study of the phytoplankton. A sedimentation method was used to concentrate samples to 30 mL. Sub-samples were placed in a count-frame (40 mm × 40 mm), and counted via an optical microscope (at 640 × magnification).

After the collection of water samples, the phytoplankton samples for qualitative identification were collected at the water surface in both ponds with a 25# phytoplankton net (pore size 64 μm) from each corner of the pond and preserved immediately with 1% Lugol’s solution. Phytoplankton was identified to the genus/species level according to the references (Zhang and Huang, 1991; Hu and Wei, 2006).

Fig. 1 – Schematic diagram of the recirculating aquaculture system and the constructed wetland. The water recycling process for the catfish farm is indicated. The basic structure and water flow inside the constructed wetland are indicated.
2.3. Off-flavor compound analysis

Unfiltered water samples from the two ponds and the influent and the effluent of the CW were collected in airtight glass bottles (capacity, 0.5 L) without headspace (biweekly in the autumn of 2006, and weekly in 2007). The odorous compounds (geosmin, MIB and \( \beta \)-cyclocitral) in the water samples were extracted by solid phase micro-extraction (SPME), and were analyzed by gas chromatography/mass spectrometry (GC/MS) (Hewlett-Packard Model 5973 and Hewlett-Packard 6890 plus) in SIM (Selected Ion Monitoring) mode according to Sung et al. (2005) and Li et al. (2005).

In 2007, three catfish in each of the two ponds were sampled monthly at random for the analysis of geosmin and MIB. The catfish were slaughtered, filleted, and stored at \(-20^\circ\)C for analysis. The stored catfish fillets were pretreated by microwave distillation followed by SPME, and the distilled samples were then analyzed for geosmin and MIB using GC/MS (Robertson et al., 2005).

2.4. Statistical analysis

All data were presented as means ± SD (standard deviation) and \( n \) refers to the number of samples. The treatment efficiency of the CW (represented as the difference between the in- and outflow values) was evaluated by paired t-test. The between-pond differences for each parameter were evaluated by non-parametric tests. The between-pond and the monthly differences in the concentrations of the three odorous compounds in the pond water were explored by a two-way analysis of variance (ANOVA). The relationship between the concentration of the two odorous compounds in the pond water were explored by a two-way correlation analysis. The statistical analysis was performed with SPSS 13.0 software package for Windows, and the statistically significant level was set as \( p < 0.05 \).

The relationships among the cyanobacteria species, odorous compounds and water quality were investigated using canonical correspondence analysis (CCA) (ter Braak, 1988). In particular, forward selection and Monte Carlo permutations were used to determine whether environmental variables exerted a significant effect upon the distribution pattern of the cyanobacteria species.

3. Results and discussion

3.1. Treatment performance of CW and pond water quality

Paired t-tests detected significant differences between the influent and the effluent of the CW in terms of the COD\(_{\text{Cr}}\), BOD\(_5\), TSS and TN values (\( p < 0.05 \)). The removal rates of BOD\(_5\), TSS and TN by the CW were 53.5–70.5%\(^\text{a}\), 52.1–81.9%\(^\text{b}\), and 48.1–58.9%, respectively, in the three-year experiment with an HLR of 0.2–0.4 m d\(^{-1}\) (Table 1). The results were similar to the results reported by Lin et al. (2003), who used CWs operated at an HLR of 0.3 m d\(^{-1}\). However, compared with the data reported in 2004 by Li et al. (2007) based on the same aquaculture system, the present study showed a large decrease in the TP removal rate in 2006 and 2007. Phosphorus removal in CWs is closely associated with the physical-chemical and hydrological properties of the filter material (Vohla et al., 2011); the lower TP removal efficiency in the present study might result from the decreased P-retention capacity of the filter material in the CW.

The mean values of the physicochemical parameters in the recirculating pond and the control pond are shown in Table 2. The recirculating pond had significantly lower COD\(_{\text{Cr}}\), BOD\(_5\), TSS, TN and TP concentrations than did the control pond (\( p < 0.05 \)), indicating that the trophic status of the recirculating pond was lower than that of the control. Considering that the fish were stocked at the same density and fed by the same method in both ponds, the differences in water quality might result from the effective purification by the CW. The three-year experiment showed that CW could be beneficial to maintain the pond water at a relatively lower trophic status.

3.2. Variation of phytoplankton assemblages in the pond water

The taxonomic composition of the phytoplankton assemblages evolved differently in the recirculating pond and the control pond (Fig. 2). In the recirculating pond, Cryptophyta (average density of 4.5 \( \times 10^6 \) ind. L\(^{-1}\) in 2004), Bacillariophyta (average density of 3.4 \( \times 10^6 \) ind. L\(^{-1}\) in 2006) and Chlorophyta (average density of 8.0 \( \times 10^6 \) ind. L\(^{-1}\) in 2007) were the

<table>
<thead>
<tr>
<th>Year</th>
<th>Influent (mg L(^{-1}))</th>
<th>Effluent (mg L(^{-1}))</th>
<th>Mean removal rates (%)</th>
<th>COD(_{\text{Cr}})</th>
<th>BOD(_5)</th>
<th>TSS</th>
<th>TN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004(^{a}) (( n = 17 ))</td>
<td>5.8 ± 2.3a</td>
<td>21.5 ± 17.0a</td>
<td>2.3a</td>
<td>0.35 ± 0.21a</td>
<td>21.0 ± 17.0a</td>
<td>2.84 ± 1.20a</td>
<td>0.05a</td>
<td></td>
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<tr>
<td>2006 (( n = 13 ))</td>
<td>17.2 ± 2.1b</td>
<td>3.9 ± 2.2b</td>
<td>1.29 ± 0.67b</td>
<td>0.03a</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2007 (( n = 14 ))</td>
<td>70.5</td>
<td>81.9</td>
<td>54.6</td>
<td>80.1</td>
<td>12.4 ± 7.7a</td>
<td>1.21 ± 0.41a</td>
<td>0.09 ± 0.03a</td>
<td>0.63 ± 0.27b</td>
</tr>
</tbody>
</table>

\( a, b \) indicated there were significant differences between two groups (\( p < 0.05 \)).

\( c \) Li et al., 2007 reported based on the same aquaculture system.
Table 2 – Water quality in the recirculating pond and the control pond (means ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Recirculating pond</th>
<th>Control</th>
<th>Recirculating pond</th>
<th>Control</th>
<th>Recirculating pond</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>24.0 ± 5.3a</td>
<td>23.6 ± 4.9a</td>
<td>23.6 ± 6.8a</td>
<td>23.4 ± 6.9a</td>
<td>25.8 ± 4.2a</td>
<td>25.5 ± 4.3a</td>
</tr>
<tr>
<td>pH</td>
<td>7.2 ± 0.3a</td>
<td>7.1 ± 0.3a</td>
<td>7.4 ± 0.3a</td>
<td>8.0 ± 0.4a</td>
<td>7.5 ± 0.2a</td>
<td>7.5 ± 0.1a</td>
</tr>
<tr>
<td>DO (mg L⁻¹)</td>
<td>4.6 ± 1.5a</td>
<td>3.6 ± 1.9a</td>
<td>4.8 ± 3.4a</td>
<td>7.5 ± 4.6a</td>
<td>3.4 ± 2.2a</td>
<td>4.9 ± 2.1a</td>
</tr>
<tr>
<td>COD (mg L⁻¹)</td>
<td>–</td>
<td>–</td>
<td>25.6 ± 13.8a</td>
<td>62.0 ± 29.6b</td>
<td>24.6 ± 10.1a</td>
<td>52.1 ± 14.9b</td>
</tr>
<tr>
<td>BOD (mg L⁻¹)</td>
<td>6.2 ± 2.0a</td>
<td>12.0 ± 2.2b</td>
<td>3.5 ± 1.6a</td>
<td>11.6 ± 6.6b</td>
<td>4.5 ± 3.2a</td>
<td>7.4 ± 2.9b</td>
</tr>
<tr>
<td>TSS (mg L⁻¹)</td>
<td>17.6 ± 8.9a</td>
<td>34.9 ± 23.1b</td>
<td>30.6 ± 7.2a</td>
<td>40.8 ± 23.7b</td>
<td>8.4 ± 6.6a</td>
<td>31.6 ± 7.9b</td>
</tr>
<tr>
<td>TN (mg L⁻¹)</td>
<td>2.07 ± 0.82a</td>
<td>3.22 ± 1.28b</td>
<td>0.83 ± 0.44a</td>
<td>3.12 ± 1.44b</td>
<td>1.32 ± 0.56a</td>
<td>1.67 ± 0.50a</td>
</tr>
<tr>
<td>TP (mg L⁻¹)</td>
<td>0.18 ± 0.12a</td>
<td>0.32 ± 0.27b</td>
<td>0.06 ± 0.02a</td>
<td>0.31 ± 0.16b</td>
<td>0.10 ± 0.04a</td>
<td>0.18 ± 0.06b</td>
</tr>
</tbody>
</table>

a, b indicated there were significant differences between two groups (p < 0.05).
c Li et al., 2007 reported based on the same aquaculture system.

3.3. Concentrations of odorous compounds in the pond water

In the autumn of 2006, the concentrations of MIB, geosmin and β-cyclocitrinal (4.0 ± 4.5 ng L⁻¹, 12.2 ± 10.5 ng L⁻¹, and U.D. (undetected), respectively, n = 6) in the recirculating pond were lower than the concentrations in the control pond (8.0 ± 19.6 ng L⁻¹, 16.9 ± 8.2 ng L⁻¹, and 1941.6 ± 1261.9 ng L⁻¹, respectively, n = 6).

The detailed variations of MIB, geosmin, and β-cyclocitrinal concentrations in the recirculating pond and the control pond were monitored in 2007 to explore the temporal variation of odorous compound concentrations in the two ponds (Fig. 3). From May to December, only a low concentration of geosmin and β-cyclocitrinal was detected in the recirculating pond. In contrast, relatively high concentrations and monthly fluctuations of the concentrations of all three odorous compounds were observed in the control pond (p < 0.05).

Previous research reported that the odor threshold concentrations (OTCs) for geosmin, MIB, and β-cyclocitrinal to produce off-flavor in drinking water are in the ranges of 4–10, 9–42, and 500–1000 ng L⁻¹, respectively (Cotsaris et al., 1995; Young et al., 1999; Watson et al., 2000). The geosmin concentration in the control pond was above the OTC throughout the entire experimental period, reaching a peak concentration of 921.4 ng L⁻¹, whereas the MIB and β-cyclocitrinal concentrations were above the OTC from August to October with the highest values of 294.9 ng L⁻¹ and 1289.6 ng L⁻¹, respectively, reached at the end of August. The off-flavor problems in the control pond lasted from May to October and were the most serious in August and September. In the recirculating pond, in contrast, the concentration of geosmin exceeded the OTC only sporadically.

3.4. Removal rates of the odorous compounds in the pond water by the CW

The analysis of the odorous compounds in the influent and effluent of the CW showed that the average removal rate for geosmin was 72.2 ± 5.5% (n = 6) in the autumn of 2006. Similarly, the average removal rate was 88.1 ± 12.6% (n = 26) in 2007, and its concentration in the effluent was generally below 20 ng L⁻¹ although the geosmin concentration in the influent of the CW fluctuated (Fig. 3). In the two-year experiment, the other two odorous compounds were not detected in the influent and effluent of the CW. These results indicate that water treatment by the CW could effectively remove odorous
compounds from the pond water given the set of conditions in this experiment.

3.5. Relationships among the odorous compounds, cyanobacteria species and water quality

The relationships among the occurrence of off-flavor problems, the presence of cyanobacteria species, and the water quality were explored by CCA based on the data for the concentrations of three odorous compounds, the density of the cyanobacterial species, and ten physicochemical variables in 2007. The two CCA axes explained a substantial proportion of the variation (44.6%) in the cyanobacteria-environment relationship (Fig. 4). In particular, Oscillatoria sp., Oscillatoria kawamurae and Microcystis aeruginosa were found to correlate with the occurrence of MIB, geosmin and β-cyclocitrinal in the pond water. The correlations were consistent with previous studies (Matsumoto and Tsuchiya, 1988; Jütter, 1995; Tucker, 2000) that attributed the prevalence of MIB, geosmin and β-cyclocitrinal to the occurrence of certain Oscillatoria and Microcystis species. The average density of Microcystis and Oscillatoria species accounted for more than 70% of the total algal density, and M. aeruginosa was the dominant species in the control pond. The period (August and September in 2007)
during which the highest concentrations of the three odorous compounds were detected overlapped with the period during which the highest algal density occurred when Cyanophyta was the dominant phylum. Because the cyanobacteria species that were detected might be the main cause of the prevalence of off-flavor compounds, and water recycling by the CW could successfully control their presence, the CW was helpful in reducing the concentration of these odorous compounds in pond water.

Via forward selection and the Monte Carlo test, CCA identified a subset of environmental variables including SRP, pH, light intensity, TSS, DO, and Cond as potential significant factors that influence the cyanobacteria community. Similarly, factors reported to be correlated with the dominance of cyanobacteria include: high nutrient loadings (especially low N/P ratio) (Smith, 1983), high pH and low carbon dioxide concentrations (King, 1970; Shapiro, 1984), low light availability (Smith, 1986), water column stability (Paerl and Tucker, 1995), and high water temperature (Mcqueen and Lean, 1987).

In addition, the CCA analysis showed that SRP, BOD₅ and TSS were positively associated with the three off-flavor compounds, whereas N/P, Cond and pH were negatively associated with the three off-flavor compounds (Fig. 4). The prevalence of off-flavor compounds in the control pond might be attributed to the eutrophic condition of the water. A principal component analysis by Parinet et al. (2010) also found that the eutrophication of water bodies was a major factor in the occurrence of off-flavor compounds. The ability of the CW to maintain the pond water at a lower trophic status could also be beneficial for the successful control of odorous compounds in the pond water.

Fig. 3 — Concentrations of geosmin, 2-methylisoborneol, and β-cyclocitrinal (ng L⁻¹) in the recirculating pond, the control pond, and the influent and effluent of the CW in 2007. Water samples were taken weekly from May 5th, 2007 to November 9th, 2007.

Fig. 4 — Two-dimensional ordination diagram of phytoplankton-environmental factors. The spatial ordination resulting from canonical correspondence analysis of cyanobacteria species with respect to physicochemical variables and odorous compounds is presented.
3.6. Concentrations of MIB and geosmin in catfish samples

In 2007, the geosmin concentration in the catfish fillets from the control pond was consistently high with a peak of 1.13 mg kg\(^{-1}\) in September, and MIB was detected four out of six times with the highest level (0.63 mg kg\(^{-1}\)) at the beginning of October (Fig. 5). In most cases, the term “off-flavor” is linked to an earthy/musty odor and taste that is caused by high concentrations of geosmin or MIB in the fish meat (Tucker, 2000). Grimm et al. (2004) reported that the OTC values of geosmin and MIB in catfish fillets were \(0.25 \pm 0.5\) mg kg\(^{-1}\) and \(0.1 \pm 0.2\) mg kg\(^{-1}\), respectively. Geosmin levels in catfish fillets in the control pond were above the lowest OTC values from July to October, and the MIB levels were above the lowest OTC values in September and October. In contrast, the concentrations of geosmin and MIB were below the lowest OTC values in the recirculating pond.

The off-flavor problems encountered in aquaculture are often ascribed to the absorption of odorous compounds from the water (From and Hurlyck, 1984; Robertson et al., 2005). In this study, positive correlations were found between geosmin and MIB concentrations in the pond water and the concentration of those compounds in the catfish fillets (\(r = 0.94, p < 0.05; r = 0.98, p < 0.05\), respectively). These results indicate that reducing the concentration of geosmin and MIB in pond water is essential to control off-flavor problems. Because the CW could control the concentrations of MIB and geosmin in the pond water by managing undesirable cyanobacteria blooms and maintaining the pond water at a relatively lower trophic status, the CW might be a promising technique to solve off-flavor problems encountered in aquaculture.

3.7. Management of the off-flavor problems in the pond water at high stocking densities

Other factors such as high feeding and stocking rates have been associated with off-flavor problems (Brown and Boyd, 1982). In general, lower stocking densities and feeding regimes would decrease profits. To avoid the occurrence of off-flavor problems at high stocking densities, reliable and reasonable water treatment processes are preferred.

In the three years of the present study, the fish were stocked at high densities (10,000–15,000 fish ha\(^{-1}\)) in the recirculating and the control pond, and the fish were fed to satiation in both ponds with feeding rates ranging from 21.6 kg ha\(^{-1}\) d\(^{-1}\) to 50.0 kg ha\(^{-1}\) d\(^{-1}\) (Table 3). However, lower concentrations of the three odorous compounds were

<table>
<thead>
<tr>
<th>Table 3 – Stocking density, feeding rate, survival rate, and yield of pond-raised fish in the recirculating pond and the control pond.</th>
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<tbody>
<tr>
<td><strong>Operating period</strong></td>
</tr>
<tr>
<td>Culture species</td>
</tr>
<tr>
<td>Stocking density (fish ha(^{-1}))</td>
</tr>
<tr>
<td>Initial body weight (g)</td>
</tr>
<tr>
<td>Feeding rate (kg ha(^{-1}) d(^{-1}))</td>
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<tr>
<td>Survival rate (%)</td>
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<td>Yield (kg ha(^{-1}))</td>
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identified in the recirculating pond in 2006 and 2007 compared with the control pond. The concentrations of MIB and geosmin in the catfish in 2007 in the recirculating pond were also lower than the concentrations in the catfish in the control pond. Furthermore, higher survival rates and yields of fish were found in the recirculating pond throughout the entire three years (Table 3), indicating that water treatment by the CW could potentially be one of the best management practices to control off-flavor problems at high stocking densities.

4. Conclusions

Severe off-flavor problems were present in the control pond and were ascribed to the higher trophic status and the dominance of Oscillatoria sp., O. kawamure and M. aeruginosa. Water treatment by the CW in the recirculating pond could control the pond water at a lower trophic status and adjust the taxonomic composition of the phytoplankton assemblages. Furthermore, water treatment by the CW could remove geosmin from the pond water efficiently. The CW might represent a promising approach to solving off-flavor problems encountered in aquaculture.

Additional research is suggested to study the mechanisms of odorous compounds removal and phytoplankton assemblage manipulation by the CW. Further studies should also focus on the effective and economical operation of the CW.

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