Rates of organic carbon and nitrogen degradation in intensive fish ponds

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Abstract

Water quality in intensive aquaculture systems is to a large extent controlled by the microbial biodegradation of organic residues. The ability to simulate processes in such systems depends on the availability of data on the rates of these processes. The first order kinetic rate constants for both organic carbon and organic nitrogen degradation in fish ponds were evaluated. The rate constants were computed by either relating the measured rate of disappearance of the substrate concentration or by the comparison of the measured with a theoretically derived evolution pattern of organic carbon or nitrogen concentrations in model ponds. The organic carbon degradation rate constant was found to be 0.15/day. The organic nitrogen degradation rate constant was expected, theoretically to be about 0.06/day and was found experimentally to be in the range of 0.05–0.09/day. These values seem to be reasonable approximations for constantly aerated-mixed ponds, at a temperature range of 20–30°C. Organic matter previously metabolized in anoxic sites at the pond (e.g. resuspended sediments), has a degradation rate of ca. 0.6/day, and can thus consume large amounts of oxygen in the water body.

Keywords: Carbon, organic —degradation; Nitrogen, organic —degradation; Organic matter; Water quality

1. Introduction

Intensive ponds are typified by the high fish biomass and respective feeding rate and by the constant aeration and mixing of the pond. Typical fish biomass is in the order of 10–100 kg/m² and the daily feed addition in the order of 200–3000 g/m². The feed flux is significantly higher than the photosynthetic flux which is estimated to have a maximal value of 10 g C/m²/day (Wetzel, 1975). Organic residues accumulation is very high. Only 30–
50% of the feed is utilized by the fish (Avnimelech and Lacher, 1979; Boyd, 1985), thus the amounts of organic residues are in the order of 100–1500 g/m²/day of dry matter. Water quality in such systems is to a large extent controlled by the microbial degradation of the organic residues. Any quantitative treatment or design of intensive aquaculture systems depend upon the availability of rate parameters describing the microbial degradation of organic residues in the pond. A modeling approach to predict nitrogen accumulation in such ponds was described elsewhere (Kochba et al., 1994). The rate constants describing organic carbon and nitrogen degradation in intensive pond systems were studied and are reported in this work.

The rate of organic matter degradation by microorganisms is usually described using either a first order kinetics or a Michaelis–Menton kinetics (e.g., Benefield and Randall, 1980). The two are practically identical in systems where the substrate, rather than the microbial biomass, is limiting. This is a common situation and thus, the first order kinetics approach is most commonly used in environmental biotechnology.

Organic carbon (C), degradation is described by:
\[
dC/dT = -K_c \cdot C
\]

where \( T \) is the time and \( K_c \) is the relevant rate constant. An equivalent expression relates the change in organic nitrogen concentrations (\( dN_o/dT \)) with the organic nitrogen concentrations (\( N_o \)) and the relevant rate constant (\( K_n \)). The rate constant of organic carbon degradation in fish ponds sediments was found to be 0.4/year (Avnimelech, 1984), but is much higher when more labile organic compounds are degraded. The rate constants for sugars, hemicellulose, cellulose and lignin in soils are 1.15, 0.10, 0.05, and 0.002/day, respectively (Reddy et al., 1986). The relationship between the level of organic substrates (expressed as COD), and the rate of their degradation (expressed as BOD), was studied in a variety of water treatment systems (Benefield and Randall, 1980). The rate constant derived from these data was found often to be in the range of 0.1–0.2/day, though, it may vary within a wider range according to the organic compounds in the water. Boyd (1973) found a high correlation between COD and BOD in fish ponds. The rate constant, \( K_c \), calculated from his data was 0.075/day. The derivation of the appropriate rate constants using BOD data is very rough, since BOD is measured along a 5-day period, and the exact rate is not specified. The organic nitrogen mineralization rate constant is more complicated, since only a part of the degraded organic nitrogen is released as inorganic nitrogen, while the rest is utilized to produce microbial proteins. The relationships between the organic carbon and nitrogen degradation rates, as affected by substrate and microbial community C/N ratios and by the microbial conversion efficiency, will be dealt with separately. An important question as to the use of predictive models for commercial aquaculture operation is the constancy of the organic matter decay rate constants. The practical use of such models will be limited if those constants are found to be site and time dependent, since an evaluation of those parameters will than be needed for each pond. Similarity in the rate parameters found in different systems will enable the use of those constants as inputs needed in predictive models.

2. Materials and methods

Data used in this work were obtained from experiments done in simulated and in actual farm ponds. The temperature in both systems was in the range of 20–30°C. The first system
Y. Avnimelech et al. / Aquaculture 134 (1995) 211-216

consisted of cylindrical P.V.C. tanks, having a diameter of 100 cm. Water level was main-
tained at 90 cm. Air was supplied through porous tubes placed radially along the tank walls
at an elevation of 30 cm from the bottom. The mixing was achieved by two paddles, 38 \times 7
cm each, placed 10 cm above the bottom of the tank, revolving at a rate of 20 rpm.

The experimental setup and plans were designed to study the effects of aeration, mixing
and addition of clay on the microbial transformations of organic carbon and nitrogen.
Detailed description of the experiment are given elsewhere (Avnimelech et al., 1992). Most
of the tanks did not include fish, so as to be able to follow the microbial processes separately.
Yet, all tanks were fed with feed pellets (25% protein) at a level of 35 g/day, 6 days a
week. This level is equivalent to that used for a fish biomass of 2.5 kg/m³. Twenty fish
(tilapia hybrid, Oreochromis niloticus \times O. aureus) were stocked in two of the tested
treatments. All treatments were triplicated.

Water was sampled 3 times a week from one of the triplicated tanks and once a week
from all tanks. Chemical analyses done immediately following sampling, included pH,
organic carbon (Raveh and Avnimelech, 1972), ammonium, nitrite and nitrate using an
autoanalyzer (EPA, 1974), total nitrogen (Raveh and Avnimelech, 1979), and total solids
(AOAC, 1980).

The rate of organic carbon degradation was evaluated through the measurement of the
oxygen consumption rates and using the appropriate stoichiometric correction to obtain the
amounts of organic carbon oxidation \((\text{O}_2/\text{C} = 32/12)\). Water sampled from the tanks was
brought to saturation by air bubbling and transferred into 8 sealed bottles. Oxygen concen-
tration was measured in two bottles every 2 hours, along an 8-hours period using a polar-
ographic electrode (APHA, 1980). The rate of organic nitrogen degradation (i.e., nitrogen
mineralization), was evaluated from the changes of inorganic nitrogen concentrations in
the tanks, between two consecutive sampling dates. The organic carbon or nitrogen degra-
dation rates were related to the appropriate organic substrate concentration so as to derive
\(K_c\) or \(K_n\), the first order degradation rate constant. Organic nitrogen degradation rates were
related to the concentration of organic nitrogen in the water along the time span between
two consecutive sampling dates.

A different way to evaluate organic carbon and nitrogen degradation rates is based upon
the solution of an equation describing the accumulation of the two components in the pond.
Organic carbon and nitrogen in fish ponds are simultaneously added and degraded.

Considering a simplified pond system where the main processes are feed addition and
the microbial degradation of the feed residues, the change in the concentration of any
organic component \((S)\) with time will consist of the addition of the specific component
minus its degradation rate, as described by Eqn. 2 and Eqn. 3.

\[
\frac{dS}{dT} = B - (K_s \cdot S) \tag{2}
\]

and the integrated form:

\[
S = \frac{B}{K_s} - \left[ \left( B - K_s \cdot S_0 \right) \cdot e^{-K_s \cdot T} \right] / K_s \tag{3}
\]

where \(B\) is the daily addition of component \(S\), \(S_0\) is the concentration of that component at
\(T=0\) and \(K_s\) is the first order degradation rate constant. It should be noted that when time,
or the product \((K_s \cdot T)\) is large, \(S\) approaches a limit equal to \(B/K_s\).
Oxygen consumption rates were measured and related to the respective organic carbon concentrations also in farm ponds at Kibbutz Ein Hamifratz and the Genosar Aquaculture Research Station (Mires et al., 1990).

3. Results and discussion

Organic carbon degradation rate constants were evaluated through the measurement of oxygen consumption and organic carbon concentrations in water sampled from experimental tanks. The results of a series of such tests done in aerated and non-aerated treatments in tanks are presented in Fig. 1. The rate constant was high and variable on the first sampling in the aerated treatments (three days following the start of feeding). This is probably because, at that time, the organic matter in the water consisted mainly of the raw pellets and the microbial consortium was not stable. A stable organic carbon rate constant was found for all the aerobic treatments in sampling dates following the initial one. The rate constant averaged for all the aerated treatments along the experimental period was found to be $0.15 \pm 0.098$ per day. It seems that a stable array of organic compounds and microorganisms dominated those systems. The rate constants for water sampled from the anaerobic tanks were significantly higher (in the range of $0.6$/day) than those for water in aerated tanks. These last samples were drawn from anoxic conditions, yet assayed under aerobic ones. The soluble organic compounds that have accumulated under anaerobic conditions were highly available for aerobic degradation, as reflected in the high degradation rate constant. This may be of significance in aquaculture systems. When organic matter from anaerobic sites in the pond reaches the aerated water (i.e., resuspension of sediments), its oxygen consumption may be significantly higher than that of an equivalent amount of organic matter found in the water. Similar results were found in several different commercial farm ponds.

Fig. 1. $k_c$ (1/day) in aerated and non-aerated tanks. Mixair = mixed and aerated treatment (24 h/day). Air = aerated treatment (24 h/day). Air 12 = aerated treatment 12 h/day.
The average organic carbon degradation rate constant, obtained for 113 sampling events was $0.145 \pm 0.068$/day. This value is practically identical to that obtained in the simulated fish tanks. The similarity of the rate constants obtained for three different systems indicates that the fish pond system tends, even under variable conditions, to build up a certain consortium of microorganisms and organic compounds.

Organic nitrogen degradation rate constant ($K_n$) was also evaluated using Eqn. 1. The average $K_n$ value, obtained for 55 sets of data, was $0.05 \pm 0.044$/day. Eqn. 3 was used as an additional means to evaluate the organic carbon and nitrogen degradation rate constants. Organic carbon concentration in that equation is given as a function of time, daily addition of organic carbon, organic carbon at $T=0$ and the degradation rate constant, $K_c$. All the parameters except the degradation constant were known. The value of $K_c$ was evaluated using a non-linear regression. The average $K_c$, 0.148 (Table 1), is practically identical to that obtained using the former, direct method. The average organic nitrogen degradation rate constant (0.087/day) obtained through Eqn. 3, is also similar to the value found using the direct method.

The availability of data on the rate of organic matter degradation in intensive fish ponds is essential for any quantitative prediction of processes in such systems. The rate constant for the degradation of organic carbon, $K_c$, was evaluated from both model and farm ponds systems, using two methods of calculation. The constant was practically identical in the tanks and in two fish farms studied, giving a value of ca. 0.15/day. The organic nitrogen degradation rate constant, $K_n$, was expected theoretically to be lower and was found to be in the range of 0.05–0.07/day (e.g. Billen, 1984). The relationship between $K_c$ and $K_n$ is rather complex. However, since the microbial consortium in different ponds seems to be similar and the C/N ratio in the feed is usually around 10, it is possible to assume that the ratio between the two constants will be similar under different conditions. The biological processes involved are certainly sensitive to a variety of environmental conditions. The constancy of the rate parameters in a variety of ponds that are constantly aerated and mixed, within the range of temperatures optimal for warm water fish, indicates that pond systems seem to reach a relatively uniform composition and microbial consortia. This seems to justify the use of the kinetic parameters found in this work for the simulation of microbial processes in aquaculture systems.

A wider test and validation of the above mentioned findings may enable the evaluation of a pond’s oxygen requirement by measuring organic carbon in the water and by the calculation of the rate of inorganic nitrogen build up from data on the organic nitrogen concentration in the pond.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>$K_c$ (1/day)</th>
<th>$\rho$</th>
<th>$K_n$ (1/day)</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerated-mixed</td>
<td>0.16</td>
<td>0.666</td>
<td>0.094</td>
<td>0.757</td>
</tr>
<tr>
<td>Aerated-mixed + Bentonite</td>
<td>0.123</td>
<td>0.894</td>
<td>0.079</td>
<td>0.907</td>
</tr>
<tr>
<td>Aerated-mixed + fish</td>
<td>0.162</td>
<td>0.736</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*aCorrelation coefficient of the non-linear regression, averaged for the replicated treatments.*
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