

MODELLING OF THE SIMULTANEOUS REMOVAL OF ORGANIC SUBSTANCES AND NITROGEN IN A BIOFILM

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ABSTRACT

A mathematical model of the simultaneous removal of organic substances and nitrogen compounds in a biofilm reactor was developed, taking account of the relationships between oxidation, nitrification, denitrification, and mass transport. The model consists of a set of simultaneous mass balance equations for organic substances, ammonium nitrogen, oxidized nitrogen, oxygen, and alkalinity within the biofilm, and another set of transport equations for these substances within diffusion layer of the biofilm. Synthetic dual and triple Monod-type kinetics describing, respectively, oxidation, and nitrification and denitrification were incorporated into the mass balance equations. The model was evaluated based on experimental data and the computer simulations. This model successfully explained the mechanism of simultaneous removal and the effects of bulk concentrations of organic substances, DO, ammonium nitrogen, and alkalinity on simultaneous removal in a submerged biofilm reactor.

KEYWORDS

Biofilm model; oxidation; nitrification; denitrification; computer simulation.

INTRODUCTION

There have been many models developed to deal with organic substances removal by oxidation (Williamson *et al.*, 1976; Harris *et al.*, 1976; Harremoes, 1978; Rittmann *et al.*, 1978), ammonium nitrogen removal by nitrification (Jansen *et al.*, 1985; Gujer *et al.*, 1986), and nitrogen removal by denitrification (Watanabe *et al.*, 1978) respectively, in a biofilm reactor. On the other hand, little research has been conducted on the modelling of simultaneous removal. Watanabe *et al.* (1984) tried to explain the phenomena in a rotating biological contactor (RBC) by the model which was developed mainly on the basis of several experimental facts and hypotheses. Principal hypotheses were: 1) surface uptake flux of oxygen is constant under constant temperature, 2) competition of oxidation with nitrification for DO consumption within a biofilm depends only on the concentration of organic substances, 3) denitrifying rate is proportional to oxidizing rate, and independent of DO concentration. Kissel *et al.* (1984) developed a mathematical model to express the phenomena in as much detail as possible, and to get new information on the phenomena by numerical analysis. This model, therefore, has not yet been verified by experimentation. Characteristics of the model basis were: 1) presence of increasing active biomass consisting of heterotrophs and autotrophs, and inactive biomass, 2) dual Monod-type expression on the kinetics of organic oxidation (COD, DO), nitrification (NH₄-N, DO; NO₂-N, DO), and denitrification (NO₃-N, COD), 3) division of a biofilm into aerobic and anoxic parts at assumed DO level. Based on these and the authors' former study, mentioned below, the present paper aims at developing a model which is based on the principle of transport and

metabolic reactions; a model which is able to show the relationship between the bulk* concentrations of related substances and the surface removal fluxes of organic substances, ammonium nitrogen, and total nitrogen; and a model which is practically useful or informative for design.

MODELLING OF SIMULTANEOUS REMOVAL

Basic Considerations

The bulk substrate removal in a biofilm reactor comprises three main processes: (a) substrate transport from the bulk to the biofilm; (b) molecular diffusion of the substrate within the biofilm; (c) metabolic reactions within the biofilm. In this study, the modelling of removal is based on all of these processes because it is difficult, especially in the case of simultaneous removal, to distinguish the limiting process among these processes.

Generally, the transport process (a) can be modelled assuming a diffusion layer on the biofilm, in which diffusion is controlled by Fick's first law, and (b) can be expressed on the basis of Fick's second law, for each of the substances concerned. The process (c), metabolic reactions, consists fundamentally of organic oxidation, nitrification, and denitrification occurring simultaneously and depending on each other. The authors (1984, 1987) showed that the simultaneous removal of organic substances and nitrogen compounds in a dispersed biomass system was influenced by the parameters of organic substances, ammonium nitrogen, oxidized nitrogen as the sum of nitrite and nitrate nitrogens, DO, alkalinity, and biomass; and that the kinetics of oxidation, and nitrification and denitrification were expressed well by synthetic dual and triple Monod types, respectively. Consequently, these kinetic models for a dispersed biomass system were adopted for process (c) in the biofilm, in this study.

Masuda *et al.* (1987) reported that oxidizing, nitrifying, and denitrifying bacteria exist almost uniformly in the whole biofilm; that organic oxidation, nitrification, and denitrification simultaneously occur at any cross-section of the biofilm under suitable conditions; and that there is no remarkable change of bacteria activity of each species from the surface to the bottom of the biofilm. From these, it is assumed that every species of bacteria (oxidizing, nitrifying, and denitrifying) exists uniformly in the whole biofilm; that the sum of all bacteria is regarded as one kind of biomass, that is, every species of bacteria is not distinguished respectively and the biomass serves as a metabolic unit, which carries out oxidation, nitrification, and denitrification simultaneously; and that the biofilm is structurally uniform. Endogenous respiration is ignored, since the effect on simultaneous removal is considered to be small under the conditions that not a little organic substances exist in bulk, as is shown in the description of the experiments of this study.

Based on the above considerations, the transport processes (a) and (b) and metabolic processes (c), and the relationships between them, are illustrated in Fig. 1.

Mathematical Model

Table 1 shows the proposed mathematical model of the simultaneous removal of organic substances and nitrogen compounds by a steady-state biofilm in completely mixed liquid. Each of the mass balance equations (1) to (5) includes a molecular diffusion term and kinetic terms of metabolic reactions; and the transport equations (6) to (10) are expressed as in the diffusion layer. Characteristics of each of the mass balance equations are as follows:

Ammonium Nitrogen Mass balance of ammonium nitrogen in a biofilm depends on the transport by diffusion and on the loss due to nitrification and biomass growth, as shown by equation (1). That is, the first term on the left side is for the molecular diffusion, and the first and second terms on the right side are for the loss by nitrification and biomass growth, respectively. (The equations (2)-(5) are also arranged similar to this equation.) Nitrification kinetics is expressed as synthetic kinetics of triple Monod type including ammonium nitrogen concentration itself, DO concentration, and alkalinity as influencing parameters. The influence of alkalinity on the nitrifying rate is shown in Fig.2, which was obtained from an experiment with the dispersed biomass of a biofilm by the authors, and can be the basis for a Monod-type expression for its influence.

Oxidized Nitrogen The mass balance equation of oxidized nitrogen ($\text{NO}_x\text{-N} = \text{NO}_2\text{-N} + \text{NO}_3\text{-N}$) is

*bulk = bulk liquid

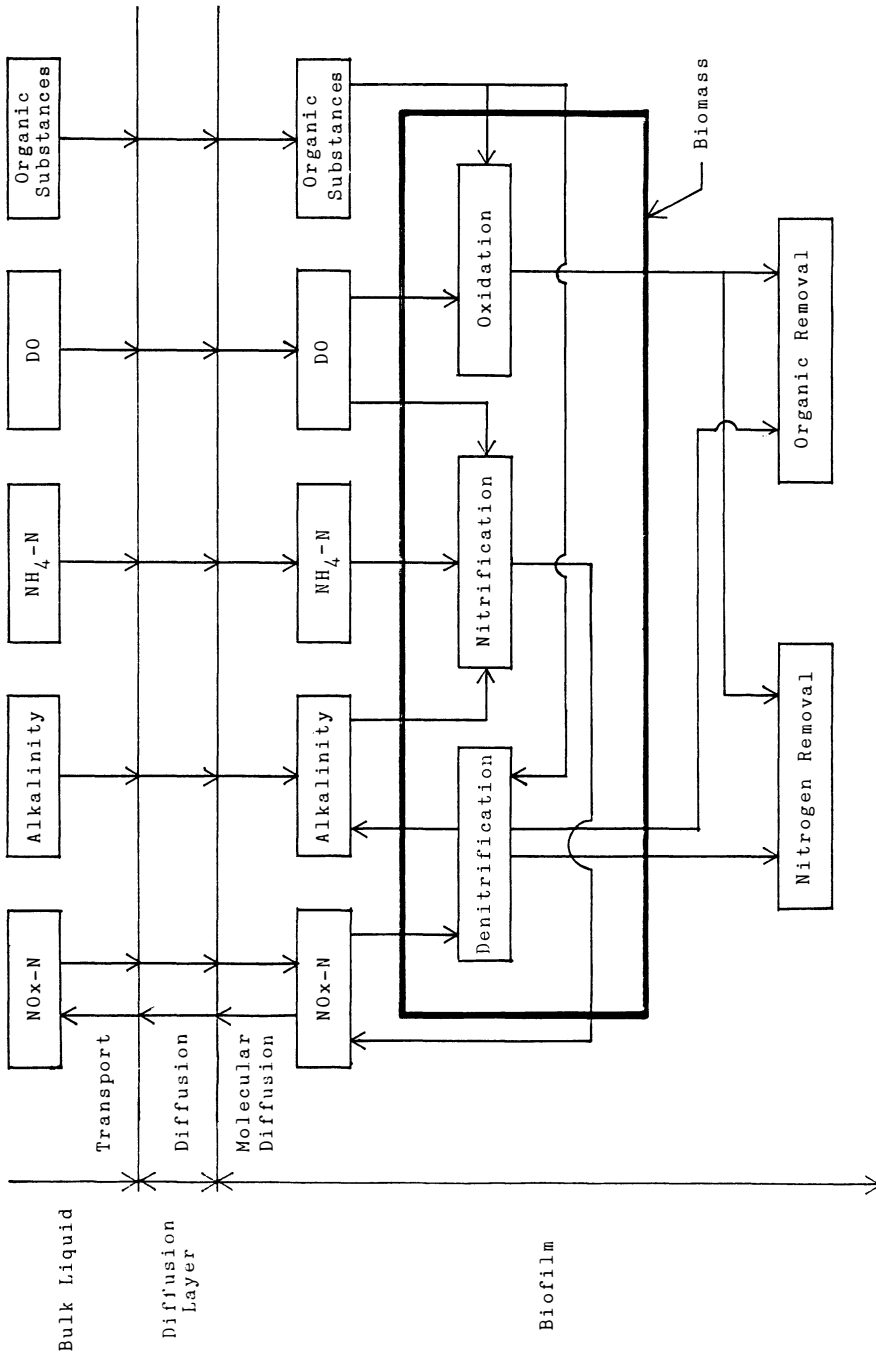


Fig. 1. Conceptual illustration of removal of organic substances and nitrogen compounds in a biofilm

TABLE 1 Mass Balance Equations and Mass Transport Equations
in a Steady-State Biofilm

Within Biofilm

$$\text{NH}_4\text{-N} \quad D_{fc_1} \frac{d^2 C_{1f}}{dZ^2} = (1 + Y_2 \cdot F_n) \frac{K_{mc_2} \cdot C_{1f}}{K_{c_1} + C_{1f}} \cdot \frac{C_f}{K_o + C_f} \cdot \frac{A_f}{K_f + A_f} X_f + Y_1 \cdot F_n \frac{K_{ms} \cdot S_f}{K_s + S_f} \cdot \frac{C_f}{K_o + C_f} X_f \quad (1)$$

$$\text{NO}_x\text{-N} \quad D_{fc_2} \frac{d^2 C_{2f}}{dZ^2} = \frac{K_{mc_3} \cdot C_{2f}}{K_{c_2} + C_{2f}} \cdot \frac{S_f}{K_s + S_f} \cdot \frac{K_{or}}{K_{or} + C_f} X_f - \frac{K_{mc_2} \cdot C_{1f}}{K_{c_1} + C_{1f}} \cdot \frac{C_f}{K_o + C_f} \cdot \frac{A_f}{K_f + A_f} X_f \quad (2)$$

$$\text{Organic Substances} \quad D_{fs} \frac{d^2 S_f}{dZ^2} = \frac{K_{ms} \cdot S_f}{K_s + S_f} \cdot \frac{C_f}{K_o + C_f} X_f + \rho \frac{K_{mc_3} \cdot C_{2f}}{K_{c_2} + C_{2f}} \cdot \frac{S_f}{K_s + S_f} \cdot \frac{K_{or}}{K_{or} + C_f} X_f \quad (3)$$

$$\text{Oxygen} \quad D_{fc} \frac{d^2 C_f}{dZ^2} = r_2 \frac{K_{ms} \cdot S_f}{K_s + S_f} \cdot \frac{C_f}{K_o + C_f} X_f + r_n \frac{K_{mc_2} \cdot C_{1f}}{K_{c_1} + C_{1f}} \cdot \frac{C_f}{K_o + C_f} \cdot \frac{A_f}{K_f + A_f} X_f \quad (4)$$

$$\text{Alkalinity} \quad D_{fa} \frac{d^2 A_f}{dZ^2} = (\omega - \sigma \cdot Y_2 \cdot F_n) \frac{K_{mc_2} \cdot C_{1f}}{K_{c_1} + C_{1f}} \cdot \frac{C_f}{K_o + C_f} \cdot \frac{A_f}{K_f + A_f} X_f + \sigma \cdot Y_1 \cdot F_n \frac{K_{ms} \cdot S_f}{K_s + S_f} \cdot \frac{C_f}{K_o + C_f} X_f - \theta \cdot \frac{K_{mc_3} \cdot C_{2f}}{K_{c_2} + C_{2f}} \cdot \frac{S_f}{K_s + S_f} \cdot \frac{K_{or}}{K_{or} + C_f} X_f \quad (5)$$

Diffusion Layer

$$F_{sb} = \frac{D_{ws}}{L_o} (S_b - S_s) \quad (6) \quad F_{cb} = \frac{D_{wc}}{L_o} (C_b - C_s) \quad (7) \quad F_{c_1 b} = \frac{D_{wc_1}}{L_o} (C_{1b} - C_{1s}) \quad (8)$$

$$F_{c_2 b} = \frac{D_{wc_2}}{L_o} (C_{2b} - C_{2s}) \quad (9) \quad F_{ab} = \frac{D_{wa}}{L_o} (A_b - A_s) \quad (10)$$

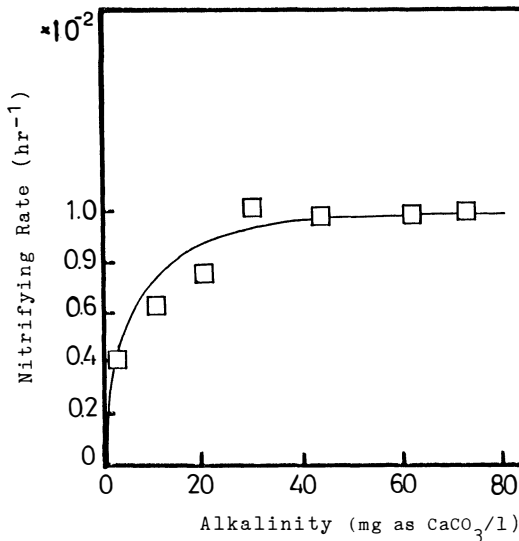


Fig. 2 The effect of alkalinity on nitrifying rate

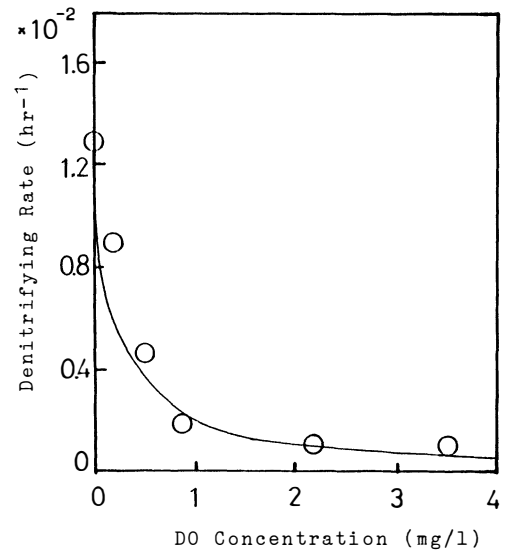


Fig. 3 The effect of DO concentration on denitrifying rate

shown as equation (2). Oxidized nitrogen is removed only by denitrification, which depends on the $\text{NO}_x\text{-N}$ concentration itself, and is influenced by the concentrations of organic substances as an electron acceptor, and DO. The effect of DO level on denitrification is shown in Fig. 3, which was obtained by a similar experiment as that mentioned above. This figure also probably gives a basis for the inhibition by DO level of denitrifying rate and may be represented as one kind of inhibition expression, $K_{or}/(K_{or} + C_f)$ as in this study.

Organic Substances The mass balance equation of organic substances is shown as equation (3). Organic removal concerns oxidation and consumption by denitrification.

Oxygen DO is consumed during organic oxidation and nitrification. The mass balance equation is expressed by equation (4).

TABLE 2 Values of Kinetic and Stoichiometric Parameters

Parameters*	Units	Value	References
D_{ws}	cm^2/day	1.09	Perry (1973)
D_{fs}	cm^2/day	0.87	
D_{wc}	cm^2/day	1.6	Williamson (1976)
D_{fc}	cm^2/day	1.44	Williamson (1976)
D_{wc1}	cm^2/day	1.5	Williamson (1976)
D_{fc1}	cm^2/day	1.2	
D_{wc2}	cm^2/day	1.4	Williamson (1976)
D_{fc2}	cm^2/day	1.3	Williamson (1976)
D_{wa}	cm^2/day	1.05	Chem. Engr. Assoc (1968)
D_{fa}	cm^2/day	0.84	
K_{ms}	1/day	3.5	
K_s	mgCOD/l	20.0	
K_o	cm^2/l	0.2	
K_{or}	mgO ₂ /l	0.2	
$K_{m_{c1}}$	1/day	0.43	
$K_{m_{c2}}$	1/day	0.31	
K_{c1}	mgN/l	5.3	
K_{c2}	mgN/l	6.2	
K_f	mg as CaCO ₃ /l	4.8	
L_o	μm	120.0	
Y_1	mgSS/mgCOD	0.31	Rittmann (1980)
Y_2	mgSS/mgN	0.17	Ide (1976)
r_2	mgO ₂ /mgCOD	0.56	
r_n	mgO ₂ /mgN	4.33	
ω	mgA/mgN	7.14	
σ	mgA/mgN	3.57	
θ	mgA/mgN	3.57	
β	mgCOD/mgN	2.68	
X_f	mgSS/cm ³	50.1	

A: Alkalinity

*See 'Nomenclature' section at end of paper for description of parameters.

Alkalinity Alkalinity is produced by denitrification and consumed by nitrification and biomass growth, as shown in equation (5).

COMPUTER SIMULATIONS

Numerical Analysis

The numerical analysis of the proposed model consisting of the simultaneous equations (1) to (10) was carried out by an initial-value adjusting method for the solution of nonlinear multipoint boundary value problems (Ojika *et al.*, 1978), based on the boundary conditions such as: a) every internal mass flux on the surface of support media is zero, b) each external mass flux correspondingly equals the internal mass flux at the biofilm surface. Most of the parameters used in computer simulation, shown in Table 2, were measured by batch experiments with dispersed biomass of the biofilm which was cultivated in a submerged biofilm reactor fed with artificial sewage (see Fig. 6 and table 3). Only diffusion coefficients, stoichiometric coefficients, and yield coefficients were taken from references. The diffusion coefficient of NOx-N was obtained by averaging those of nitrite and nitrate. The diffusion coefficient of alkalinity is assumed to be that of the bicarbonate ion, because the main component of alkalis is the bicarbonate ion (Hanya, 1960) at bulk pH between 7 to 8, which was usually seen in the experiments of this study. In a biofilm, the diffusion coefficients of NOx-N, bicarbonate, and acetate which was chosen as an organic source in this study, are reduced to 80% of those in water, respectively (Williamson *et al.*, 1976). Biofilm thickness was measured from a photograph of the cross-section of the biofilm taken with a stereo-microscope. The density of the biofilm was obtained from the measured volume and the mass of the biofilm on a disk. Thickness of diffusion layer on the biofilm surface was calculated by equation (12), which was simplified from the expression, previously reported by the authors (1987), calculating surface organic removal flux:

$$L_0 = D_{ws} \cdot \left\{ S_b / F_{sb} - F_{sb} / (2.0 \cdot D_{fs} \cdot K_{ms} \cdot X_f) \right\} \quad (12)$$

where $F_{sb} = 0.36$ (mg/cm² day) measured in bulk, $S_b = 4.0$ mg/l, $L_0 = 120$ μm.

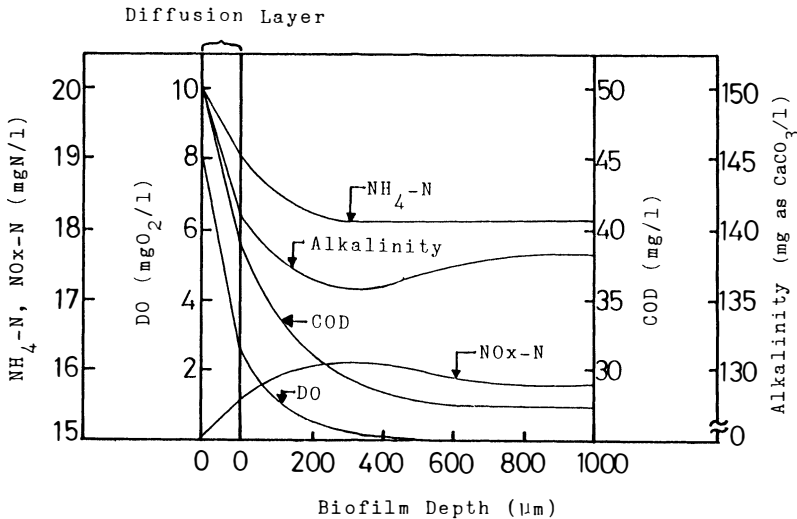


Fig. 4 Simulation of the concentration profiles in a biofilm

Example of Simulation

Figure 4 shows an example of the simulated concentration profiles of COD, DO, $\text{NH}_4\text{-N}$, $\text{NO}_x\text{-N}$, and alkalinity in a biofilm. In this study, COD(cr) was used as a parameter representing organic substances. It can be seen that organic oxidation and nitrification occur at aerobic parts, and denitrification occurs at lower DO level or anoxic parts of the biofilm, that is, the simultaneous removal of organic substances and nitrogen occurs in the biofilm. Every concentration change of these parameters along the direction of biofilm depth is consistent with that which can be anticipated from the kinetic characteristics of oxidation, nitrification, denitrification, and the relationships between these reactions and parameters. As an example of this in the figure, with decreasing DO level at aerobic parts of the biofilm, the concentrations of $\text{NH}_4\text{-N}$ and alkalinity decreased, whereas $\text{NO}_x\text{-N}$ increased. The reason is that $\text{NH}_4\text{-N}$ and alkalinity are simultaneously consumed, and at the same time $\text{NO}_x\text{-N}$ is produced by nitrification.

As an example of the simulations of the effects of influencing factors (such as biofilm thickness and bulk concentrations of the substrates) on the surface removal fluxes of organic substances, ammonium nitrogen, and total nitrogen, and on the surface consumption flux of alkalinity, Figure 5 shows the effect of biofilm thickness. The surface removal flux of total nitrogen is defined as the sum of two surface removal fluxes of ammonium nitrogen and $\text{NO}_x\text{-N}$ in the direction normal to biofilm surface. It was shown that all of these surface fluxes increase with thickness in the region up to about 1000 μm and become constant in the region above 1000 μm . This means that under the bulk conditions shown in the figure, the effective biofilm thickness for substrate removal is about 1000 μm . This value is nearly the same as those obtained from the simulations using the bulk conditions shown in Table 4.

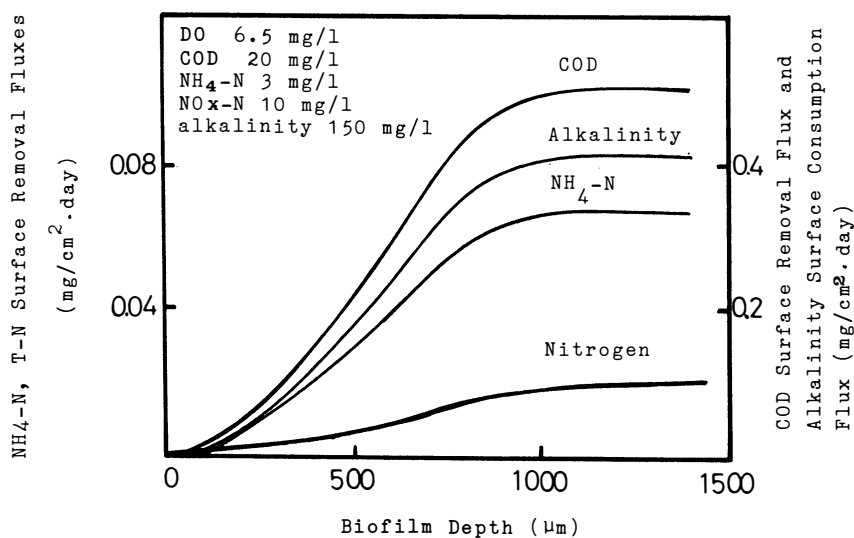


Fig. 5. Simulation of relationship between surface fluxes of COD, $\text{NH}_4\text{-N}$, total nitrogen and alkalinity and biofilm thickness

COMPARISON OF THE RESULTS FROM THE EXPERIMENTS AND THE SIMULATIONS

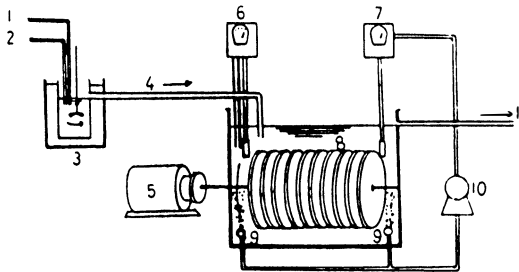
Experiments

The biofilm used in these experiments was continuously cultivated with the artificial sewage shown in Table 3, in a biofilm reactor shown in Fig. 6, in which 20 pieces of rotating disc were submerged. After cultivating for two months, all removal percentages of substrates became nearly constant: 90 % of organic substances, 90 % of ammonium nitrogen and 60 % of nitrogen. From this time, the biofilm was regarded as steady. Subsequently, continuous experiments for about 24 hours were carried out in the reactor, under the experimental conditions of influent and bulk DO concentration shown in Table 4, until the water quality of effluent became almost constant. The surface flux of the substrate concerned was calculated from its concentrations in influent and effluent, flow rate, and biofilm surface area. The thickness and density of the biofilm in every run were measured by the method already described in the section on numerical analysis. In all runs, hydraulic retention time (HRT) was controlled at 11 hours, temperature was 20°C, and rotating speed was 13 rpm. The concentration of the suspended solids in bulk was kept below 30 mgSS/l.

TABLE 3 Composition of Synthetic Sewage

Component	Concentration(mg/l)
Acetate	233.5
NH ₄ Cl	76.9
NaHCO ₃	123.7
K ₂ HPO ₄	12.6
KH ₂ PO ₄	5.0
Na ₂ HPO ₄ 12H ₂ O	26.0
MgSO ₄ 7H ₂ O	6.6
CaCl ₂	8.0
FeCl ₂	0.22

- 1 Tap Water
- 2 Feed
- 3 Cooling Tank
- 4 Influent
- 5 Rotating Motor
- 6 pH Controller
- 7 DO Controller
- 8 Disc
- 9 Diffuser
- 10 Air Pump
- 11 Effluent

Reactor Features

Disc Number 20
Diameter 15 cm
Volume 8 l

Cultivating Condi-
tions

HRT 11 hrs
Rotating Speed
13 rpm
Temp. 20°C
DO Level 5 mg/l
(controlled)

Fig. 6. Schematic of a submerged biofilm reactor

TABLE 4 Experimental Conditions

No.	Influent COD	Influent NH ₄ -N	Influent alkalinity	Bulk DO Conc. (Controlled)
Run 1	47-150 mg/l	20-28 mg/l	300 mg/l	0.5-7.0 mg/l
Run 2	45-200	15-30	200	6.0
Run 3	50-113	10-38	200-320	6.5
Run 4	53-63	18-28	38-350	6.5

All experiments were carried out at 20°C temp. and HRT of 11 hours. NO₃-N conc. of the influents was below 3 mg/l.

Comparison

To clarify the experimental and theoretical relationships between the surface removal fluxes of the substrates and water quality in bulk, and to evaluate the presented model, experimental results are discussed, and compared with simulation results. In Table 5, which shows the experimental data for simulations, each of the bulk concentrations in each run was obtained by averaging a set of concentrations measured during each experiment, except for DO concentration which was controlled and the concentration which was changed to investigate its effect on the surface removal fluxes. The parameters used in the simulations are the same as those shown in Table 2. The biofilm thickness was between 1000 to 1300 μm in all runs, and was fixed at 1000 μm for the simulations (above 1000 μm the thickness scarcely influenced the surface removal fluxes of organic substances, ammonium nitrogen, and total nitrogen, as shown in Fig. 5).

Effect of bulk DO concentration on the surface removal fluxes Figures 7 and 8 indicate results of the experiment and model simulation regarding the effect of bulk DO concentration on the surface removal fluxes of organic substances, and ammonium nitrogen and total nitrogen, respectively. These experimental results were obtained from run 1. These figures indicate that organic substances, ammonium nitrogen, and total nitrogen were simultaneously removed from bulk in a wide range of bulk DO concentration (above zero to 7 mg/l); that the surface removal fluxes of organic substances and ammonium nitrogen increased with an increase of bulk DO concentration; and also that the simulation curve agreed closely with the experimental results. These observations were also supported by the simulation of DO profile — DO penetrated deeper parts of biofilm with an increase of bulk DO under the above experimental conditions.

Regarding total nitrogen removal, it was shown in Fig. 8 that (1) the surface removal flux of

TABLE 5 Experimental Data Used in the Simulations

No.	S_b (mg/l)	C_b (mg/l)	C_1 (mg/l)	C_2 (mg/l)	A_b (mg/l)
RUN 1	31.2	0.0-7.0	10.8	9.5	150.3
RUN 2	0.0-4.0	6.0	8.3	10.9	147.6
RUN 3	10.5	6.5	0.0-12.0	14.3	149.8
RUN 4	10.9	6.5	7.5	15.6	0.0-220.0

S_b : Bulk COD conc.; C_b : bulk DO conc.; C_1 : Bulk $\text{NH}_4\text{-N}$ conc.;
 C_2 : Bulk $\text{NO}_x\text{-N}$ conc.; A_b : Bulk Alkalinity

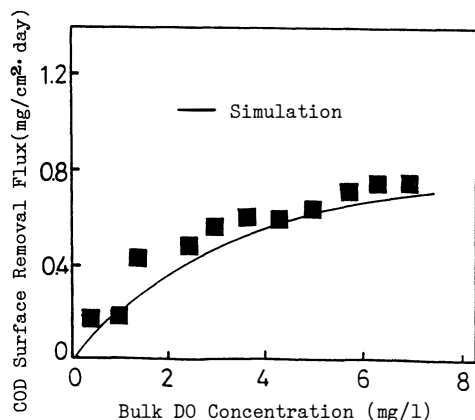


Fig. 7 The effect of bulk DO concentration on COD surface removal flux

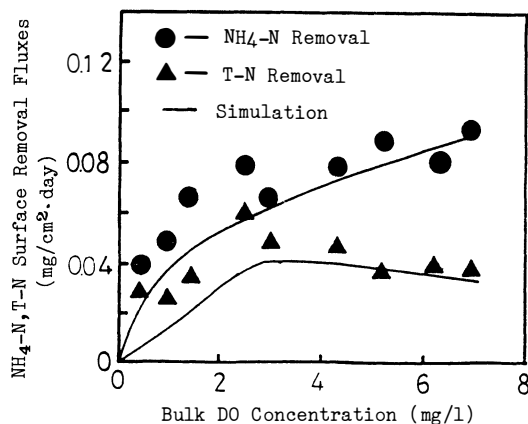


Fig. 8. The effect of bulk DO concentration on surface removal fluxes of $\text{NH}_4\text{-N}$ and total nitrogen

total nitrogen increased with bulk DO concentration in the region below 2.5 mg/l, (2) decreased with an increase of DO above 2.5 mg/l, and consequently, (3) at about 2.5 mg/l of bulk DO level, the maximum removal flux was obtained. These phenomena can be explained as follows:

(a) In the region of (1), nitrification in the biofilm proceeded with an increase of bulk DO, but produced $\text{NO}_x\text{-N}$ was sufficiently denitrified in an anoxic part of the biofilm.

(b) In the region of (2), with more increase of bulk DO, it penetrated to a deeper part of the biofilm, and the anoxic part was reduced.

(c) As for (3), at the bulk DO concentration giving the maximum surface removal flux of total nitrogen, the aerobic and anoxic parts within the biofilm balanced well the progress of nitrification and denitrification in the whole biofilm.

Therefore, it was reconfirmed that bulk DO concentration is a very important parameter for the progress of the reactions of simultaneous removal of organic substances and nitrogen compounds.

Effect of bulk concentration of substrates on simultaneous removal Figures 9 and 10 show the results of the experiment and simulation on the effect of bulk concentration of COD. The experimental results were obtained from run 2. These figures indicate that the simulations agreed well with the experimental results, and that the surface removal fluxes of organic substances, ammonium nitrogen, and total nitrogen depended on the bulk COD concentration. The removal fluxes of COD and total nitrogen increased with the bulk COD concentration. This is probably because COD penetrated a deeper part of the biofilm with the increase of the bulk COD. Consequently, not only organic oxidation but also denitrification occurred actively in the biofilm. Figure 10 also indicates that the surface removal flux of ammonium nitrogen became smaller when bulk COD concentration became larger. This is because organic oxidation competed with nitrification for DO consumption.

From the dependence of the surface removal fluxes of organic substances, ammonium nitrogen and total nitrogen on the bulk concentration of COD, it was found to be favorable for simultaneous removal that bulk COD concentration was kept at a relatively large value, about 30 to 40 mg/l.

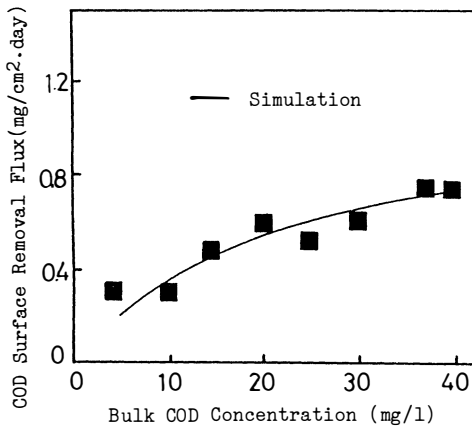


Fig. 9. The effect of bulk COD concentration on COD surface removal flux

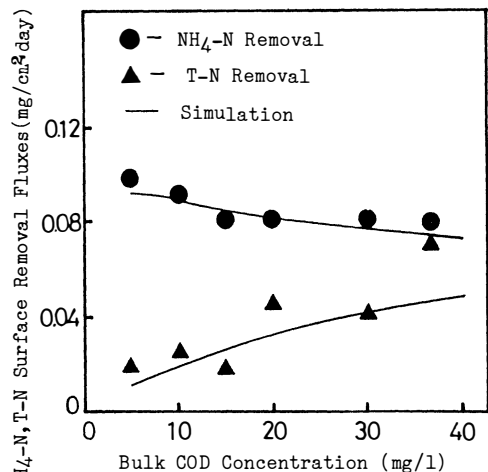


Fig. 10. The effect of bulk COD concentration on surface removal fluxes of $\text{NH}_4\text{-N}$, total nitrogen

Figure 11 shows the effects of bulk concentration of ammonium nitrogen on the surface removal fluxes of it and total nitrogen. In this figure, both fluxes increased with the bulk concentration of ammonium nitrogen. However, the increase rate of the flux of total nitrogen was smaller compared with that of the flux of ammonium nitrogen. The reason for the latter may be that nitrogen removal by denitrification was limited due to insufficient COD. The simulations of surface removal flux of total nitrogen were less consistent with the experimental results than that of ammonium nitrogen. This was presumed to be because the bulk COD concentrations in the experiments of this run were a little different, compared with those of other runs, and the appropriate average value of them for the simulations could not be obtained.

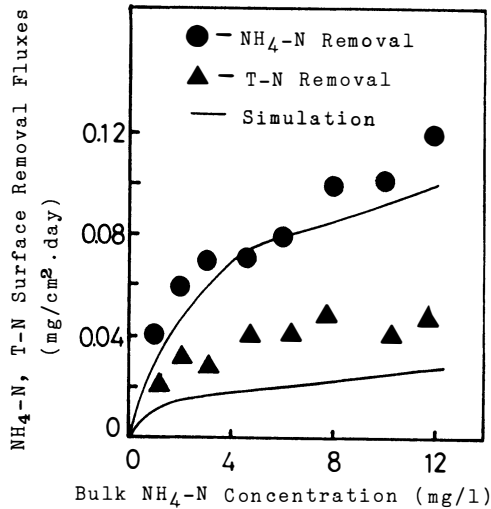


Fig. 11. The effect of bulk $\text{NH}_4\text{-N}$ concentration on surface removal fluxes of $\text{NH}_4\text{-N}$ and total nitrogen

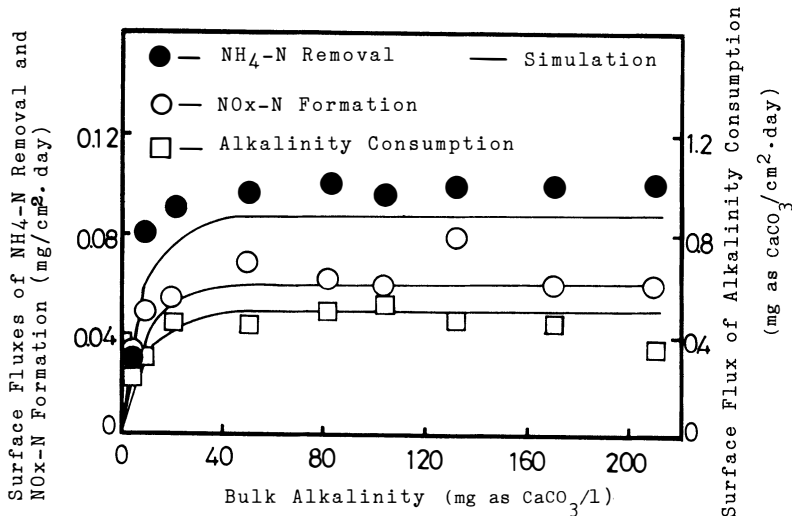


Fig. 12. The effect of bulk alkalinity on surface fluxes of $\text{NH}_4\text{-N}$ removal, $\text{NO}_x\text{-N}$ formation and alkalinity consumption

Effect of bulk alkalinity on ammonium nitrogen removal Figure 12 indicates that ammonium nitrogen removal flux was influenced by bulk alkalinity at low levels and independent of it above 50 mg/l as CaCO_3 , at the 7.5 mg/l of bulk ammonium nitrogen concentration. From this, it can be estimated that bulk alkalinity should be controlled, for ammonium nitrogen removal, above the level of 6.7 mg/l for 1 mg/l of bulk ammonium nitrogen concentration. However, if denitrification proceeds completely, this value is expected to become lower, because alkalinity is produced from denitrification.

CONCLUSIONS

The author developed a mathematical model of the simultaneous removal of organic substances and nitrogen compounds in a biofilm reactor, taking account of the relationships among oxidation, nitrification, denitrification, and mass transport. The model consists of a set of simultaneous mass balance equations for organic substances, ammonium nitrogen, oxidized nitrogen, oxygen, and alkalinity within the biofilm, and another set of transport equations for these substances within a diffusion layer on the biofilm. Synthetic dual and triple Monod-type kinetics describing, respectively, oxidation, and nitrification and denitrification were incorporated into the mass balance equations. Also the influence of bulk conditions on simultaneous removal was experimentally studied.

(1) From the experiment on the removal of organic substances and nitrogen compounds from the bulk liquid, the effects of bulk concentrations of DO, organic substrate, ammonium nitrogen, and alkalinity on simultaneous removal were found to be as follows:

(a) Bulk DO concentration is one of the most important operating factors for the reactions of simultaneous removal, that is, organic oxidation, nitrification, and denitrification. In particular, the maximum surface removal flux was obtained at the bulk DO concentration at which the aerobic and anoxic parts within the biofilm balanced well the progress of nitrification and denitrification in the whole biofilm, about 2.5 mg/l in this study.

(b) For simultaneous removal to occur, it was favorable that bulk COD concentration was kept at a relatively large value, about 30 to 40 mg/l in this study.

(c) The increase of bulk ammonium nitrogen raised the surface removal flux of total nitrogen, and consequently induced a further removal of organic substances.

(d) Bulk alkalinity influenced the surface removal flux of ammonium nitrogen. When the alkalinity was controlled above 6.7 mg/l as CaCO_3 for 1 mg/l of bulk concentration of ammonium nitrogen, the removal flux was independent of it.

(2) The simultaneous removal of organic substances and nitrogen compounds can sufficiently be achieved by keeping the bulk conditions at the state favorable for it. The conditions in this study were that the bulk DO concentration was about 2.5 mg/l, the bulk COD concentration about 30 to 40 mg/l, and the bulk alkalinity above 50 mg/l as CaCO_3 .

(3) The presented model showed well the concentration profiles of COD, DO, $\text{NH}_4\text{-N}$, $\text{NO}_x\text{-N}$, and alkalinity within a biofilm. The simulated results agreed well with the experimental data concerning the effects of bulk conditions on the simultaneous removal of organic substances and nitrogen compounds.

(4) From the above results, it can be concluded that simultaneous organic oxidation, nitrification, and denitrification in a biofilm depend on each other, and consequently are influenced by bulk water quality. The proposed model was found to be satisfactory enough to explain these phenomena.

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NOMENCLATURE

Symbol	Dimension	Description	Symbol	Dimension	Description
A_b	mg/cm^3	Bulk alkalinity	A_s	mg/cm^3	Alkalinity at biofilm surface
A_f	mg/cm^3	Alkalinity within biofilm	C_b	mg/cm^3	Bulk DO conc.
C_f	mg/cm^3	DO conc. within biofilm	C_s	mg/cm^3	DO conc. at biofilm surface
C_{1b}	mg/cm^3	Bulk $\text{NH}_4\text{-N}$ conc.	C_{1f}	mg/cm^3	$\text{NH}_4\text{-N}$ conc. within biofilm
C_{1s}	mg/cm^3	$\text{NH}_4\text{-N}$ conc. at biofilm surface	C_{2b}	mg/cm^3	Bulk NOx-N conc.
C_{2f}	mg/cm^3	NOx-N conc. within biofilm	C_{2s}	mg/cm^3	NOx-N conc. at biofilm surface
D_{fa}	cm^2/day	Diffusion coefficient of alkalinity within biofilm	D_{fc}	cm^2/day	Diffusion coefficient of DO within biofilm
D_{fc1}	cm^2/day	Diffusion coefficient of $\text{NH}_4\text{-N}$ within biofilm	D_{fc2}	cm^2/day	Diffusion coefficient of NOx-N within biofilm
D_{fs}	cm^2/day	Diffusion coefficient of acetate within biofilm	D_{wa}	cm^2/day	Diffusion coefficient of alkalinity in bulk
D_{wc}	cm^2/day	Diffusion coefficient of DO in bulk	D_{wc1}	cm^2/day	Diffusion coefficient of $\text{NH}_4\text{-N}$ in bulk liquid
D_{wc2}	cm^2/day	Diffusion coefficient of NOx-N in bulk	D_{ws}	cm^2/day	Diffusion coefficient of acetate in bulk
F_n	mg/mg	Nitrogen percentage in biomass	F_{ab}	$\text{mg}/\text{cm}^2\text{day}$	Alkalinity flux to biofilm
F_{cb}	$\text{mg}/\text{cm}^2\text{day}$	DO flux to biofilm	F_{c1b}	$\text{mg}/\text{cm}^2\text{day}$	$\text{NH}_4\text{-N}$ flux to biofilm
F_{sb}	$\text{mg}/\text{cm}^2\text{day}$	CODcr flux to biofilm	F_{c2b}	$\text{mg}/\text{cm}^2\text{day}$	NOx-N flux to biofilm or from biofilm
K_{c1}	mg/cm^3	Saturation coefficient for $\text{NH}_4\text{-N}$	K_{c2}	mg/cm^3	Saturation coefficient for NOx-N
K_f	mg/cm^3	Saturation coefficient for alkalinity	K_{mc2}	day^{-1}	Maximum rate of nitrification
K_{mc3}	day^{-1}	Maximum rate of denitrification	K_{ms}	day^{-1}	Maximum rate of CODcr removal
K_o	mg/cm^3	Saturation coefficient for DO	K_{or}	mg/cm^3	DO inhibition coefficient of denitrification
K_s	mg/cm^3	Saturation coefficient for CODcr	L_o	cm	Thickness of diffusion layer
L_f	cm	Biofilm thickness	r_2	mg/mg	DO-use coefficient for organic oxidation
r_n	mg/mg	DO-use coefficient for nitrification	S_b	mg/cm^3	Bulk CODcr conc.
S_f	mg/cm^3	CODcr conc. in biofilm	S_s	mg/cm^3	CODcr conc. at biofilm surface
X_f	mg/cm^3	Biomass density reaction	Y_1	mg/mg	Biomass yield coefficient for CODcr removal
Y_2	mg/mg	Biomass yield coefficient for $\text{NH}_4\text{-N}$ removal	Z	cm	Biofilm depth
σ	mg/mg	Alkalinity production coefficient for denitrification	β	mg/mg	COD-use coefficient for denitrification
ω	mg/mg	Alkalinity consumption coefficient for nitrification	θ	mg/mg	Alkalinity consumption coefficient for biomass formation

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