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WASTEWATER BIOCHEMICAL TREATMENT MANAGEMENT BY BIOTIC FACTORS EFFECT

Abstract. *The reasons of need to insure effectiveness of management of wastewater biochemical treatment with factors that influence parameters of process are presented. It is underlined that the key factors having effect on the efficiency of biological treatment are temperature, oxygen concentration in bioreactor, balance of the main nutrients, load of pollutants on active sludge, rate of reproduction of active sludge. It's follows from presented fundamental regularities of enzyme kinetics that with concentration increase in substrate the oxidation capacity of system increases, but there is a limitation caused by sludge properties and external factors. Oxidation capacity has the largest value in absence of process limitation by substrate, i.e. at high concentrations of pollutions. Dynamic analysis of experimentally obtained data determined that concentrations of phosphorus and nitrogen have a significant impact on biomass growth in bioreactor. Regulation of biotic factors of process increases quality of management of treatment facilities.*

Keywords: process management; effect factors; biochemical treatment; fermentative kinetics

Problem formulation

Wastewater biochemical treatment system is the complex system, which is influenced by both internal (technical, social, economic and environmental) and external (social and political conflicts, global environmental problems, external debt, structural limitations) factors. The main causes of deterioration of the quality of biochemical wastewater treatment can be identified as a high concentration of pollutants in wastewater, sharp fluctuations of quantitative indicators and quality of effluents, suboptimal content of nutrients in the culture fluid and so on. In addition, the old treatment equipment is unable to cope with the continuing increase in wastewater certain chemicals, including phosphates. Therefore, it is important to consider factors of treatment effect in the context of complex systems that can be developed.

Analysis of research and publications

The main current approaches to management of water utilities and wastewater treatment in Ukraine include general management principles without considering technical and technological features, especially as for biochemical processes [1]. To increase effectiveness of municipal wastewater treatment factors that influence parameters of process should be taken into account [2, 3].

The processes of biochemical treatment of wastewaters that proceeds in the voidage or on the carrier surface are the result of metabolic activity of microorganisms the basis of which is composed of reactions catalyzed by enzymes both inside and outside the cell. The mathematical description of the kinetics of enzymatic reactions is based on the assumption of the existence of the enzyme substrate complex and dependence of the reaction rate on the decomposition rate of this complex with formation of the reaction product and free enzyme [4]. According to this hypothesis for the enzymatic reactions proceeding by the scheme

$$E + S \leftrightarrow E\,S \leftrightarrow E + P \qquad (1)$$

where S – substrate concentration, E – enzyme concentration, ES – enzyme-substrate concentration, P – concentration of reaction products.

Michaelis and Menten derived a well known equation:

$$V = \frac{V_{\max} S}{S + K_m}, \qquad (2)$$

where V – rate of biochemical substrate destruction referred to a unit of active biomass of microorganisms, *mg/g·h*, V_{max} – the maximum specific rate of biochemical substrate destruction referred to a unit of active biomass of microorganisms or the reaction rate without limiting by substrate, *mg/g·h*, S – substrate concentration (the amount of organic matters in the treated water, *mg/l*), K_m – the Michaelis constant characterizing affinity of the substrate enzyme, *mg/l*.

According to this equation the dependence of the reaction rate on the concentration of an organic matter is expressed by the hyperbolic function.

Kinetics of oxidation of organic pollutants of wastewaters estimated by biological oxygen demand

(BOD), as well as oxidation of specific ingredients and oxidation of ammonium nitrogen (nitrification) are considered by many authors similarly to kinetics of enzymes' analysis [4-8] and described by the Michaelis-Menten equation. The complex structure of organic matters in the wastewater in this case is approximated by a simple source of carbon nutrition.

The article purpose

The purpose of this article is to establish and analyze the effect of biotic factors on efficiency of wastewater biochemical treatment. For this it's necessary to resume fundamental scientific approach to the problem and study dependence of biomass growth from the main parameters of process experimentally.

Effect of biotic factors on efficiency of biochemical treatment

In order to describe more complex enzyme reactions a great number of relevant modifications of this equation was developed which reflect the mechanisms of the interaction of the enzyme, substrate, inhibitors and other components of the reaction.

The use equations (1) and (2) is convenient in processing of experimental data for the purpose of determining the kinetic constants in order to assess and compare the biological oxidation capacity and calculate the processes of treatment of different organic matters and types of wastewaters.

The most important characteristic of biological treatment is the rate of the growth of microorganisms. The studies of Monod and Iyerusalimsky [8, 9] showed that the biomass growth rate (μ) is described by the equation similar to the Michaelis-Menten equation:

$$\mu = \frac{\mu_{max} S}{S + K_m}, \tag{3}$$

where the growth rate is expressed by the equation:

$$\mu = \frac{1}{X}\frac{dX}{dt}, \tag{4}$$

and the rate of biomass buildup is equal to

$$\frac{dX}{dt} = \mu X, \tag{5}$$

where X – concentration of microorganisms. Then the rate at which organisms are washed out from the reactor will be determined by formula:

$$-\frac{dX}{dt} = \frac{XQ}{W} = XT.$$

Therefore, the total increase will be:

$$\mu X - \frac{X}{T} = X\left(1 - \frac{1}{T}\right).$$

The relationship between the rate of the substrate consumption and the rate of the biomass growth is expressed by the approximation by using a coefficient of proportionality Y, the so called "economic coefficient", which characterizes the biomass yield per unit of the substrate consumed:

$$\frac{dX}{dt} = Y\frac{dS}{dt}, \ldots \ldots \frac{dX}{dS} = Y.$$

The rate of the substrate consumption is determined by the following equation:

$$-\frac{dS}{dt} = -\frac{dS}{dX}\frac{dX}{dt}.$$

It is obvious that any change in the substrate concentration in the culture (*dS/dt*) is equal to the input of the substance minus yield of the substance plus its consumption, or

$$\frac{dS}{dt} = \frac{S_0}{T} - \frac{S_1}{T} - \frac{X}{YT}.$$

However, in a steady state the rate of substrate concentration (*dS/dt*) is equal to zero. Then

$$\frac{S_0}{T} = \frac{S_1}{T} - \frac{X}{YT},$$

or

$$X = Y(S_0 - S_1).$$

Bacteria that carry out the deep removal of heavily oxidizable and bio-resistant organic matters possess an efficient metabolism and low growth rates. The removal of heavily oxidizable organic matters in the biological treatment facilities with free-floating active sludge often fails to give a proper result in consequence of washing out from the system the microorganisms that oxidize these matters since they have low growth rates. The retention of such microorganisms in the biological treatment facilities in the voidage is practically impossible.

Actually, at an insignificant sludge increase, e.g. 0.1 *mg/mg* of the removed BOD, the retention of sufficient amount of free-floating active sludge in the aerotank is impossible [10]. In oxidation of wastewater with *BOD* = 75 *mg/l* (15 *mg/l* at outlet) the increase will be 6 *mg/l*, the washout of active sludge from the secondary sedimentation tanks for a well flocculating sludge at the best case is 10…12 *mg/l*, which exceeds the increase of microorganisms. Therefore, in this case the advanced and reliable water treatment can be achieved only by using the immobilized microorganisms not washed out with the water flow.

The population of the sludge microorganisms has the entire spectrum of species that slowly grow. Except the latter the species can appear that grow in these conditions faster than initial ones. The substitution of initial forms by them results in the population alteration. According to the Mozer analysis, one species (*A*) replaces the other (*B*) provided that $\mu_a > \mu_b$. The larger difference between the specific rates of growth the faster this replacement takes place and selection in favor of the fast-growing species acts more efficient.

Mozer characterizes the pressure of selection as a difference in specific rates of growth of the given species [7]:

$$\sigma = \mu_a - \mu_в .$$

In the absence of the process limitation by the substrate concentration the growth rates and oxidation rates are close to maximum ones and selection is carried out in favor of the microorganisms that grow with the maximum rate $\mu_{\max}$.

At high concentrations of the substrate there are spectra of species that grow with the maximum rate μ_a and μ_b, with $\mu_a > \mu_b$.

According to equation (3), the expression may be written as:

$$\mu_a = \mu_{a\max} S/(K_{am} + S),$$
$$\mu_{â} = \mu_{â\max} S/(K_{âm} + S).$$

Considering (4) and (5) and that the change in the concentration of biomass of both species of microorganisms (Xa, $Xв$) at flow-through cultivation is determined not only by the increase, but also by the allocation of a part of biomass, the expression may be written as:

$$dX_a/dt = \mu_a X_a - X_a/T,$$
$$dX_в/dt = \mu_в X_a - X_в/T,$$

where T is the time of residence or aeration in the reactor, h

At a steady state at which $dX/dt = 0$ a system of equations will take on form:

$$\left(\mu_a - \frac{1}{T}\right)X_a = 0, \quad \left(\mu_a - \frac{1}{T}\right)Y(S_0 - S_1) = 0;$$
$$\left(\mu_B - \frac{1}{T}\right)X_a = 0, \quad \left(\mu_B - \frac{1}{T}\right)Y(S_0 - S_1) = 0;$$
$$\left(\mu_a = \frac{1}{T}\right), \left(\mu_B = \frac{1}{T}\right),$$

then

$$\left(\frac{\mu_{a\max}S}{(K_{am}+S)} - \frac{1}{T}\right)Y(S_0 - S_1) = 0;$$
$$\left(\frac{\mu_{B\max}S}{(K_{Bm}+S)} - \frac{1}{T}\right)Y(S_0 - S_1) = 0. \quad (6)$$

At substrate concentrations not limiting the growth when $S >> K_{am} = S_o$ and $S >> K_{Bm} = S_o$, we can concede that $K_{am}+S = S$ and $K_{Bm}+S=S$.

In this case:

$$\mu_a \cong \mu_{a\max}, \quad \mu_b \cong \mu_{b\max},$$
$$\left(\mu_{a\max} - \frac{1}{T}\right)Y_a(S_0 - S_1) = 0,$$
$$\left(\mu_{B\max} - \frac{1}{T}\right)Y_B(S_0 - S_1) = 0.$$

If $S_1 = S_o$, then we can write as:

$$\left(\mu_{a\max} - \frac{1}{T}\right)Y_a = 0;$$
$$\left(\mu_{B\max} - \frac{1}{T}\right)Y_B = 0.$$

The obtained equations show that the main parameter determining the species in the reactor at constant effluent discharge (at the same T) and oxidation of easily oxidable organic matters which are characterized by sufficiently high economic coefficient ($Y_a \approx Y_B$) is the value of the maximum growth rate. The pressure of selection is generally determined by the difference of the maximum growth rates:

$$\sigma = \mu_{a\max} - \mu_{в\max}.$$

So, in active sludge biocenosis during oxidation of easily oxidable organic substrate with high economic coefficient the most fast-growing species, which have the highest maximum rates of growth and oxidation, are automatically separated.

In the reactor in the integrated treatment when the substrate concentration is usually low, $So >> S$, ($S << K_{am}$ і $S << K_{вm}$), one can concedes that $K_{am} + S \cong K_{am}$ and $K_{em} + S \cong K_{вm}$. In this case the rates of growth of the species under consideration are lower than maximum ones ($\mu_a >> \mu_b$ і $\mu_b << \mu_{b\max}$) and their values are generally determined by the value of parameter K_m:

$$\mu_a \cong \frac{\mu_{a\max}S}{K_{am}}, \quad \mu_B \cong \frac{\mu_{B\max}S}{K_{Bm}}.$$

Then the change in the concentration of biomass of both species of microorganisms at a steady state by analogy with a system of equations (6) can be presented as:

$$\left(\frac{\mu_{a\max}S}{K_{am} - \frac{1}{T}}\right)Y_a S_0 = 0,$$
$$\left(\frac{\mu_{B\max}S}{K_{Bm} - \frac{1}{T}}\right)Y_B S_0 = 0. \quad (7)$$

In oxidation of heavily oxidizable organic pollutants when Ya and $Y_B => 0$, it follows from a system of equations (7) that in reactor operating in mode of integrated treatment, at low substrate concentration, species are selected not by the maximum growth rate, but by the minimum value of constant K_m, and it is this value that determines, under conditions of substrate limitation, the value of growth rate of the basic active species.

The difference between the growth rates of species is determined by the difference of inverse values of constants K_m:

$$\sigma = \frac{1}{K_{Bm}} - \frac{1}{K_{am}}, \quad K_{Bm} < K_{am}.$$

In this case culture “*B*” will prevail in reactor.

So, in oxidation heavily oxidizable organic matters or in operation of the reactor in the mode of integrated treatment the automatic selection and selection of species is aimed at decrease of constant K_m, decrease of substrate concentration, limiting growth.

Taking into account activation by oxygen and inhibition by products of metabolism of active sludge microorganisms [11], oxidation capacity (*OC*) of facility can be expressed by the following equation:

$$OC = \frac{V_{\max} S C_0 X}{\left(K_m C_{02} + K_{0_2} S + C_{02} S\right)\left(1/\left(1+\phi X\right)\right)} K_T, \quad (8)$$

where V_{max} – the maximum specific rate of biochemical substrate destruction referred to a unit of active biomass of microorganisms; S – substrate concentration (amount of organic matters in treated water, *mg/l*); C_0 – concentration of dissolved oxygen, *mg/l*; X – concentration of active sludge microorganisms, *g/l*; K_m – the Michaelis constant equal to substrate concentration at which reaction rate is half of the maximum rate, *mg/l*; C_o – constant of oxygen dissociation, *mg/l*; K_m – coefficient making allowance for effect of ambient temperature; φ – coefficient of inhibition by degradation products of active sludge, *l/g*.

As it is clear from equation (8), with concentration increase in substrate the oxidation capacity of system increases, but there is a certain limitation caused by sludge properties and external factors (temperature).

The substrate together with the concentration of dissolved oxygen has a marked effect on the rate of biochemical destruction under aerobic conditions. It follows from equation (8) that oxidation capacity has the largest value in the absence of the process limitation by substrate, i.e. at high concentrations of pollutions. The optimum value of dissolved oxygen concentration depends on the requirements to the quality of the treated water, reactor type and economical efficiency of aeration equipment. The positive effect largely becomes apparent in the use of tonnage oxygen or enriched air during biological treatment [5; 6].

The increase sludge doze also significantly increases the oxidation capacity of treatment plants, but it increases not proportionally to sludge doze (*X*), but gradually damps out with increase of the latter up to 15…20 *g/l*. In conventional aerotanks the sludge doze is limited by capacities of secondary sedimentation tanks which under normal hydraulic loads does not allow the sludge doze (*X*) to exceed 4…5 *g/l* [11].

The technological characteristics of bioreactors with stable active sludge concentration facilitate the practically complete absence of washout of microorganism cells and hence the increase of their concentration per unit of volume 3…4 times, which, in its turn, increases the rate of biochemical reaction at 1.6 times (including the processes of nitrification/denitrification), improves the quality of treatment and rejects the need for the secondary sedimentation tank. Also, the advantages of this process include reduction of time of residence of wastewater in facilities due to which facilities of such type can receive greater amount of wastewaters at stable functioning of active sludge.

The experiment to determine the dynamics of dependence of rate of biomass growth on content of heavily oxidizable matters in wastewater at outlet, the content of main microelements (phosphorus, nitrogen) was carried out during 140 days with determination of quantity of biomass formation per day and dynamics of efficiency of treatment (for chemical oxygen demand (COD), Fig.1-2).

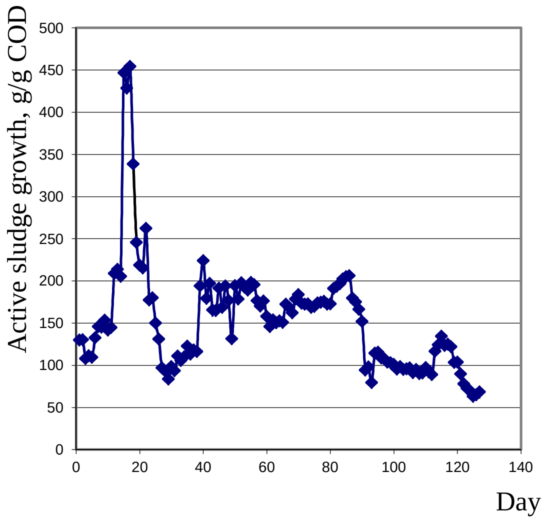

Figure 1 – Dynamics of active sludge growth

In order to analyze dependence of treatment efficiency on nitrogen content, it was taken into consideration that if the total conversion of COD takes place, sludge formation F_{SP} per 1 m^3 of water allowance for the biomass increase coefficient can be written as follows:

$$F_{SP} / Q_1 = C_1 Y_{набл}.$$

where $Y_{набл}$ – coefficient of biomass grow observed for given conditions (*kg COD/kg* of *COD* added); C_1 – COD at inlet in treatment plant.

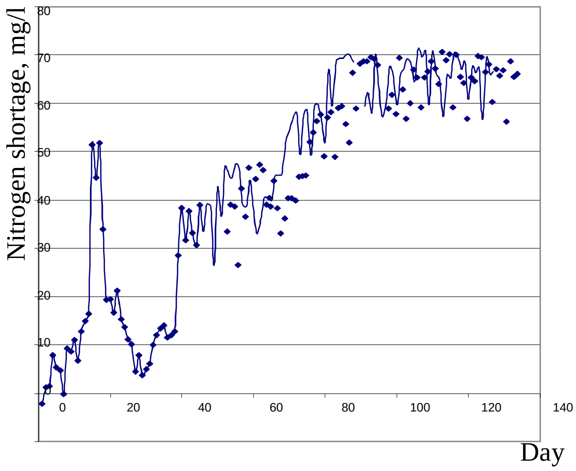

Figure 2 – Dynamics of nitrogen shortage in bioreactor

Consequently, nitrogen and phosphorus demand will be respectively equal to:

$$D_N = f_{X,N} F_{SP} / Q_1.$$

$$D_P = f_{X,P} F_{SP} / Q_1,$$

where D_N, D_P – nitrogen and phosphorus demand, respectively; $f_{X,N}$, $f_{X,P}$ – content of nitrogen and phosphorus in sludge *N/COD*, *P/COD*, respectively (standard values for active sludge – 7 % *N/COD* and 1.5% *P/COD*) [11].

The quantity of a shortage of nitrogen was also calculated. As is seen from Fig.1, the dependence takes place because with increase of quantity of active sludge in bioreactor occurring due to absence of its washout from reactor volume, biomass demand for nitrogen increases.

After the 80th day nitrogenous matters were added in small quantity in reactor (Fig. 2). In the period to 83rd day there was a gradual decrease of biomass growth, which was connected with increase of shortage of nitrogen in bioreactor. After the 85th day, because of decrease of effect of inhibition of biochemical treatment processes and shortage of nitrogen in bioreactor, there were stabilization and some increase in biomass growth.

The similar dependence was obtained in studies of Masse [12] et al. In the whole range of sludge age (10-110 days) it was ensured high efficiency of removal of organic matters (90…93%) assessed for total COD.

Conclusions

The fundamental regularities of enzyme kinetics highlight to the fullest extent physical essence of biochemical treatment processes. The use of these regularities for investigation, description and analysis of biochemical treatment processes can provide necessary information for development of science-based methodology of determining effects of temperature, oxygen concentration in bioreactor, balance of the main nutrients, loading on active sludge, oxidation capacity of biological treatment plants etc.

Oxidation capacity of system increases with increase substrate concentration, but there is a certain limitation caused by sludge properties and external factors. Dynamic analysis of experimentally obtained data determined that concentrations of phosphorus and nitrogen have a significant impact on the growth of biomass in bioreactor. Determination of the main biotic factors that influence on the biochemical process of waste water treatment and their operation make treatment plants management effective.

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УПРАВЛІННЯ БІОХІМІЧНИМ ОЧИЩЕННЯМ СТІЧНИХ ВОД ШЛЯХОМ ВПЛИВУ БІОТИЧНИХ ФАКТОРІВ

Анотація. *Обґрунтовано необхідність забезпечення ефективного управління біохімічним очищенням стічних вод шляхом впливу визначальних факторів процесу. Підкреслюється, що основними факторами, які впливають на ефективність біологічного очищення, є температура, концентрація кисню в біореакторі, баланс основних поживних речовин, питоме навантаження забруднювачів на активний мул, швидкість росту мікроорганізмів активного мулу. З представлених фундаментальних закономірностей кінетики ферментативних реакцій випливає, що зі збільшенням концентрації субстрату окисна здатність системи збільшується, але є певні обмеження, викликані властивостями мулу і зовнішніх факторів. Окисна потужність має найбільше значення за відсутності обмеження процесу по субстрату, тобто за високих концентрацій забруднюючих речовин. Динамічний аналіз експериментально отриманих даних дозволив встановити, що концентрації фосфору й азоту мають значний вплив на зростання біомаси в біореакторі. Показано, що регулювання біотичних факторів процесу підвищує якість менеджменту очисних споруд.*

Ключові слова: управління процесом; фактори впливу; біохімічне очищення; ферментативна кінетика

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УПРАВЛЕНИЕ БИОХИМИЧЕСКОЙ ОЧИСТКОЙ СТОЧНЫХ ВОД ПУТЕМ ВОЗДЕЙСТВИЯ БИОТИЧЕСКИХ ФАКТОРОВ

Аннотация. *Обоснована необходимость обеспечения эффективного управления биохимической очисткой сточных вод путем влияния определяющих факторов процесса. Подчеркивается, что основными факторами, влияющими на эффективность биологической очистки, является температура, концентрация кислорода в биореакторе, баланс основных питательных веществ, удельная нагрузка загрязнителей на активный ил, скорость роста микроорганизмов активного ила. Из представленных фундаментальных закономерностей кинетики ферментативных реакций следует, что с увеличением концентрации субстрата окислительная способность системы увеличивается, но есть определенные ограничения, вызванные свойствами ила и внешними факторами. Окислительная мощность имеет наибольшее значение при отсутствии ограничения процесса по субстрату, то есть при высоких концентрациях загрязняющих веществ. Динамический анализ экспериментально полученных данных позволил установить, что концентрации фосфора и азота имеют значительное влияние на рост биомассы в биореакторе. Показано, что регулирование биотических факторов процесса повышает качество менеджмента очистных сооружений.*

Ключевые слова: управление процессом; факторы влияния; биохимическая очистка; ферментативная кинетика

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