Modeling of enzymatic waste water treatment

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Abstract. Processing and recycling of waste water is an important environmental problem. One possible and promising way to use the generated sludge is production biofertilizers for agriculture. However, in view of the risks of chemical and bacteriological contamination, it is necessary to develop technologies that ensure a high level of conditioning and stabilization of sludge. Maximum enzyme activity is observed in a microbubble medium under the conditions of a mesophilic process. To accelerate the biochemical transformation of pollutants, an enzyme-cavitation method has been developed, based on the stimulation of growth processes of microorganisms in bioreactors by low and high intensity cavitation created by turbojets. It has been established that the quality and duration of sludge treatment depends on the pressure of the substrate at the entrance to the oxidizing jets. It has been proven that at a pressure $p = 0.30-0.35$ MPa, the processing time of the sludge before stabilization of the chemical oxygen consumption at 16% is 8 hours. Microscopic studies found that the processed substrate is an accumulation of microorganisms with a total surface of up to $100$ m² per 1 gram of dry matter that provides high sorption properties with respect to moisture.

1. Introduction

The operating principle of typical wastewater treatment plants is based on aerobic or anaerobic principles of biological impact on the organic components of the effluent. Such treatment facilities occupy large areas, they are characterized by high energy consumption of the compressor facilities and environmentally faulty. The aerobic destruction of organic substances is accompanied by the removal of nitrogen compounds, which contains as ammonium ions in the wastewater. Finally, the nitrification process is expressed by the equation [1]:

$$\text{NH}_4^+ + 2\text{O}_2 \rightarrow \text{NO}_3^- + \text{H}_2\text{O} + 2\text{H}^+,$$

that is, reactions proceed under the influence of oxygen.

The sludge obtained after wastewater treatment can be used as a biofertilizer in agriculture. In [2], the efficiency of biofertilizers has been evaluated in comparison with traditional chemical fertilizers. Biofertilizers have been obtained by composting sawdust and chicken manure, sawdust and sewage
sludge, and only sawdust with microbial culture to accelerate the destruction processes. After composting for 20 days, the efficiency of biofertilizers has been evaluated by cultivating corn in the field. It is noted that all compositions of biofertilizers enhance the growth of maize plants, and, accordingly, can be used instead of chemical fertilizers.

In [3], the possibility of using waste water sediments has been researched taking into account environmental indicators—heavy metals, pathogens and daptomycin residues, toxicity, and so on. Waste water sediments formed during the production of daptomycin as a nutrient substrate for growing lettuce and barley.

The results of researches have showed that all residues (sediment, anaerobic digestate and compost) are characterized by high concentrations of macronutrients $N, P, K$ at acceptable concentrations of heavy metals and pathogenic microorganisms. They have a positive effect on the vegetation of plants, what makes them suitable for reuse in agriculture.

The work [4] is also the confirmation of the prospect of using wastewater sludge as a biofertilizer in the agricultural cultivation. During the ten-year period of comparative researches of chemical fertilizers and wastewater sludge effect on the biogeochemical and agrotechnical indicators of the soil and the corn yield, the sludge has proved its effectiveness in completely replacing phosphorus fertilizer and trace elements, and partially replacing nitrogen fertilizer without reducing the yield. The authors of the work [5] note that the processing and recycling of domestic, industrial and agricultural waste water is an important environmental problem. One possible and promising way to use the generated sludge is production biofertilizers for agriculture. However, due to the risks of chemical and bacteriological contamination, it is necessary to develop technologies providing a high level of conditioning and stabilization of sludge.

Thus, the analysis of modern research on handling and utilization of organ-containing waste generated as a result of human economic activity indicates the reasonability of their applications as fertilizer substrates for growing crops. A necessary condition for organic waste application in agriculture is environmentally acceptable concentrations of polluting components that can be achieved only by lengthy dewatering and neutralization in silt fields. In this regard, the purpose of the research was to develop a technology for domestic wastewater treatment and the sediment stabilization, which provides an environmentally sound fertilizer substrate for growing crops.

2. Methods and materials

The enzyme-cavitation method [6-9], implemented in bioreactors, has been developed to intensify the process of wastewater and sludge treatment, as well as increase the resource efficiency of the technology biochemical degradation of pollutants coming to treatment plants. The schematic diagram of the setup is shown in figure 1.

Contaminated wastewater come into the biological treatment unit, having passed the mechanical treatment unit, which includes the capture of coarse and fine impurities using the gravitational precipitation process, and hydrophobic substances, using the flotation process, and wastewater averaging with low-intensity cavitation treatment, stimulating the growth of microorganisms. This unit includes three autonomous aerobic-anaerobic bioreactors 1, 2, 3, interconnected by a transport system, which includes equipment for moving liquids and gases 7 with the necessary pipelines 8, equipped with turbojets 9 and oxidizing jets 10, shut-off and control valves with control and measuring appliances 11.

The reactors are vertically column apparatus in which sorption and oxidation of the water-sludge mixture occurs in the activated sludge biocenosis and on the biofilm immobilized on carriers 5. Each reactor forms its own biocenosis of activated sludge and biofilm, which differs from the previous one by a wider species composition.

Bio-purification is accompanied by at least twice (depending on the degree of pollution of the wastewater) recirculation of the water-sludge mixture through each reactor and its subsequent flow from the reactor to the reactor. Saturation of the water-sludge mixture with air is achieved during the process of recirculation of water-sludge mixture through pipelines in reactors.
The water-sludge stream in the reactors moves along an ascending-descending path 4, at first flows around the outer zone of the reactors (ascending branch), and then descends down the central part of the reactors (descending branch) and passes through a biofilm immobilized on carriers. Mixing of activated sludge with a water-sludge mixture occurs sequentially in an upward-downward flow by turbulization.

Figure 1. The schematic diagram of the wastewater treatment plan [10]: I – Contaminated wastewater; II – Mechanical treatment unit; III – Water-sludge mixture; IV – Biological treatment unit; V – Water-sludge mixture or sludge component; VI – Physicochemical treatment unit; VII – Clarified water component; VIII – Disinfection unit; IX – Purified water; X – Sludge component; XI – Discharge of dehydrated sludge; XII – Over sludge water.

The ascending branches of the flow are more enriched with oxygen than internal ones that makes it possible to alternate between nitrification and denitrification processes, in which at first the oxidizing pollution biocenosis absorbs oxygen from the water-sludge mixture and then expends it intensively to oxidize the pollution.

After the biological treatment unit, the water-sludge mixture containing swollen activated sludge, comes to the physicochemical treatment unit to the stage of separation of the water-sludge mixture into components by at least a two-stage (depending on the amount of swollen activated sludge) sedimentation and flocculation process. The clarified water component is discharged into the disinfection unit using traditional methods, and the sludge component is divided into two streams by the time the critical volume is reached:

1) the first stream - from 10 to 15% of the sludge component is returned to the reactor 1 for the regeneration process by at least double circulation under aeration conditions of oxidizing jets and low intensity cavitation processing by turbojets;

2) the second stream - from 85 to 90% of the sludge component is returned to the reactor 3 for the process by at least triple circulation under aeration conditions of oxidizing jets and cavitation treatment of low and high intensity by turbojets.

During the process regeneration and lysis of the corresponding sludge component streams, reactors 1 and 3 are isolated, and the biological treatment process is stopped.

In the process of the sludge component lysing in the reactor 3 the shells of microorganisms are destroyed by cavitation, enzymes are secreted ensuring the functioning of the living microflora in the reactor 3. After at least triple circulation under aeration conditions with oxidizing jets and cavitation treatment by low and high intensity turbojets, the process is interrupted at the same time the value of dehydrogenase activity reaches its minimum. The saturation of the sludge component with air ensures its ascent and compaction in the reactor 3. Over sludge water with enzymes is easily removed through the lower outlet of the reactor 3 to the initial stage of purification due to its higher density than the sludge.
component. The sludge component comes to the dehydration stage of the physicochemical treatment unit using the centrifugation and pressfiltration process.

The research was carried out in domestic wastewater treatment plants in Volgograd, Russia. In the process of domestic waste water and sludge treatment the amount of oxygen consumed for the oxidation of pollutants (chemical oxygen consumption) was recorded in real time at an inlet pressure of 0.20 to 0.35 MPa with an interval of 0.05 MPa and an oxygen concentration of ≈ 9 mg/l by the conductometric method. The oxygen concentration in the stream was measured continuously by a potentiometric method using multi-parameter liquid analyzer. The sedimentation characteristics of processed sediments were evaluated using kinetic curves for decreasing the phase interface (deposition rate). For this purpose, a 200 mm high measuring cylinder was filled with a substrate and the height of the over sludge water column was measured after 30 min. The chemical composition of processed precipitation was obtained by standard methods in test laboratory [7].

3. Results and discussion

The microcavitation or microbubble medium has a favorable effect on the growth and activity of microorganisms, including enzymes that break down the molecules of organic substances. At temperatures \( t \leq 0 \, ^{\circ}C \) and \( t \geq 80 \, ^{\circ}C \), the enzymes do not show signs of vital activity, and their maximum activity has been fixed at \( t \approx 40 \, ^{\circ}C \) (figure 2), so it is in the temperature range of the mesophilic process, and \( pH = 7 \) [1, 11].

The quality and duration of the sludge treatment by enzyme-cavitation method essentially depends on the substrate’s pressure of the inlet to oxicity. At this setup, the inlet flow pressure was varied in the range of 0.20-0.35 MPa (figure 3). The quality criterion of sludge treatment was reducing the chemical oxygen consumption \( \xi \) to a constant value that was the indicator of the process completion.

The reference value of \( \xi \approx 100\% \) indicates to a strong bond between organics and other undesirable components in the substrate. The sludge treatment has been completed when the \( \xi \) index stabilizes and it is \( \approx 16\% \) (after drying to a moisture content of 35-45%). This has been achieved at \( p = 0.30-0.35 \) MPa after 8 h of treatment. The process is being implemented at \( p = 0.25 \) MPa also, but the treatment time increases to 11 h [6-8].

![Figure 2. The activity of enzymes \( \omega \) depending on temperature \( t \) and \( pH \).](image1)

![Figure 3. Change in \( \xi \) depending on the pressure and sludge treatment time.](image2)

In the course of statistical analysis of the experimental data presented in figure 3, a regression equation has been obtained, which characterize the dependence between \( \xi \) and the time of sludge treatment \( \tau \) at different pressures in the system:
\[ \xi = a \cdot e^{b \tau}, \]  
where \( a, b \) – coefficients of the regression equation (table 1).

### Table 1. The values and significance of the regression coefficients.

| Pressure \( \rho \), MPa | Coefficient Values | Student criterion |
|--------------------------|--------------------|-------------------|
| \( a \)                  | \( b \)            | \( \text{cr.} \)  |
| 0.20                     | 99.0               | -0.043            | 2.05 | 69704 | 30.3 |
| 0.25                     | 97.7               | -0.16             | 2.05 | 2870  | 4.7  |
| 0.30                     | 97.4               | -0.21             | 2.05 | 2068  | 4.5  |
| 0.35                     | 96.5               | -0.23             | 2.05 | 1877  | 4.4  |

\( \text{a Critical value} \)
\( \text{b Calculated value} \)

Comparing the calculated and critical values of the Fisher criterion \( F \) (table 2), it has been found that the obtained regression equation adequately describes the nature of the change in \( \xi \) depending on \( \tau \).

### Table 2. The results of regression statistical analysis.

| Pressure \( \rho \), MPa | \( R^2 \) | \( R \) | Pearson criterion \( \chi^2 \) | Cochrren criterion \( G \) | Fisher criterion \( F \) |
|--------------------------|---------|---------|-------------------------------|--------------------------|--------------------------|
| \( \text{calc.} \) a     | \( \text{calc.} \) b | \( \text{cr.} \) a | \( \text{cr.} \) b | \( \text{calc.} \) a | \( \text{cr.} \) b | \( \text{calc.} \) a | \( \text{cr.} \) b | \( \text{calc.} \) a | \( \text{cr.} \) b |
| 0.20                     | 0.96    | 0.98    | 2.50                         | 1.52                     | 3.84                     | 0.22 | 0.37 | 1.23 | 2.18 |
| 0.25                     | 0.99    | 0.99    | 1.76                         | 1.75                     | 3.84                     | 0.22 | 0.37 | 1.01 | 2.18 |
| 0.30                     | 0.97    | 0.98    | 4.90                         | 1.43                     | 3.84                     | 0.16 | 0.37 | 1.07 | 2.18 |
| 0.35                     | 0.98    | 0.99    | 5.30                         | 1.87                     | 3.84                     | 0.15 | 0.37 | 1.05 | 2.18 |

\( \text{a Critical value} \)
\( \text{b Calculated value} \)

It has been established that for all experiments the average relative error \( \bar{\delta} \) does not exceed 6%, and the obtained values of correlation coefficients \( R \) and determination \( R^2 \) are close to one, which indicates a close correlation between the values of \( \xi \) and \( \tau \).

According to the results of the calculation of \( \chi^2 \), it has been proved that the dependence of the \( \xi \) on the treatment time \( \tau \) does not contradict the normal distribution law, and according to the Cochren criterion \( G \), the influence of random factors on the objective function is insignificant and the hypothesis of homogeneity of variances is not rejected. The hypothesis about the significance of the regression coefficients is also not rejected, since \( t_p > t_{cr} \) (table 2).

The processing of the found coefficients by the method of polynomial regression analysis made it possible to derive a general equation for the dependence \( \xi \) on the sludge treatment time and working pressure in the system:

\[ \xi = 93.53 \cdot 1.01^{1/p} \cdot e^{(10.2 \cdot 6.8 \cdot 0.91 \cdot p - 6.8 \cdot 0.91 \cdot \tau)}, \]  
the solution is also presented in figure 3 (markers - experimental data; curves - theoretical data).

### 4. Conclusion

Analysis of researches, for example, [12, 13] indicates the reasonability of waste water and silt sludge application in agriculture as fertilizer irrigation or organic granular fertilizers in agricultural fields after deep cleaning and treatment. It has been proved that after deep multi-stage fermentation of organ-containing waste, the resulting substrate is an environmentally sound organic substance containing available forms of nitrogen (2.5%), phosphorus (4.2%), potassium (1.2%) and sulfur (up to 2 g/kg). In this regard, a research to assess the application effectiveness of processed sludge as a fertilizer for
agricultural crops is relevant in perspective.

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