

Запропоновано метод очищення стічних вод від сполук азоту і фосфору на дисковому біореакторі повного витіснення. Розроблений метод очищення стічних вод на біореакторі повного витіснення є дуже перспективним і може застосовуватися для очистки стічних вод, які містять велику кількість органічних речовин. Ефективність очищення мінерального азоту досягає 98,9 %, фосфатів до 40–50 %, зменшується вміст загального азоту в 4–6 разів і загального фосфору в 2–2,5 рази. Запропоновано сумісне очищення поверхневого стоку з сільськогосподарських угідь і побутових або промислових стічних вод на мульдах з фільтруючими насадками і на біореакторі повного витіснення.

Проведені мікробіологічні дослідження показали, що в процесі очищення сполуки азоту видаляються комплексно: в результаті нітри-денітрифікації та процесу аноксидного окиснення. Трансформація мінеральних сполук азоту при нітрифікації спостерігалася на поверхні біодисків у присутності кисню і всередині структурних елементів біодисків, що характерне для аноксидного окиснення під час процесу ANAMMOX. Ефективність очищення стічних вод з території сільськогосподарського використання складає: за завислими речовинами – 98 %; за мінеральним азотом – 99 %; за ХСК – 99 %; за фосфатами – 50 %. Схема очистки на мульдах і біореакторі повного витіснення може використовуватися для стічних вод молочної промисловості, тваринницьких ферм, комунального господарства і поверхневого стоку. Застосування запропонованих методів очищення стічних вод сприятиме оздоровленню водних екосистем

Ключові слова: поверхневий стік, сільськогосподарські угіддя, очистка, мульди, дисковий біореактор повного витіснення

METHOD OF AGRICULTURAL SEWAGE WATER PURIFICATION AT TROUGHS AND A BIOSORPTION BIOREACTOR

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1. Introduction

The problem of pollution of surface water affects all countries of the world. The main sources of pollution of water objects in agricultural areas are the surface runoff from cultivated lands, dairy farms and livestock farms and sewage water of communal utilities and industrial enterprises.

Application of mineral and organic fertilizers and pesticides leads to an inflow of a large amount of pollutants into water bodies. Sewage water from dairy farms and livestock farms contains organic matter pollutants, in particular nitrogen and phosphorus.

Human economic activity has led to intensive development of the near-riverbed territory for agricultural purposes. Excessive cultivation of land is a cause of the process of erosion. A significant amount of suspended particles and

biogenic substances gets to water bodies with a surface runoff from agricultural lands. This contributes to occurrence of shoals in rivers, a growth of large floodplains, narrowing of rivers and, as a result, flooding of low and plain-lowered areas of floodplains for a long time during high water periods and rain showers.

There are often livestock farms and dairy farms, agricultural processing enterprises and communality facilities in small towns and villages. Not only surface runoff from industrial sites of these enterprises enters water bodies, but also industrial sewage water discharges, which are not sufficiently purified or not purified at all.

An inflow of surface runoff from agricultural land is a significant cause of silting and pollution of water bodies. Specific features of a mode of formation and a way of an inflow of sewage water (rain or melt water) to water objects

complicates solution of the problem. Development of measures to reduce an inflow of untreated surface water in water bodies taking into account specific features of formation of this type of sewage water is an expedient issue for today.

The European Council Directive 91/676 as of 12.12.1991 on protection of waters against pollution caused by nitrates from agricultural sources requires EU States-Members to take measures to reduce a negative impact of agricultural sewage on sources of drinking water and aquatic ecosystems [1].

Development of a system of water protection measures that would protect rivers from erosion, silting and would facilitate interception and purification of surface runoff and sewage water, which contain biogenic substances, is an urgent task. Reducing of an impact of sewage water from agricultural land will make possible to improve the ecological status of water bodies significantly.

2. Literature review and problem statement

Development of industry and agriculture and a constant growth of urbanization lead to deterioration of the environment. One of the factors that cause pollution of the environment is rain and melt sewage water. Work [2] considered the ecological status of natural waters and methods for assessment of a pollution level of water bodies. But authors of the work did not pay enough attention to an influence of diffuse sources of pollution on the state of surface water.

Paper [3] presented new methods for determination of the environmental risk of deterioration of a state of river basins at the state, regional and local levels. There was analysis of causes of pollution of surface water carried out. Determination of the risk of welfare failure in an aquatic ecosystem made possible to improve water protection strategy [3]. But proposals for improvement of the water protection strategy contained only generalized provisions on a need to reduce a negative impact of surface runoff on aquatic ecosystems. There were no specific measures for sewage water purification in this paper.

There was a more detailed study on causes of surface water pollution in work [4]. Authors established that sewage water discharges, diffuse sources of pollution, economic use of water catchment area, climate changes, landscape and geographical features of river basins influence formation of natural water quality. A work showed that diffuse sources of pollution of surface water play significant role in deterioration of the state of aquatic ecosystems [4]. However, authors did not propose specific measures to reduce a load of diffuse sources of pollution on the ecological state of surface water.

The contamination of a surface runoff is unstable (it depends on an area of precipitation) and mainly depends on climatic conditions, relief, water catchment surface, soil type, etc.

Authors of paper [5] explored the Yarlung Zangbo River Basin (China), which was severely affected by climate change. They analyzed values of average temperature, precipitation and runoff using the Global Land Data Assimilation System (GLDAS). The results showed that rainwater is a major factor, which affects a change of natural runoff and river evolution facing the global warming. But the paper did not consider the issue of reducing of this negative factor on the Yarlung Zangbo River basin.

Authors of paper [6] stated that agricultural drainage water can cause pollution of surface water bodies with nitrogen and phosphorus. Constructed wetlands can help to

mitigate effects of agricultural diffuse sources of pollution and to remove various pollutants from sewage water. But the method of purification of surface water has significant disadvantages:

- built wetlands are artificial structures of a large size, which in turn requires large capital expenditures;
- complexity in maintenance (large areas require constant care);
- absence of any drainage system for drainage of rainwater, and as a result, slower filtration of runoff with possible floods and flooding of adjacent areas in spring;
- absence (or insignificant percent) of anaerobic processes of surface runoff purification.

It is possible to recommend this method of protection of water objects from effects of agricultural drainage water after additional research only.

An inflow of nitrogen and phosphorus from agricultural areas threatens aquatic ecosystems, especially in areas with high yields of agricultural crops, as in some areas of the Netherlands [7]. Work [7] proposed controlled drainage as an effective option for optimization of soil moisture conditions for agriculture and reducing of unnecessary losses of fresh water and nutrients. Authors of the work developed a small (1 ha) field experiment for the study on hydrological and chemical changes after introduction of controlled drainage [7]. But there are disadvantages of such experiment:

- a use of pumps to pump out excess runoff into reservoirs increased an economic component of this facility and increases maintenance costs;
- an experimental plant had the area of only 1 ha and this is not significant for agricultural land, and a use of larger areas of 100 ha or more may become very uneconomical;
- permanent silting of drainage pipelines with silt and iron oxides;
- there was no significant reduction in a concentration of nitrogen and phosphorus compounds after drainage, since the plant had the main task of slower distribution and filtration of runoff along the entire surface of the land and not purification of rain runoff.

We believe that controlled drainage does not solve the problem of contamination of water bodies with surface runoff from agricultural land.

Authors of patent [8] proposed Bi-phasic bioretention system as a method for purification of surface water. The system is an in-depth part of a relief (artificial or natural) in which, during rain falls, rainwater runoff accumulates from a surface of a water catchment. It is gradually infiltrated to the soil. This method uses anaerobic and aerobic methods for purification of rainwater runoff, which leads to the process of biodegradation for many organic contaminants. Purification goes not only for organic impurities, but also for inorganic substances. But this model does not pay attention to a use of filtering nozzles, because the main filter element is ordinary sand.

Paper [9] proposed a use of filtration nozzles in the form of basalt crumb, limestone, wood sawdust and polyurethane foam (PPU) as additional elements of rainwater purification to improve the purification process and a rate of filtration of natural or artificial depressions in soil, the so-called troughs. The papers showed improvement of efficiency of surface runoff purification with a use of polyurethane foam granules as a filtering nozzle. It is possible to use the method to purify surface runoff from both urbanized and agricultural land.

But measures used to purify surface runoff are not very effective for purification of sewage water, which contains a

large number of organic compounds, in particular nitrogen and phosphorus.

An impact of agricultural objects as sources of inflows of biogenic elements to watercourses increases with an increase in the amount of cultivated land with a use of mineral and organic fertilizers, with construction of farms and livestock complexes.

Processes of eutrophication of water bodies occur due to the inflow of biogenic substances, which in turn leads to negative consequences. Compounds of nitrogen and phosphorus intensify growth processes of most algae. Their dying leads to changes in organoleptic properties of water. We can observe the highest growth of aquatic organisms at the concentration of phosphorus of 0.09 to 1.8 mg/dm³, of nitrate nitrogen of 0.9–3.5 mg/dm³.

Authors of paper [10] conducted a study of nitrogen content in the Baltic Sea basin with a use of MESAW statistical model. The results showed that a total annual load was 570,000 tons of nitrogen in the Baltic Sea basin. The largest accumulation of nitrogen was in the basins of the Neva River (104,000 tons of nitrogen), 55,000 tons of nitrogen – in the Wisla River and 32 000 tons of nitrogen – in the Oder River. The results will make it possible for the Helsinki Commission (HELCOM) to improve its objectives in relation to nutrition in the Baltic Sea Action Plan (BSAP) and to identify cost-effective measures to reduce nutrients in the Baltic Sea better.

Article [11] presented results of the study on possibility of a use of filters for treatment of sewage water with a high ammonia content. There was a significant decrease in a content of organic substances, total nitrogen and ammonia, and the average removal efficiency of ammonia nitrogen varied from 73.6 to 80.3 % during purification. The efficiency of nitrogen removal varied from 74.4 to 79.8 %. The efficiency of phosphorus formation was low and varied from 32.0 to 33.7 % due to aerobic conditions during treatment. Studies confirmed the effectiveness of a use of filters for purification of sewage water with a high concentration of ammonia nitrogen. But the article did not considered efficiency of sewage water purification of other pollutants. We can recommend this method for a local purification of compounds of nitrogen and phosphorus only.

Paper [12] presented results of research on influence of electric current density and type of external source of carbon on removal efficiency of nitrogen and phosphorus from sewage water with physical and chemical parameters, which are characteristic for urban sewage water. Authors established that denitrification efficiency depends on a type and a dose of carbon and on density of electric current. A total content of phosphorus was removed in the processes of electrocoagulation and biomass growth. Using an electric current density of 210 mA/m² made it possible to reach 87.61 (±1.6) % denitrification efficiency and 97.69 (±2.1) % efficiency of de-phosphoring. We should note that this method of sewage water purification is energy-consuming. The use of electrocoagulation for purification of sewage on territories for agricultural purposes is economically inappropriate.

Sewage water from agricultural land, from processing enterprises, dairy farms and livestock farms, residential buildings and melioration systems gets into water bodies. This problem requires a comprehensive solution. A use of separate measures for purification of surface runoff from agricultural lands and purification of domestic sewage water is not an effective solution to this problem.

Analyzed modern methods for purification of sewage water from biogenic substances are energy-consuming, expensive, complex in operation and therefore unsuitable for a use in countryside. Therefore, it is necessary to develop a method for purification of agricultural sewage water of biogenic substances, which is effective, easy to operate and economically attractive.

3. The aim and objectives of the study

The objective of the study is to develop a method for purification of agricultural sewage water of biogenic substances on troughs and a bioreactor of full displacement.

We set the following tasks to achieve the objective:

- improvement of the technology of purification of sewage water formed on agricultural lands;

- determination of efficiency of purification of sewage water of nitrogen and phosphorus compounds on a disk bioreactor of full displacement;

- determination of possibility of implementation of an integrated method of purification of agricultural sewage water on troughs and a bioreactor of full displacement.

4. Methods for purification of sewage water from agricultural lands

4.1. Development of a method for purification of sewage water of nitrogen and phosphorus compounds on a disk bioreactor of full displacement

A large amount of compounds of nitrogen and phosphorus gets into water objects with surface runoff from agricultural lands. This contributes to eutrophication of water bodies. Phosphorus stimulates absorption of nitrogen by plants, increased algae growth, which leads to pollution of water bodies. We observe the highest growth of aquatic organisms at the concentration of phosphorus of 0.09 to 1.8 mg/dm³, nitrate nitrogen of 0.9–3.5 mg/dm³.

An influence of agricultural objects as sources of biogenic elements for watercourses increases with an increase in the amount of cultivated land, with a use of mineral and organic fertilizers and with construction of farms and livestock complexes.

There are known and often used methods that reduce the concentration of compounds of nitrogen and phosphorus in sewage water, which gets into water objects. But all of them have their disadvantages due to formation of intermediate by-products and insufficient depth of removal of pollutants.

We propose using a disk bioreactor of full displacement to increase efficiency of removal of nitrogen and phosphorus compounds.

We performed experimental studies on removal of nitrogen and phosphorus compounds from the model runoff under anoxide conditions in a disk bioreactor.

We carried out studies on a laboratory plant, which was a horizontal bioreactor of the disk type (Fig. 1). The bioreactor had a recirculation pump. The capacity of the bioreactor was 72 dm³/day, the volume of the reactor operation area, which was filled with purified water, was 17 dm³ (Fig. 1).

The bioreactor equipped with disks made of polycarbonate had a cell surface for maintenance of biomass. We calculated the distance between disks so that the biomass immobilized on one disk was not encountered with the

biomass of the adjacent discs. That is, the width of walls of cells of the biodisk and the distance of one disk from another one was 10 mm. The number of disks was 24 pcs. with a diameter of 280 mm. When sewage water or a model solution automatically went to the bioreactor, discs rotated so that part of the disk was in water (40 % of the disk area) and the other part was on the surface. Thus, biomass immobilized on discs contacted in turn with water and atmospheric air.

The feature of the purification process was absence of forced supply of air in the reactor. Oxygen came directly from atmospheric air.

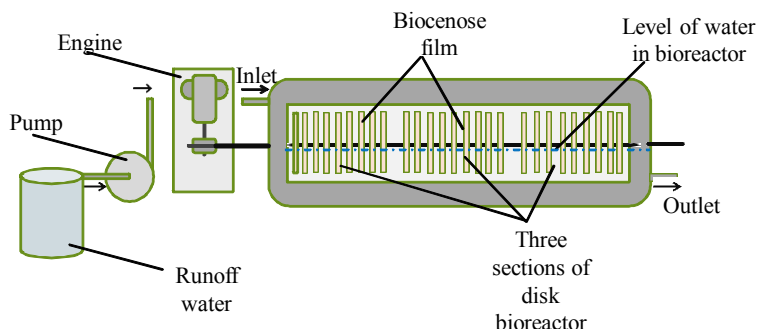


Fig. 1. Scheme of the laboratory disk reactor for bioabsorption purification of full displacement

We filled the reactor with an active silt of local biological structures and with adapted biomass of ANAMMOX complex previously grown under anoxide conditions. The suspension of the biomass of ANAMMOX complex and active silt was absorbed on constantly rotating discs. At the beginning, we added a model mixture, which consisted of mineral components only (with absence of organic compounds), to the reactor. It operated under periodic conditions of the closed mode.

The source of power and energy for microorganisms were nitrogen compounds of ammonium, nitrate, phosphate, potassium, and magnesium compounds. Biomass was absorbed and adapted on the surface and inside discs within a few weeks (Fig. 2).



Fig. 2. Bioreactor disks with immobilized biomass

There was a change in the biocenoses during this period. Microorganisms that needed an organic source of power died or were removed from the system, or sorbed on the surface of disks in the form of biofilm, but they were in inactive anabiotic state.

We monitored the purification process by the following indicators: CCO, BCO₅, ammonium nitrogen, nitrates,

nitrites, total nitrogen, phosphates, pH, dissolved oxygen, biomass density of biocenoses.

We controlled the process of biomass adaptation and removal of nitrogen compounds from the model solution by dynamics of ammonium nitrites and nitrates. Outside, immobilized biomass was a thin whitish layer of light-milky color.

At the second stage, we added a model solution, which contained organic compounds – proteins, fats, carbohydrates, ammonium nitrogen, nitrites, nitrates, phosphates, etc. to the plant with immobilized biomass on disks. The bioreactor operated in the flow mode.

4. 2. Development of an integrated method of purification of agricultural sewage water on troughs and a bioreactor of full displacement

Sources of surface water pollution in agricultural areas are surface runoff from agricultural land, from industrial sites of dairy farms and livestock farms, from processing enterprises, housing sector, and household sewage water.

We propose to use in-depth areas of the relief (troughs) to purify surface runoff. Troughs must purify the primary surface runoff of suspended matter, organic compounds of various types and a small percentage of inorganic substances (generally by ion exchange). Drainage water, which pass through troughs, falls into the drainage sewage system and can be supplied then to local sewage water purifying plants or to be disposed to a water object (if it meets quality criteria).

Authors of work [9] proposed to increase efficiency of surface runoff purification by application of filter nozzles of different types. Polyurethane granules (PPUs) have the highest purification efficiency (CCO – 83.5 %, petroleum products – 96 %, suspended matter – 98 %) [9].

The schematically presented plant includes the surface layer of soil and the filtration zone with corresponding filtration elements (nozzles), which leads to an increase in adsorption of organic matter and as a result more qualitative purification (Fig. 3). We can divide the plant into two zones – aerobic one and anaerobic one.

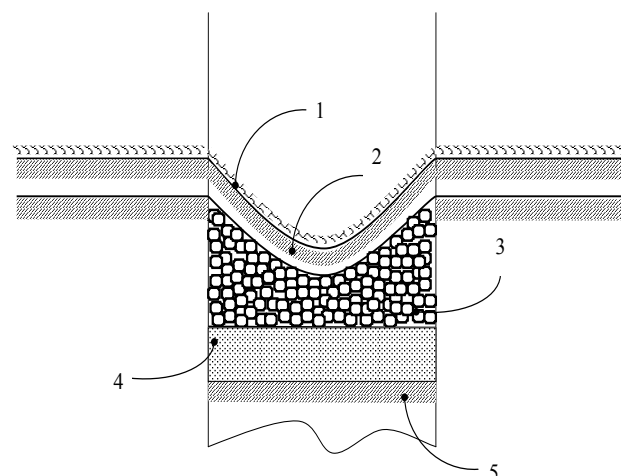


Fig. 3. Scheme of bio-trench: 1 – vegetation cover, 2 – upper layer of soil, 3 – filtration area, 4 – layer of sand mixture, 5 – lower layer of soil

The aerobic zone includes a vegetation cover, an upper layer of soil, a filtration area, where the main purification

process occurs. Sizes of each zone form based on definition of a catchment area and required amount of rain that will enter a plant. The layer of sand mixture refers to the anaerobic zone. The anaerobic zone receives sewage water purified on polyurethane granules and it is an element of pre-purification, after which purified runoff is filtered to the lower layer of soil.

Purification processes occur in the aerobic zone by deposition of suspended substances on a surface of the vegetation cover, adsorption of contaminants on granules of PPU and aerobic biodegradation. If the upper layer of soil has significant infiltration ability (5 cm/h or more), aerobic purification capabilities will be maintained. Otherwise, anaerobic conditions may emerge, which will not give possibility to filter rainwater runoff more quickly. Accumulation of water on the surface of soil will continue and, as a result, reproduction of water insects in the deepened area of the structure occurs.

A use of only these methods will not provide full purification to the established norms and standards, because infiltration purification plants do not filter some pollutants. Therefore, we advise to combine the filtration method on troughs with a disk biofilter, which is more aimed at purification from large concentrations of organic contaminants (Fig. 4).

We consider it expedient to use such a system of surface runoff purification in combination with household sewage water or industrial sewage water, which contain a large amount of nitrogen and phosphorus (for example, from dairy enterprises).

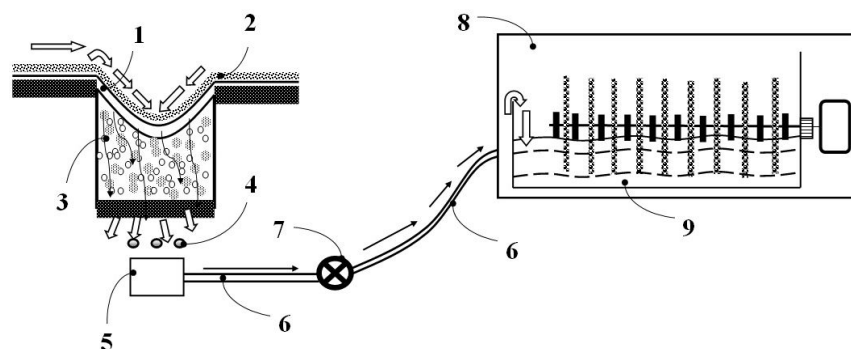


Fig. 4. Scheme of application of infiltration methods of purification of surface runoff by local purification plants: 1 – structure for purification of surface runoff; 2 – upper layer of soil (green plantations); 3 – filtering elements of structure (nozzles); 4 – drainage pipes, which make it possible to faster remove the purified runoff; 5 – accumulating capacity; 6 – system of pipelines from a rain sewage network to local purification structures; 7 – pump(s) for pumping of rain runoff in case of large deviation of a surface; 8 – system of local purification structures; 9 – disk bioreactor of full displacement

Sewage water from agricultural land (surface runoff from cultivated land, industrial sites, residential sector, and household water) comes to troughs with filtering nozzles. It is possible to install troughs near each source of pollution; both diffuse pollution (surface runoff) and point pollution (enterprises of processing of agricultural products, dairy farms and livestock farms, communal facilities, etc.). Sewage water passes through the top layer of soil, filtering nozzles and enters the storage tank. Further, it goes through the system of pipelines from the rain sewage network and enters to the local purification plant on a disk of bioreactor of full displacement. This purification scheme is easy to apply, economically attractive and environmentally friendly for agricultural areas.

5. Results of studying the efficiency of methods of purification of sewage water from territories for agricultural purposes

5. 1. Efficiency of sewage purification on disk bioreactor of full displacement

We pumped a model solution to the reactor with an immobilized biofilm in a flow mode. Purified water went to the settling tank by natural stream after contact with immobilized biomass. We did not foresee return of active silt, because died cells were removed by themselves from the purification zone, but viable organisms were fixed on the surface and inside the carrier (Fig. 1).

We controlled duration of a contact of the model solution with immobilized biomass by flow velocity and calculated it based on a load on biomass by BCO₅ indicator.

During several days, we observed an intensive growth of biomass on disks and a significant reduction in BCO₅ integral index in purified water, including reduction of nitrogen compounds. Spent active silt, residual biomass formed on disks during the process of water purification was unilaterally removed during movement of water without additional influence. Table 1 presents the results of the analysis of water purification of nitrogen compounds by immobilized biocenoses in the laboratory bioreactor.

Table 1

Indicators of water purified in the laboratory bioreactor by immobilized adapted biocenoses

No. of experiment	Duration of purification, h	units of pH	N-NO ₂ ⁻ , mg/dm ³	N-NO ₃ ⁻ , mg/dm ³	N-NH ₄ ⁺ , mg/dm ³	PO ₄ ³⁻ , mg/dm ³	CCO, mgO/dm ³	BCO ₅ , mgO ₂ /dm ³	N _{tot} , mg/dm ³	P _{tot} , mg/dm ³
1	0	6.52	0.091	3.54	38.07	32.4	1200	620	68.5	56.1
	3	8.33	0.04	<0.5	2.4	29.47	–	–	–	–
	4	8.63	<0.03	<0.5	0.42	16.77	–	–	–	–
	5	8.38	<0.03	<0.5	0.17	18.8	21	10	11.2	22.0
2	0	4.09	<0.03	1.81	25.0	34.4	600	420	53.8	48.6
	2	6.86	<0.03	0.54	1.23	37.6	–	–	–	–
	3	8.07	<0.03	<0.5	0.63	21.9	–	–	–	–
	4	8.18	<0.03	<0.5	0.56	19.2	80	10	14.0	24.16
3	0	7.40	0.37	19.61	12.25	3.75	38.0	–	–	–
	3	7.52	0.30	9.25	1.36	1.81	–	–	–	–
	5	7.92	<0.03	<0.5	0.5	–	22.0	–	–	–

The results of the experiment showed that during the purification process:

- a value of active reaction of the medium changed significantly to the side of the alkali, which is typical for processes of denitrification and anoxide oxidation of nitrogen;
- total removal of mineral nitrogen reaches in average 98.9 %;
- total nitrogen decreases by 4–6 times;
- reduction of phosphates reaches 40–50 %;
- there was a decrease in total phosphorus by 2–2.5 times.

We measured the content of nutrients and organic substances every hour during the experiment. We constructed curves of the dependence of purification efficiency on duration of purification (Fig. 5) based on experimental data.

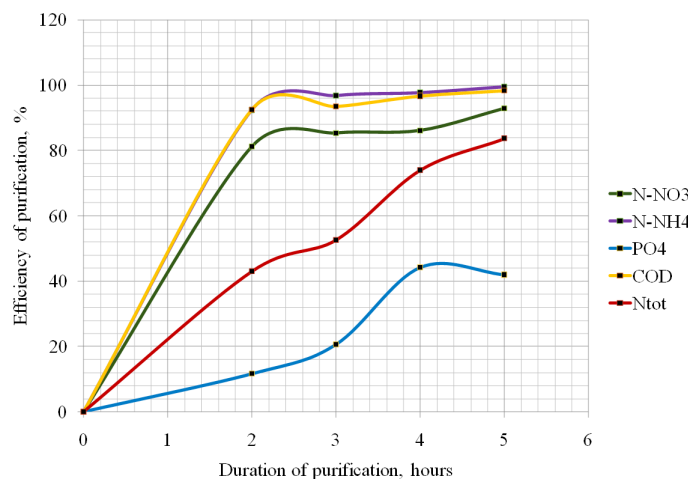


Fig. 5. Graph of the dependence of purification efficiency on duration of purification of sewage water under anoxide conditions of the disk bioreactor

We obtained the dependences of purification efficiency on duration of purification:

- for $N-NO_3$:

$$Y = 27,878Ln(x) + 51,458, \quad (1)$$

where Y is the purification efficiency, %; x is the duration of purification.

correlation coefficient: $R=0.839$;

- for $N-NH_4$:

$$Y = 25,065Ln(x) + 60,052 \quad (2)$$

correlation coefficient: $R=0.84$;

- for PO_4 :

$$Y = 3,475e^{0.559(x)} \quad (3)$$

correlation coefficient: $R=0.958$;

- for CCO :

$$Y = 22,751Ln(x) + 64,369 \quad (4)$$

correlation coefficient: $R=0.831$;

- for N_{tot} :

$$Y = 38,504Ln(x) + 17,976 \quad (5)$$

correlation coefficient: $R=0.993$.

We obtained mathematical dependences of purification efficiency on purification duration using the EXCEL software, and correlation coefficients – using the software STATISTIKA. It is advisable to clarify the dependences obtained on a larger number of factual data for further practical use.

If we consider dynamics of transformation of total elemental nitrogen ($N-NH_4$, $N-NO_2$ and $N-NO_3$) during purification for 4 to 5 hours, we can note reduction by more than 41.0 mg/dm^3 (from 41.70 mg/dm^3 in source water, up to 0.7 mg/dm^3 in purified water) with about 30 mg/dm^3 of nitrogen spent for oxidation of organic substances. Thus, we can assume that we removed more than 10 mg/dm^3 of molecular nitrogen from sewage water during purification. Due to the lack of sufficient quantities of organic compounds and oxygen in water at the end of the purification, the process of oxidation of ammonia nitrogen occurs and residual nitrogen concentrations are removed in the form of N_2 gas molecules due to this process.

We observed processes of anoxide oxidation of ammonium by bacteria of ANAMMOX complex as a result of contact of adapted biocenoses with model sewage and sewage water under conditions of low concentrations of oxygen and organic substances in the medium.

Indicators of nitrogen ammonia and BCO_5 reached the normative values for discharge into water objects in the purified water.

5.2. Experiment results of improvement of the method for purification of sewage water formed on agricultural territories

We carried out microbiological studies to determine efficiency of purification of sewage water from agricultural territories.

We divided the bioreactor conventionally into 3 zones in dependence on time spent by purified water in it to monitor transformation processes of nitrogen compounds and to determine density of immobilized biomass. We attached removable markers to disks of each of three zones. Markers were fragments of polycarbonate with known area and weight. Biomass sorbed on the markers just like on disks, its microorganisms participated in the purification of the model sewage. Each zone corresponded to different periods of contact of purified water with biomass: there was water purification for 1–2 hours in the first zone, 2–3 hours – in the second zone and 3–4 hours – in the third one. We determined in the course of the study that the density of biomass immobilized on disks varied during the flow of water. The biomass density was 3.72 mg/cm^2 on disks of the first zone, 0.32 mg/cm^3 – on disks of the second zone, 4.62 mg/cm^3 – on disks of the third zone. We can explain this by the fact that an intensive process of oxidation of organic substances occurred in the first zone and heterotrophic bacteria developed in biocenoses mostly. Their metabolism was aimed to a constructive exchange, that is why we observed the biomass increase. The second zone received water with a lower concentration of organic substances, which caused a change of biocenoses by the trophic level – autotrophic bacteria, which use energy due to oxidation of ammonia, probably became activated. In the third zone, we observed the highest density of immobilized biomass, but the black color indicated accumulation of biomass died out with formation of hydrogen sulfide. But this biomass disappeared from the reactor itself with time.

We carried out bacteriological studies of biomass to determine taxonomic groups of immobilized microorganisms, which participated in transformation of chemical compounds of the model sewage.

We removed markers from the bioreactor. We took off the biomass from them and analyzed it for presence of heterotrophic microorganisms, autotrophic ones (ammonifiers, nitrification agents, denitrifiers and microorganisms of ANAMMOX complex) for determination of group composition of immobilized bacteria.

To determine the growth of these bacteria, we took 0.5 g of biomass from each marker, stirred it in 10 ml of sterile water and prepared decimal dilutions (the method of limiting dilutions). Then, we carried out sowing of suspensions on nutrient media: nutrient agar (for determination of ammonifiers), Vinogradskiy medium (for determination of nitrification agents), Hiltey medium (for determination of denitrifiers), and the selective medium for microorganisms of ANAMMOX complex. The cultivation conditions for denitrifiers were for:

- heterotrophs – 24 hours at temperature of 37 °C;
- ammonifiers and nitrification agents – 7 days at a temperature of 28 °C;
- denitrifiers – 7 days at a temperature of 28 °C;
- bacteria of ANAMMOX complex – 2 weeks.

After cultivation, we determined presence of microorganisms based on the following:

- for heterotrophs – by a growth of colonies in the nutrient medium;
- for ammonifiers – by the presence of NH⁴⁺ and H₂S in the medium;
- for nitrification agents – by the presence of NO₂⁻ and NO₃⁻ in the medium;
- for denitrifiers – by the presence of NO₃⁻, gas and pH in the medium;
- for bacteria of ANAMMOX complex – by the presence or absence of NH⁴⁺ and NO₃⁻ in the medium.

Tables 2–5 give results of analysis on the presence and density of microorganisms, which transform nitrogen compounds.

Table 2

Indicators of growth of nitrifying bacteria during water purification in the bioreactor

Place of taking sample in the bioreactor	Sowing repetition	Decimal dilution								The most probable number of bacteria in 1 g of biocenoses
		1:10 ²		1:10 ³		1:10 ⁴		1:10 ⁵		
		signs of development of nitrification agents								
		NO ₂ ⁻	NO ₃ ⁻	NO ₂ ⁻	NO ₃ ⁻	NO ₂ ⁻	NO ₃ ⁻	NO ₂ ⁻	NO ₃ ⁻	
Zone 1	1	-	-	-	-	-	-	-	-	9.5·10 ⁵
	2	-	-	-	-	-	-	-	-	
	3	+	+	+	-	-	-	-	-	
Zone 2	1	+	+	+	-	-	-	-	-	4.5·10 ⁴
	2	+	+	+	+	+	+	-	+	
	3	+	+	-	+	+	+	-	+	
Zone 3	1	-	-	-	-	-	-	-	-	2.5·10 ⁴
	2	-	-	-	-	-	-	-	-	
	3	+	-	-	-	-	-	-	-	

Notes: “+” – presence of a sign; “-” – absence

Table 3

Indicators of growth of ammonifying bacteria during water purification in the bioreactor

Place of taking sample in the bioreactor	Sowing repetition	Decimal dilution											The most probable number of bacteria in 1 g of biocenoses	
		1:10 ²			1:10 ³			1:10 ⁴			1:10 ⁵			
		signs of development of nitrification agents												
		Turbidity, sediment	NH ⁴	H ₂ S	Turbidity, sediment	NH ⁴	H ₂ S	Turbidity, sediment	NH ⁴	H ₂ S	Turbidity, sediment	NH ⁴	H ₂ S	
Zone 1	1	+	-	-	+	-	-	+	-	-	+	-	-	15.5·10 ⁴
	2													
	3	+	-	-	+	-	-	+	-	-	+	-	-	
Zone 2	1	+	+	+	+	+	+	+	+	+	+	-	-	9.5·10 ⁷
	2													
	3	+	+	+	+	+	+	+	+	+	+	-	-	
Zone 3	1	+	+	+	+	+	+	+	+	-	+	-	-	1.5·10 ⁴
	2	+	+	+	+	+	+	+	+	+	+	-	-	
	3	+	-	-	+	-	-	+	-	-	+	-	-	
	2	+	+	+	+	+	+	+	+	+	+	-	-	

Table 4

Indicators of growth of denitrifying bacteria during water purification in the bioreactor

Place of taking sample in the bioreactor	Sowing repetition	Decimal dilution												The most probable number of bacteria in 1 g of biocenoses		
		1:10 ²			1:10 ³			1:10 ⁴			1:10 ⁵					
		signs of development of nitrification agents														
Gas emission	NO ₃ ⁻	pH	Gas emission	NO ₃ ⁻	pH	Gas emission	NO ₃ ⁻	pH	Gas emission	NO ₃ ⁻	pH	Gas emission	NO ₃ ⁻	pH		
Zone 1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.5·10 ⁵
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Zone 2	1	+	+	+	+	+	+	+	+	+	+	+	-	-	-	110.0·10 ⁷
	2	+	+	+	+	+	+	+	+	+	+	+	-	-	-	
Zone 3	1	+	+	+	+	+	+	+	+	+	-	+	-	-	-	140.0·10 ⁷
	2	+	+	+	+	+	+	+	+	+	+	+	-	-	-	
	3	+	+	+	+	+	+	-	+	-	-	+	-	-	-	

Table 5

Indicators of group composition of bacteria immobilized on bioreactor disks

Duration of purification, h	Heterotrophic bacteria, cells/g	Ammonifiers, cells/g	Nitrification agents, cells/g	Denitrifiers, cells/g	ANAMMOX-complex bacteria, cells/g
1–2 (Zone 1)	6.6·10 ⁹	1.5·10 ⁵	9.5·10 ⁵	9.5·10 ⁵	absent
2–3 (Zone 2)	2.6·10 ⁵	9.5·10 ⁷	4.5·10 ⁴	11.0·10 ⁷	present
3–5 (Zone 3)	2.8·10 ³	9.5·10 ⁴	2.5·10 ⁴	14.0·10 ⁷	present

Microbiological biomass research on group composition showed presence of heterotrophic microorganisms and all groups of nitrogen-transforming bacteria-ammonifiers, nitrification agents and denitrifiers in all three zones. There was also an increase in bacteria of ANAMMOX complex on the selective medium. Data in Table 5 shows that the highest concentration of heterotrophic microorganisms was in the first two hours of purification, it was 6.6·10⁹ cells/g. Density of heterotrophs decreased to 2.8·10³ cells/g during 3–5 hours of purification. We can explain this by the decrease in organic matter in a water flow. We could observe ammonifiers, nitrification agents and denitrifiers agents throughout the whole purification chain, but their density also varied. The highest density of ammonifiers was in 2–3 hours of purification and further it showed a tendency to decrease. The highest density of nitrification agents was in the first two hours of purification and then it began to decrease. The density of denitrifying bacteria, on the contrary, increased in the process of purification. Bacteria of ANAMMOX complex were isolated from biomass of the second and third markers, that is, their manifestation was in 2–3 hours of purification.

Thus, microbiological biomass studies showed presence of all groups of bacteria that transform nitrogen compounds – ammonifiers, nitrification agents, denitrifiers in all three zones. In addition, in 2–3 hours of purification, there was a presence of bacteria of ANAMMOX complex.

We should note that a natural change of the biocenoses occurred in the process of purification. The change depended on a change of substrate during the purification process.

There was an oxidation of organic matter and beginning of nitrification in the first conditional zone. Further, there was anaerobic oxidation of ammonium in presence of carbon sources and nitrates in the depths of the biofilm immobilized inside the carrier. And there was anoxide oxidation (ANAMMOX process) in the final zone under conditions of low oxygen content with residues of organic compounds and presence of ammonia and nitrites. The concentration of biomass in the bioreactor was 9–15 g/dm³.

Table 6 provides data on efficiency of purification of sewage formed on the territory for agricultural purposes with a use of troughs and a bioreactor of total displacement.

The results of the experiment showed that during the purification process:

- the concentration of organic substances decreased mainly due to filtration methods (purification 83.5 %), as well as suspended substances (purification is 98 %);
- the value of active reaction of the medium changed to the side of alkali significantly, which is typical for processes of denitrification and anoxide oxidation of nitrogen;
- total removal of mineral nitrogen reached in average 98.9 %;
- general nitrogen decreased by 4–6 times;
- reduction of phosphates reached 40–50 %;
- there was a decrease in general phosphorus by 2–2.5 times.

Table 6

Efficiency of purification of sewage water from agricultural territory on troughs and a bioreactor of full displacement

Purification of sewage water	pH	Suspended substances, mg/dm ³	N-NO ₂ ⁻ , mg/dm ³	N-NO ₃ ⁻ , mg/dm ³	N- NH ₄ ⁺ , mg/dm ³	PO ₄ ³⁻ , mg/dm ³	CCO, mgO/dm ³	BCO ₅ , mgO/dm ³	N _{tot} , mg/dm ³	P _{tot} , mg/dm ³
Inflowing sewage water	6.52	280	0.091	3.54	38.07	32.4	1200	620	68.5	56.1
Purified water	7.40	<5	<0.03	<0.5	0.56	19.2	<10	10	14.0	24.16

6. Discussion of the need for application of the proposed methods of surface water purification

The use of the proposed methods for purification of surface runoff is very relevant, especially in areas with a missing or poorly functioning sewage system. Introduction of the proposed methods is appropriate for purification of surface runoff from agricultural land, small farms, garbage dump sites and forest fires.

The reasons for prospects of the use of troughs for surface runoff purification are ease of introduction and operation, efficiency of purification and economic availability.

We offered improvement of these structures by means of application of filtering nozzles. The conducted experimental studies showed that the greatest purification effect shows the use of filter nozzles of polyurethane granules [9].

We know that surface runoff from agricultural land also contains a large amount of biogenic substances and gets to water without purification in practice. Therefore, introduction of the proposed purification scheme has the following objectives:

- reduction of the negative influence of rain and melt sewage water on water objects and groundwater by reduction of inflowing pollution substances;
- application of the proposed purification scheme in arid areas will make possible to restore and increase groundwater resources due to a more effective system of rainwater sewage;
- the proposed scheme of purification is economical and easy to use;
- it is possible to apply a combined purification of surface runoff and household sewage water in agricultural areas and agricultural processing enterprises.

The conducted studies showed that purification in a disk bioreactor is expedient to use without regeneration mode, since biocenoses creates corresponding trophic chains that regulate the amount of biomass in the immobilized layer eliminating a need for mechanical purification of a carrier.

But we should note that after a certain amount of sewage water passed through a laboratory plant (simulation of the purification process in troughs), we observed a silt raid, both on the surface of the upper layer and on particles of filter nozzles (PPU granules). We should note that we found this in all experimental columns already after the main experiment. We should consider this phenomenon as a negative aspect of the use of this type of plants. And further it is necessary to provide work on purification and recovery of filter materials and a surface of filtration. Experiments on the study of properties and an influence of silting on the process of purification of rainwater sewage will be the subject of study for future work.

7. Conclusions

1. We developed a method for purification of sewage water, including rain and melt water, which contain a significant amount of nitrogen, phosphorus and other organic substances, on a bioreactor of full complete displacement. The essence of the method consists in biochemical processes, which pass within a volume of one structure. Nitrite-denitrification processes, processes of destruction of organic compounds, a process of anoxide oxidation of ammonium with participation of ANAMMOX bacterial complex and partial dephosphocation occur in the biosorption reactor. Also, distinguishing features of the method are its economy, absence of necessity for oxygen supply, mobility, compactness and environmental friendliness.

We carried out laboratory studies on the model sewage, which was close to actual sewage water by the content of biogenic substances. The results of the experiment showed efficiency of purification of mineral nitrogen (98.9 %), total nitrogen in 4–6 times, phosphates up to 40–50 % and total phosphorus by 2–2.5 times. The presence of an immobilized biomass of ANAMMOX complex and its ability to adapt to the unstable composition of sewage water affect purification efficiency.

The method of sewage purification in the bioreactor of full displacement is very promising. We can apply it both at dairy enterprises, in communal utilities or for purification of surface runoff from agricultural land, which also contain a large amount of organic substances.

2. We proposed combined purification of surface runoff from agricultural lands and domestic or industrial sewage water on troughs with filtering nozzles of polyurethane granules and a bioreactor of full displacement. A use of these type of nozzles will improve a rate of infiltration and increase efficiency of purification for such types of plants.

The conducted microbiological studies of biomass showed presence of all groups of bacteria that transform nitrogen compounds – ammonifiers, nitrification agents, denitrifiers in all three zones. Also, there were bacteria of ANAMMOX complex observed for 2–3 hours of purification.

Efficiency of purification of sewage water from territories of agricultural purposes is: by suspended substances – 98 %; by mineral nitrogen – 99 %; by CCO – 99 %; by phosphates – 50 %. The proposed purification scheme is economically attractive, environmentally friendly; it does not require large areas and difficulties in operation.

Introduction of the proposed methods of surface runoff purification will help to protect water objects from pollution, sedimentation, and eutrophication and will promote improvement of surface water.

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