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RELIABLE AND ACCESSIBLE POINT-OF-USE WATER DENITRIFICATION SYSTEM

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This paper describes the design and operation of a reliable and accessible point-of-use water denitrification system. The system includes a U-shaped submersible denitrifying biofilter and a bubble-film extractor. The biofilter utilizes the combined actions of denitrifying, sulfate-reducing, and sulfur bacteria. Denitrifying bacteria convert nitrates into nitrogen gas and reduce the calcium hardness of water in proportion to the nitrate concentration. When the water is contaminated with both nitrates and sulfates and the bacterial community receives excess nutrients (ethanol), some sulfates are converted into hydrogen sulfide. This process facilitates the removal of heavy metal ions from the water in the form of hydrosulfides. When the sulfate-reducing bacteria produce excess hydrogen sulfide, the sulfur bacteria convert it into colloidal sulfur at the biofilter outlet. The bubble-film extractor removes colloidal sulfur, heavy metal hydrosulfides, calcium carbonate dispersions, and hydrogen sulfide from the filtrate. The system is user-friendly, requiring no special skills or knowledge for installation and maintenance. The proposed system demonstrates cost-effective denitrification and water polishing over long-term use.

Keywords: denitrification, water treatment, biofiltration, bubble-film extraction, cost-effective device.

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Introduction

Nitrogen is one of lives six most important chemical elements and accounts for 3% of the human body weight. It is a part of proteins, nucleic acids, and ATP. However, when nitrogen enters the human body in large doses of nitrate ions with food and drinking water, it poses a health hazard [1].

Nowadays, severe techno-genic pollution of surface and groundwater with nitrates occurs worldwide [2]. The application of nitrogen fertilizers in field farming continues, as does the discharge of insufficiently purified household industrial and livestock nitrogen-containing effluents into natural reservoirs. As a result, the nitrogen cycle breaks, and an increasing amount of nitrates enters the groundwater. The population living without a centralized water supply and sewerage are at main risk because their liquid household waste is disposed of through simple cesspools and septic tanks. This practice increased nitrate concentration in upper aquifers in residential areas by up to hundreds of milligrams per liter [2]. The maximum permissible concentration of nitrates in drinking water is 45 mg/dm^3. Therefore, the population must either buy very costly bottled water or have equipment for denitrification to bring raw water quality indicators up to sanitary and hygienic standards.

To solve the problem, one can use reverse osmosis, electro dialysis, catalysis, and adsorption on the surface of natural and synthetic materials [3]. Each of these methods makes it possible to reduce the concentration of nitrates in water to physiologically acceptable values. However, only reverse osmotic and ion exchange systems have become widespread and most suitable for operation at decentralized water treatment. The advantages of these systems are simple to service and convenient construction, which allows quick replacement of outworn membranes and resins.

At the same time, these two systems, which are in widespread use, also have disadvantages. In particular, there are no anion exchange resins with higher selectivity to nitrate ions than anions usually present in groundwater. The effect of this factor in the course of ion exchange treatment of water significantly violates its mineral composition. There is also no way to regenerate ion-exchange resins without additional environmental pollution by washing water. As for using reverse osmotic systems for water denitrification, their membranes retain all other ions significantly better than the NO_3^- ions and are better applicable for total dissolved solids removal [4]. Therefore, to avoid receiving water with a depleted mineral composition, additional procedures are required. If calcium, magnesium, and iron ions concentrations exceed MAC, reverse osmotic membranes also need water pretreatment. The mentioned limitations require the search for new improvements in nitrate water treatment's point-of-use and point-of-entry systems.

This paper describes the design and function of a newly developed point-of-use/point-of-entry denitrification biofilter modernized by a bubble-film extraction unit for the filtrate post-purification. This innovative system ensures the removal of nitrates and related impurities from problematic water sources for its use as drinking water.

Biological denitrification is widely used in centralized drinking water supply (DWT) and sewage treatment plants (SWT) due to its high selectivity and efficiency up to 100%. Heterotrophic and autotrophic bacteria denitrify water, acting in attached or free-floating states. The heterotrophic bacterial colonies have higher denitrification performance.

The first biological denitrification pilot plant for drinking water started work in France in 1983 [5]. Since the 1980s, water experts in many countries have built similar industrial biological denitrification plants for drinking water supply [6]. The principle of their operation always includes denitrification of water under anoxic conditions and its subsequent treatment under aerobic conditions and sterilization by standard methods.

Generally, biological denitrification require strict compliance with the water treatment conditions. These relate to nitrate concentration, filtration rates, dissolved oxygen (DO) concentration in the treated water [7] and doses of electron donors and consumable carbon. Variations in these factors can enable or inhibit bacterial metabolism with oxygen uptake from nitrate ions for cell respiration and growth.

Today, centralized drinking water treatment plants (DWTPs) and sewage water treatment plants (SWTs) use different technological schemes of biological denitrification. These schemes explore single and mixed bacterial cultures [8]. Their application experience has revealed the characteristics of the processes in systems with fixed and floating filtration loads.

In systems with densely packed biofilter beds, biofouling slime can block the pore space during operation. If the preventive flushing is not strong enough, than channeling occurs. This is when part of the biofilter bed loses its functionality due to the formation of passages with reduced hydraulic resistance. Nitrogen gas bubbles can also block the pore space of the biofilter when they released by denitrifying bacteria because of respiration. As the size of the bubbles increases, gas plugs form and block biofiltration. The smaller the particle size of the biofilter bed, the more this phenomenon interferes with the operation of the submerged biofilter [9]. Main and circulation pumps provide the hydraulic water retention time inside the biofilter and the required water flow when washing the biofilter grains from the excess of the resulting biomass. Dosing units supply macro and micronutrients for bacterial nutrition. These factors are crucial in nitrate removal efficiency from the water.

Fluidized bed reactors do not have of stated disadvantages. However, the flow rate of the denitrified water must be high. Recirculation makes it possible to ensure the required hydraulic retention time at the water treatment. Alternatively, several units are connected in series. Fluidized bed reactors increase the denitrification efficiency, but are complex in design.

In point-of-use or point-of-entry systems, the peripherals can be very expensive compared to the biofilter itself. Therefore, a packed bed submerged biofilter with a specific grain size and exceptional design is the best option for decentralized water denitrification. This biofilter allows different bacterial colonies to be in an active state along the length of the biofilter with an appropriate concentration of dissolved oxygen in the denitrified water. Clogging and channeling of the filter bed avoids by correct selecting specific parameters such as grain shape and size, equipment configuration and operating mode. This ensures that colonies of different types of bacteria can operate according to their specialization, keeping the biofilter running smoothly. Even nitrogen bubbles released during the denitrification of water will not block the operation of the biofilter. To create a practical and affordable denitrifying point-of-use device, the authors identified and solved the following eight tasks/conditions:

1. Anoxic conditions in the water inside the biofilter should be originated and maintained by the activity of the bacteria themselves.
2. The surface area of the biofilms in the filtration

bed array must provide the necessary degree of nitrate removal from the entire volume of water for a sufficient period.

3. The design of the biofilter and the shape and dimensions of its filter bed elements must ensure free discharge of the released nitrogen to the atmosphere while minimizing contamination of the filtrate by bacterial plankton.

4. The mode of operation of the biological filtration shall be such that frequent flushing of the biofilter bed is not required.

5. Exceeding the required hydraulic residence time of the water in the biofilter should not degrade the quality of the filtrate.

6. The indicators of denitrified water quality should not deteriorate with the length of the filtration path inside the biofilter.

7. The peripheral module for filtrate post-treatment should be structurally simple, efficient, and economical.

8. The construction of the denitrifying DWTS must be trouble-free and easy to maintain by an average user.

Experimental, results and discussion

The analysis of the conditions necessary for the effective operation of a small-scale denitrification unit (point of use) led to the scheme shown in Fig. 1A. Photographs of the laboratory plant built according to this scheme are in Fig. 1B and C. The plant consists of the original submerged biofilter and the post-treatment unit. The biofilter has a U-shape [10]. It consists of two vertically installed bends (elbows) made of standard polyvinyl chloride pipes with a diameter of 110 mm and a length of 1200 mm, with muffled bottoms and open tops. At 50 mm from the bottom, a hydraulic bridge with a drain valve connects the bends. Extensions (300 mm long compensating fittings) with perforated caps are located at the top of both pipes in a U-shaped module. The perforation in the caps allows the produced gas (N_2) from denitrified water to escape freely to the atmosphere. 1200 mm high HDPE filter media in mesh capsules freely removable from the biofilter housing fills the interior of both elbows. This allows a trouble-free to install the devise and maintain it by an average user.

The post-treatment unit (made of the same materials as the biofilter housing) is equipped with a bubble film extractor [11] and connected to the outlet elbow of the biofilter. An anoxic environment in a biofilter reaches when bacteria consume dissolved oxygen for respiration. The decrease in dissolved oxygen concentration along the filtration path is proportional to its local concentration. Surfactants released by active, live bacteria adsorb to the water surface (forming a densely packed amphiphilic monolayer at the water mirror in the inlet elbow of the biofilter) and provide an additional diffusion barrier to the ingress of oxygen from atmospheric air into the water [12].

When the flow of oxygen from the atmospheric air through the water surface (mirror) into the water bulk becomes less than the bacteria consume, an anoxic conditions are quickly established in the next parts of the biofilter body.

The HDPE filtration media chips provide a large surface area for bacterial colony growth in the filter bed. The chips diameter and height are of a specific size. This, together with the developed surface, creates channels in the biofilter bed with a cross-section that impedes convective flow. However, the cross section

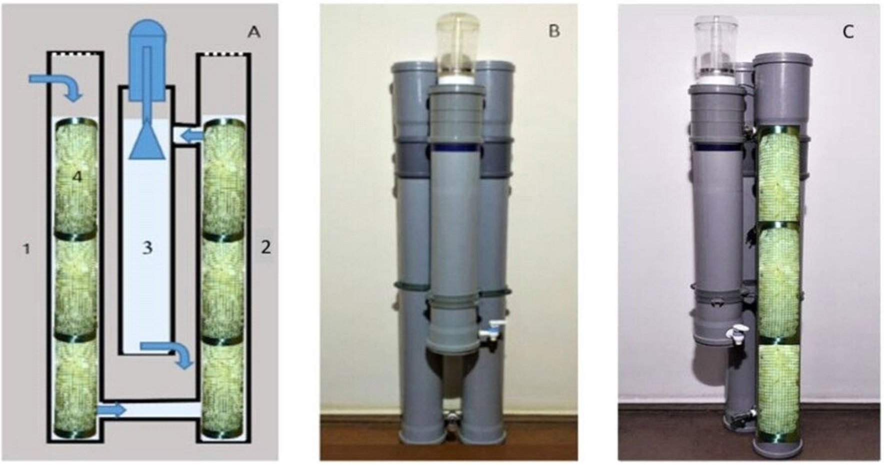

Fig. 1. Block scheme (A) and photographs of a denitrifying biofilter with a bubble-film extraction post-treatment device, front view (B) and side view (C): 1 – biofilter inlet elbow; 2 – biofilter outlet elbow; 3 – post-treatment unit; 4 – segmented HDPE filter media in mesh capsules freely removable from the biofilter housing

of the water channels is still sufficient for the nitrogen bubbles produced by the denitrifying bacteria to rise along them. To facilitate the removal of nitrogen bubbles from the biofilter body to the atmosphere, the biofilter is designed as an open system with a symmetrical U-shape and vertical orientation of its inlet and outlet bends (elbows).

The filtration mode is the critical factor in determining the efficiency and reliability of the biofilter. To ensure maximum conversion of nitrate nitrogen to molecular nitrogen, the retention time of the denitrified water in the biofilter should be prominent. The required retention time mainly ensures the use of a slow filtration rate. On the other hand, the washing flow rate should be high to ensure that the excess mass of biological slime is removed (washed out) from the grains of the filter load inside the biofilter. These conditions are met by the displacement (piston) filtration mode [13]. In this mode, the water feds to the biofilter in one gulp (fast) in separate portions (pulses) at recommended intervals. At the same time, the consumer immediately receives an equivalent amount of denitrified water. Under the effect of the pulsed water flow (turbulent flow) supplied to the biofilter, the excess denitrifying biomass is flushed from the biofilter bed, refreshing the zone of intensive growth, and the flushed biomass moves to the next part of the biofilter where the starving bacteria are located. The starving bacteria use the washed out material from the denitrifying biofouling to maintain their vital activity. In this way, metabolic activity reduces biofilter clogging.

In the case of displacement filtration, the amount of water introduced may be 20-50% of the water capacity of the biofilter bed and may remain there for a long time (up to several days). However, the supply of water portions into the biofilter and the synchronous obtaining of the filtrate occur quickly (in 5–30 seconds). The duration of pauses between successive additions of water to the biofilter (several hours to several days) determines the completeness of denitrification.

During the denitrification period, the water in each point of the biofilter is in a calm state. The only disturbance is the appearance of nitrogen bubbles. Therefore, denitrification in a biofilter is like an ideal operation of a displacement reactor.

Microbiological denitrification and the associated reduction of calcium hardness in the filtrate, sulfate reduction with the formation of hydrogen sulfide and insoluble hydrosulfides of heavy metals, and bacterial oxidation of hydrogen sulfide to elemental sulfur take place inside the biofilter under the kinetic equations of first order reactions. Due to the extended hydraulic retention time, the water leaving the biofilter does not contain undesirable contaminants in concentrations that make them difficult to remove by the post-treatment unit.

The effect of the sulfate reduction on the quality of the filtrate is minimized by deliberately lengthening the filtration path compared to that required for denitrification proper. In this case, the sulfate reduction zone is followed by an extended zone in which sulfur (thionic) bacteria act. The sulfur bacteria absorb the hydrogen sulfide, thus facilitating the final polishing of the filtrate by the post-treatment unit.

At the outlet of the biofilter, some undesirable contaminants may appear in the water when the bacterial community is overfed. These are the rests of hydrogen sulfide and detached biological fouling (bacterial plankton). It can also be the dispersed phase of heavy metal sulfides, calcium carbonates, magnesium carbonates, etc.

Figure 2 shows the cross-section of the biofilter, the position of the filtration bed within it, and a schematic representation of the functional zones at start-up and during long-term operation. The bacterial community in biofilms formed on the surface of the HDPE filter medium performs water treatment. The distribution (relocation) and functional activity of different bacterial colonies along the filtration pass changes depending on the nutritional conditions and duration of the device use. Initially, denitrifying bacteria occupy all available surfaces in the filtration bed as shown in Fig. 2A. Sulfate-reducing bacteria appear behind the denitrifying bacteria at overfeeding of denitrifying bacteria and, over time, sulfur bacteria appear behind the sulfate-reducing bacteria as shown in Fig. 2C.

The filtrate polishes in an advanced flotation device, a bubble film extractor. The operation principle of this device is that dissolved gases, endogenous surfactants and dispersed impurities are adsorbed (and absorbed) by a stream of air bubbles in the treated water and then discharged through a channel of specific geometry (a bubble film extractor) outside the bulk of water. Endogenous surfactants released by bacteria play a critical role in this process. During of bubble film extraction, endogenous surfactants act as ionic and associative collectors of dispersed particles [11].

Figure 3 shows the dynamics of nitrate conversion to nitrogen gas during the start-up period and in a chronically operated biofilter. Initially (during the start-up period, when nitrate-containing water is first filled into the apparatus and the change in nitrate ion concentration monitored over time), the water denitrification occurs slowly. A first-order kinetic equation describes the process with a rate constant of

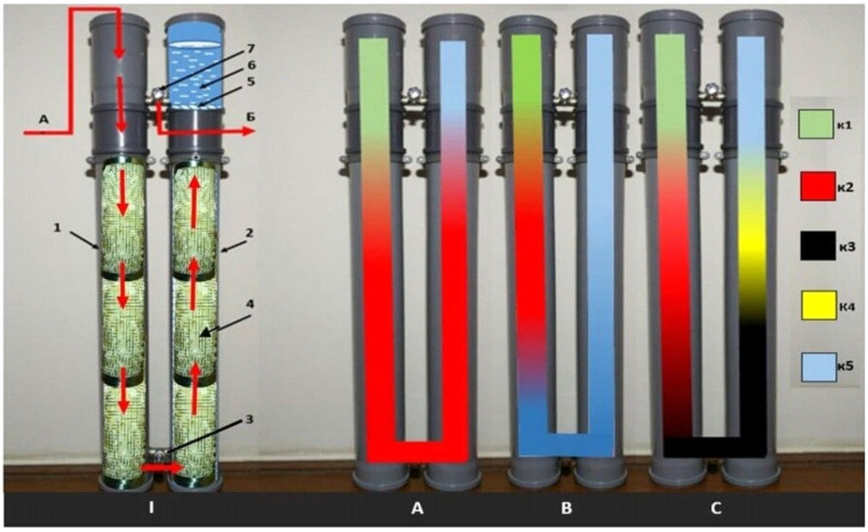

Fig. 2. The biofilter in detail (I) and the distribution of functional zones in it during the start-up period (A) and within long-time operation (B and C): 1 – the inlet elbow; 2 – the outlet elbow; 3 – the connecting jumper; 4 – filtration bed; 5 – the limiting grid; 6 – denitrified water; 7 – the output tubing. The arrows indicate the direction of shifting portions of denitrified water inside the biofilter. The marcs of A–C: k1 is the zone of entered water; k2 is the denitrification zone at the start-up period and at the stationary run; k3 is the sulfate reduction zone; k4 is the location of functioning sulfur bacteria; and k5 is the zone of received filtrate

about 0.56 day^{-1} ($6.48 \cdot 10^{-6}$ s^{-1}) [10]. The ratio of the current nitrate concentration (C) to the initial nitrate concentration in the water (C_0) in a quiescent state inside the biofilter decreases with each subsequent day, as shown by the serial arrangement of dotted lines 1, 2, 3 and 4 in Fig. 3a. The concentration of nitrate ions in the water inside the biofilter bed decreases exponentially with time.

When the biofilter was started in the displacement filtration mode (piston filtration), with a daily water supply of approximately 20% of the total biofilter capacity by volume, the denitrification dynamics remain the same as observed in the case of quiescent water. In Fig. 3b, the step-dot and envelope curves show the decrease of nitrate concentration in the filtrate on days 1, 2, 3 and 4.

As the biofilter reaches steady-state operation, denitrification shifts mainly to the entry zone of the inlet elbow (shown in red in Fig. 2B) and the process rate increases. The dashed lines in Fig. 3b and c show the change in nitrate concentration over the length of the filtration path. When the fed substrate is added in excess to the influent water, the denitrification rate constant reaches 1.4–2.4 day^{-1} or $(1.62–2.78) \cdot 10^{-5}$ s^{-1} [13]. In this case, ecological niches appear behind the denitrification zone where sulfate reducing and sulfur bacteria act. The distribution of these niches is shown in black and yellow in Fig. 2C. The relative change in concentration of nitrate (dashed line), hydrogen sulfide (solid line) and sulfur (dotted-dashed line) in the active biofilter operating in piston mode with an excess of supplied nutrients is shown schematically in Fig. 3c.

Denitrification of water by heterotrophic bacteria requires the supply of a bacterial nutrient substrate to the water. Denitrification with feeding by ethyl alcohol leads to the reduction of NO_3^- to N_2 according to the following equation [6]:

$$\begin{aligned} & NO_3^- + 0.55C_2H_5OH + 0.137O_2 \rightarrow \\ & \rightarrow 0.046C_5H_7O_2N + 0.74HCO_3^- + \\ & + 1.12H_2O + 0.13CO_3^{2-} + 0.477N_2, \end{aligned} \tag{1}$$

If ethanol addition to denitrified water stops, then the reduction of NO_3^- to N_2 occurs by the nutrition of bacteria with their biomass. Denitrification continues at a decreasing rate [13,14] until the biomass depletes. In this case, the denitrification equation has the following form:

$$\begin{aligned} & NO_3^- + 0.25C_5H_7O_2N + 0.25H_2O \rightarrow \\ & \rightarrow HCO_3^- + 0.25NH_4HCO_3 + 0.5N_2. \end{aligned} \tag{2}$$

In both instances, about 0.5 moles of nitrogen gas bubbles are produced for every mole of nitrate ions. These bubbles rise along the water channels in the biofilter bed. Upon reaching the water surface,

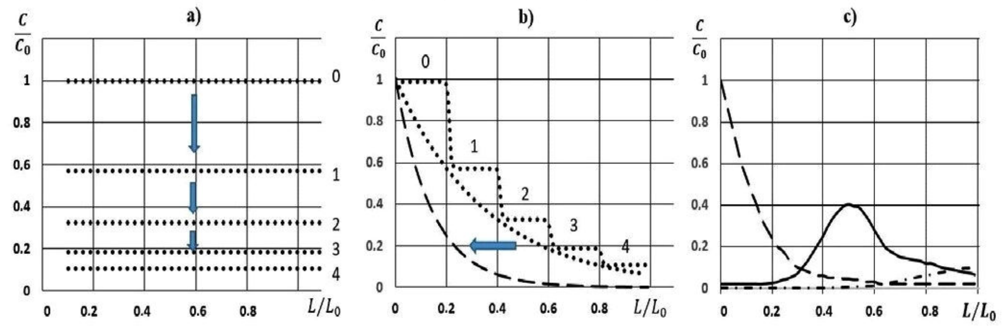

Fig. 3. The course of denitrification in the biofilter during the start-up period and in a regularly operated device: a) dynamics of water denitrification in the starting period in the absence of a duct through the biofilter; b) dynamics of water denitrification in the starting period in the mode of displacement biofiltration; the decrease in the concentration of nitrates in the portions of filtrate depicts the step-dot line and its envelope dot line of averaged values; and c) dotted line shows the change in the relative concentration of nitrates along the length of the filtration path; solid line shows the change in the relative concentration of hydrogen sulfide, and dashed line shows the change in the relative concentration of sulfur

the bubbles burst in the biofilter elbows and release their contents into the atmosphere through perforated covers that seal the upper ends of the inflow and outflow elbows. Thus, denitrifying bacteria's vital activity is not impaired by nitrogen.

Due to the denitrification process, the filtrate accumulates HCO_3^- and OH^-. Excess hydroxide ions cause the bicarbonate ions to transform into CO_3^{2-}. The interaction of CO_3^{2-} with calcium cations (which are present in the water as a component of its initial hardness) results in the formation of the dispersed phase of $CaCO_3$ as per the following equations:

$$HCO_3^- + OH^- \leftrightarrow CO_3^{2-} + H_2O, \quad (3)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow. \quad (4)$$

As a result, the hardness and concentration of dissolved salts in the denitrified water decline, leading to a decrease in the TDS index but an increase in turbidity.

If ethanol is added to the supplied portions of denitrified water in quantities more significant than required by equation (1), the biofilter displays the presence of sulfate-reducing bacteria. Following the equation, sulfate reduction occurs:

$$3SO_4^{2-} + 2C_2H_5OH = 3HS^- + 3H_2O + CO_2 + 3HCO_3^-. \quad (5)$$

Hydrogen sulfide also appears through the hydrolysis of hydrosulfide ions according to the equation:

$$HS^- + H_2O \leftrightarrow H_2S + OH^-. \quad (6)$$

The filtration path where hydrogen sulfide accumulates at an excessive dosage of ethanol to denitrified water creates an ecological niche for the functioning of sulfur bacteria. These bacteria oxidize dissolved hydrogen sulfide to elemental sulfur and sulfate ions according to the equations:

$$H_2S + 1/2\,O_2 \rightarrow S + H_2O, \quad (7)$$

$$S + 1/2\,O_2 + H_2O \rightarrow H_2SO_4. \quad (8)$$

An ecological niche for sulfur bacteria appears in a U-shaped biofilter in the upper part of its output elbow. Here, oxygen from the atmospheric air penetrates through the perforated cover. The zone of functioning of sulfur bacteria indicated in Fig. 2C is yellow, and the change in sulfur concentration in relative units along the length of the filtration path shown in Fig. 3c with a dashed-dotted line.

In such a way depending on the biofilter's operating conditions, denitrification and sulfate reduction are manifested in various filtration sections.

After biological filtration, denitrified water directs to a storage unit fitted with a bubble-film extractor. Bubble film extraction is the process based on the ability of surfactants to adsorb on the surface of air bubbles and volatiles to be absorbed by the gas phase of bubbles. Bubble film extraction is similar to flotation in the principle of operation, but its efficiency in terms of SAS (endogenic and exogenic surfactants) and other impurities removal is much higher than that of flotation [11].

The quality of water denitrification in a U-shaped biofilter and after-treatment in storage equipped with a bubble-film extractor illustrates the data in Table. The column 1 in Table refers to the water's source quality indicators. The column 2 refers to the quality indicators of water samples taken from the entering compartment inside the biofilter the following day before the new portion of water is directed for filtration. The column 3 refers to samples taken from the bottom zone of the junction of the inlet and outlet elbows of the biofilter. The column 4 refers to water samples taken from the biofilter outlet when turned off the bubble-film extractor in the post-treatment unit, and the column 5 refers to water taken from the biofilter outlet with the bubble-film extractor operating.

The water fed to the displacement filtration (with a concentration of dissolved sodium nitrate equal to 250 mg/dm^3 and ethanol dosing of 80 mg/dm^3) has a pH 7.7–8.2; NTU=0.8–1.2; TDS=360–380 mg/dm^3; and dissolved O_2=7.8–8.3 mg/dm^3. It does not contain hydrogen sulfide and its redox potential Eh=+(128÷135) mV. This water changes its indicators on contact with the biofilter bed during the day: the concentration of nitrates, dissolved oxygen, and TDS decrease in samples taken from the inlet compartment. Redox potential and odor index remain the same, but pH and turbidity increase significantly.

The water sampled from the junction zone of inlet and outlet elbows of the biofilter shows an additional decrease in nitrate and dissolved oxygen concentrations. The pH is also significantly lower than in the water at the biofilter inlet, and the turbidity is considerably higher. Dramatic changes occur in the redox potential, and its value decreases by 360–380 mV compared to the redox potential in the water at the entrance to the biofilter. The smell of hydrogen sulfide is present in the water, and a qualitative chemical reaction on hydrogen sulfide confirms this.

When the bubble-film extractor is off, the water turbidity at the biofilter outlet has magnitudes intermediate between the entrance and bottom. The TDS indicator remains the same as at the bottom of the biofilter. The dissolved oxygen concentration is lower than that in raw water: the redox potential and intensity of the smell of hydrogen sulfide indicate its presence in the filtrate.

The water at the outlet of the biofilter with the bubble-film extractor turned on shows the lowest concentration of nitrates and turbidity; its pH reaches a value of 8.6, and the DO concentration becomes in equilibrium with the concentration of oxygen in the atmospheric air. The redox potential in the denitrified water treated with a bubble-film extractor practically does not differ from the ORP of the source water, and it has no extraneous tastes and odors. The hydrogen sulfide is absent.

Conclusions

A pilot model of a low-cost, affordable denitrifying water purifier point of use has been developed. The apparatus consists of a U-shaped denitrifying biofilter of the submersible type and a bubble film extractor for polishing the filtrate. The coordinated action of denitrifying sulfate reducing and sulfur bacteria treats the water. The denitrifying bacteria cause NO_3^- removal and increase the pH to reduce the calcium hardness of the water. When both nitrates and sulfates contaminate the water and the bacteria are overfed, partial conversion of the sulfates to hydrogen sulfide occurs. The appearance of hydrogen sulfide in the water leads to the possibility of removing heavy metal ions from the water in the hydrosulfide state.

The excess hydrogen sulfide produced by sulfate-reducing bacteria is converted to colloidal sulfur by the action of sulfur bacteria. Colloidal sulfur, hydrosulfides of heavy metals, dispersions of calcium carbonates and hydrogen sulfide are removed from the filtrate by bubble film extraction, and self-induced (biological) surfactants ensure the efficiency of this process.

The denitrifying water purifier is designed for operation at the point of use. Its installation and maintenance do not require any special skills or knowledge from the potential user.

Indicators of water quality inside the different parts of the biofilter and in storage equipped with a bubble-film extractor

Indicator	Value				
	1	2	3	4	5
$C(NO_3^-)$, mg/dm^3	250	13	12	12	12
pH	7.7–8.2	8.4–8.5	7.8–7.9	8.6–8.7	8.6–8.7
Hardness, mmol/dm^3	2.58			1.5	1.5
Turbidity, NTU	0.8–1.2	1.2–1.9	1.4–2.5	0.75–1.12	0.3–0.5
TDS, mg/dm^3	360–380	297–300	290	287–290	287–290
$O_{2\ \text{dissolved}}$, mg/dm^3	7.8–8.3	0.6	0.4	1.3	8.3
smell*	–	–	+	+/–	–
Eh, mV	+(128÷135)	+(126÷130)	–(230÷265)	+(126÷132)	+(128÷135)

Note: * – the «smell» refers to hydrogen sulfide, determined organoleptically; the sign «–» means «absent» and the sign «+» means «present».

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REFERENCES

1. *Review* on groundwater nitrate contamination: causes, effects and remedies: a guideline for efficient management strategies / Fazal A., Imaizumi M., Ishida S., Kawachi T., Tsuchihara T., Takeuchi, J., et al. // J. Rainwater Catchment Syst. – 2003. – Vol.8. – No. 2. – P.15-33.

2. *Global* diagnosis of nitrate pollution in groundwater and review of removal technologies / Abascal E., Gomez-Coma L., Ortiz I., Ortiz A. // Sci. Total Environ. – 2022. – Vol.810. – Art. No. 152233.

3. *Removal* techniques of nitrate from water / Mohsenipour M., Shahid S., Ebrahimi K. // Asian J. Chem. – 2014. – Vol.26. – P.7881-7886.

4. *Nanofiltration* and reverse osmosis membrane for nitrate removal: performance study and economic evaluation / Touir J., El-Ghzizel S., Belhamidi H.Z.S., Elazhar F., Taky M.T.M., Elmidaoui A. // Moroc. J. Chem. – 2021. – Vol.9. – P.057-068.

5. *Large scale* biological nitrate and ammonia removal / Rogalla F., Ravarini P., De Larminat G., Couttelle J. // Water Environ. J. – 1990. – Vol.4. – P.319-328.

6. *Mohseni-Bandpi A., Elliott D.J., Zazouli M.A.* Biological nitrate removal processes from drinking water supply – a review // J. Environ. Health Sci. Engineer. – 2013. – Vol.11. – Art. No. 35.

7. *Aerobic* denitrification: a review of important advances of the last 30 years / Ji B., Yang K., Zhu L., Jiang Y., Wang H., Zhou J., et al. // Biotechnol. Bioprocess. Eng. – 2015. – Vol.20. – P.643-651.

8. *Influence* of hydrogen electron donor, alkaline pH, and high nitrate concentrations on microbial denitrification: a review / Albina P., Durban N., Bertron A., Albrecht A., Robinet J., Erable B. // Int. J. Mol. Sci. – 2019. – Vol.20. – Art. No. 5163.

9. *Hvozdiak P.I., Sapura O.V.* Denitrification of drinking water by using probiotic bacteria // Microbiol. Biotechnol. – 2017. – Vol.2. – P.81-89.

10. *Gevod V.S., Chernova A.S.* Water denitrification by displacement biofiltration // Voprosy Khimii i Khimicheskoi Tekhnologii. – 2021. – No. 4. – P.11-20.

11. *Gevod V.S.* Bubble-film extraction fundamentals and application // Handbook of surface and colloid chemistry. – Boca Raton: CRC Press, 2015. – P.585-630.

12. *Gevod V., Chernova A., Kovalenko I.* Use of auto-induced surfactants for clarification of biodenitrified water by bubble-film extraction method // Chem. Chem. Technol. – 2022. – Vol.16. – P.660-668.

13. *Gevod V.S., Chernova A.S.* Water denitrification by displacement biofiltration: transition of designed biofilter to the stationary mode // Voprosy Khimii Khimicheskoi Tekhnologii. – 2021. – No. 4. – P.21-26.

14. *Buffer* effects in submersed denitrifying biofilter / Gevod V.S., Chernova A.S., Zhumadulayeva A.I., Dossybayeva G.N., Syzdykova M., Shymelkova R.Zh., et al. // J. Ecol. Eng. – 2022. – Vol.23. – P.145-154.

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НАДІЙНА ТА ДОСТУПНА СИСТЕМА ДЕНІТРИФІКАЦІЇ ВОДИ В ТОЧЦІ СПОЖИВАННЯ

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В статті описано конструкцію і роботу надійної та доступної системи денітрифікації води в точці споживання. Система включає U-подібний занурювальний денітрифікуючий біофільтр та бульбашково-плівковий екстрактор. Біофільтр використовує комбіновану дію денітрифікуючих, сульфатредукуючих і сірчаних бактерій. Денітрифікуючі бактерії перетворюють нітрати в газоподібний азот і знижують кальцієву жорсткість води пропорційна концентрації нітратів. Коли вода забруднена як нітратами, так і сульфатами, а бактеріальна спільнота отримує надлишкове живлення (етанол), частина сульфатів перетворюється на сірководень. Це перетворення дозволяє видалити іони важких металів з води у вигляді гідросульфідів. За умов надлишку сірководню, сірчані бактерії перетворюють його на колоїдну сірку на виході з біофільтра. Бульбашково-плівковий екстрактор видаляє з фільтрату колоїдну сірку, гідросульфіди важких металів, дисперсії карбонату кальцію та сірководень. Користувачі не потребують спеціальних навичок або знань для встановлення та обслуговування біофільтра для отримання очищеної води. Запропонований біофільтр демонструє економічну ефективність денітрифікації та доочищення води при тривалому використанні.

Ключові слова: денітрифікація, очищення води, біофільтрація, бульбашково-плівкова екстракція, економічно ефективний пристрій.

RELIABLE AND ACCESSIBLE POINT-OF-USE WATER DENITRIFICATION SYSTEM

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This paper describes the design and operation of a reliable and accessible point-of-use water denitrification system. The system includes a U-shaped submersible denitrifying biofilter and a bubble-film extractor. The biofilter utilizes the combined actions of denitrifying, sulfate-reducing, and sulfur bacteria. Denitrifying bacteria convert nitrates into nitrogen gas and reduce the calcium hardness of water in proportion to the nitrate concentration. When the water is contaminated with both nitrates and sulfates and the bacterial community receives excess nutrients (ethanol), some sulfates are converted into hydrogen sulfide. This process facilitates the removal of heavy metal ions from the water in the form of hydrosulfides. When the sulfate-reducing bacteria produce excess hydrogen sulfide, the sulfur bacteria convert it into colloidal sulfur at the biofilter outlet. The bubble-film extractor removes colloidal sulfur, heavy metal hydrosulfides, calcium carbonate dispersions, and hydrogen sulfide from the filtrate. The system is user-friendly, requiring no special skills or knowledge for installation and maintenance. The proposed system demonstrates cost-effective denitrification and water polishing over long-term use.

Keywords: denitrification; water treatment; biofiltration; bubble-film extraction; cost-effective device.

REFERENCES

1. Fazal A, Imaizumi M, Ishida S, Kawachi T, Tsuchihara T, Takeuchi J, et al. Review on groundwater nitrate contamination: causes, effects and remedies: a guideline for efficient management strategies. *J Rainwater Catchment Syst.* 2003; 8(2): 15-33. doi: 10.7132/jrcsa.kj00000795202.

2. Abascal E, Gomez-Coma L, Ortiz I, Ortiz A. Global diagnosis of nitrate pollution in groundwater and review of removal technologies. *Sci Total Environ.* 2022; 810: 152233. doi: 10.1016/j.scitotenv.2021.152233.

3. Mohsenipour M, Shahid S, Ebrahimi K. Removal techniques of nitrate from water: a review. *Asian J Chem.* 2014; 26(23): 7881-7886. doi: 10.14233/ajchem.2014.17136.

4. Touir J, El-Ghzizel S, Belhamidi HZS, Elazhar F, Taky MTM, Elmidaoui A. Nanofiltration and reverse osmosis membrane for nitrate removal: performance study and economic evaluation. *Moroc J Chem.* 2021; 9(1): 57-68. doi: 10.48317/imist.prsm/morjchem-v9i1.24357.

5. Rogalla F, Ravarini P, Larminat GD, Couttelle J. Large scale biological nitrate and ammonia removal. *Water Environ J.* 1990; 4: 319-328. doi: 10.1111/j.1747-6593.1990.tb01400.x.

6. Mohseni-Bandpi A, Elliott DJ, Zazouli MA. Biological nitrate removal processes from drinking water supply-a review. *J Environ Health Sci Engineer.* 2013; 11: 35. doi: 10.1186/2052-336x-11-35.

7. Ji B, Yang K, Zhu L, Jiang Y, Wang H, Zhou J, et al. Aerobic denitrification: a review of important advances of the last 30 years. *Biotechnol Bioproc Eng.* 2015; 20: 643-651. doi: 10.1007/s12257-015-0009-0.

8. Albina P, Durban N, Bertron A, Albrecht A, Robinet JC, Erable B. Influence of hydrogen electron donor, alkaline pH, and high nitrate concentrations on microbial denitrification: a review. *Int J Mol Sci.* 2019; 20(20): 5163. doi: 10.3390/ijms20205163.

9. Hvozdiak PI, Sapura OV. Denitrification of drinking water by using probiotic bacteria. *Microbiol Biotechnol.* 2017; 2(38): 81-89. doi: 10.18524/2307-4663.2017.2(38).105022 (*in Ukrainian*).

10. Gevod VS, Chernova AS. Water denitrification by displacement biofiltration. *Voprosy Khimii i Khimicheskoi Tekhnologii.* 2021; (4): 11-20. doi: 10.32434/0321-4095-2021-137-4-11-20.

11. Gevod VS. Bubble-film extraction fundamentals and application. Chapter 14. In: KS Birdi, editor. *Handbook of surface and colloid chemistry. 3rd ed.* Boca Raton: CRC Press; 2008. p. 585-630.

12. Gevod V, Chernova A, Kovalenko I. Use of auto-induced surfactants for clarification of biodenitrified water by bubble-film extraction method. *Chem Chem Technol.* 2022; 16(4): 660-668. doi: 10.23939/chcht16.04.660.

13. Gevod VS, Chernova AS. Water denitrification by displacement biofiltration: transition of designed biofilter to the stationary mode. *Voprosy Khimii i Khimicheskoi Tekhnologii.* 2021; (4): 21-26. doi: 10.32434/0321-4095-2021-137-4-21-26.

14. Gevod V, Chernova A, Zhumadulayeva A, Dossybayeva G, Syzdykova M, Shymelkova R et al. Buffer effects in submersed denitrifying biofilter. *J Ecol Eng.* 2022; 23(4): 145-154. doi: 10.12911/22998993/146634.