Nitrite oxidation by phototrophic bacteria of Chlorobium, Thiocapsa and Lamprocystis genera under the influence of inorganic pollutants

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Proliferation of inorganic nature (acids, alkalis, mineral salts of different composition, metals) change the course of biological processes of environmental purification, but their influence on the physiologic properties of phototrophic sulfur bacteria has not been studied enough. The usage of nitrite ions as an electron donor of anoxygenic photosynthesis by cells of phototrophic green and purple sulfur bacteria Chlorobium limicola IMV K-8, Thiocapsa sp. Ya-2003 and Lamprocystis sp. Ya-2003, isolated from Yavorivske Lake, under the influence of the most widespread inorganic pollutants – hydro- and dihydrophosphates, sulfates, chlorides and chlorates, has been studied. It is shown that KH2PO4, K2HPO4, Na2SO4, NaCl, and KClO3, present in the van Niel medium with 4.2 mM NaNO2 at concentrations that are 0.5, 1.0, 2.0, 3.0, 4.0 times different from the maximum permissible concentrations (MPC), influenced the biomass accumulation and nitrite ions oxidation by phototrophic green and purple sulfur bacteria. In media with hydro- and dihydrophosphate ions at concentrations 4.0 times higher than the MPC, inhibition of bacterial growth was up to 1.7 times lower than in the control. The biomass accumulation by bacteria in media with chloride and chlorate ions at concentrations 3.0–4.0 times higher than MPC was 2.0–2.8 times lower compared to the control. In the medium with Na2SO4 at concentrations 2.0–4.0 times higher than MPC, the biomass was 2.0–4.0 times lower than in the control. Nitrites' oxidation by all strains in the media with the studied pollutants was slowed down. The residual content of nitrite ions in media with hydro- and dihydrophosphate, chloride and chlorate ions at their concentrations 4.0 times higher than MPC, exceeded the NO2\textsuperscript{−} content in the control variants up to 1.7 times. If in the medium without pollutants the cells of C. limicola IMV K-8, Thiocapsa sp. Ya-2003 and Lamprocystis sp. Ya-2003 strains oxidized 72.7%, 72.2% and 71.4%, respectively, of nitrite ions present in the medium, then in the medium with sulfate ions at concentration 4.0 times higher than the MPC, bacteria oxidized nitrite ions only at 39.6%, 34.4% and 27.0%, respectively. Oxidation of a lower quantity of nitrites by phototrophic bacteria in the media with inorganic pollutants led to the production by them of a lower quantity of nitrites. The content of NO2\textsuperscript{−} in the media with hydro-, dihydrophosphate and chlorate ions at all concentrations was up to 1.9 times lower than in the control. In media with sulfate ions at concentrations 2.0–4.0 times higher than MPC and chloride at concentration 4.0 times higher than MPC, the content of nitrate ions was 2.1–4.3 and 2.0 times, respectively, lower than in the control variants. Inorganic pollutants stimulated the synthesis of intracellular carbohydrates in C. limicola IMV K-8. If the content of intracellular glucose in cells grown in the medium without pollutants was 10.3 mg/g dry cell weight, then in cells grown in media with KH2PO4, K2HPO4, Na2SO4, NaCl, and KClO3 at concentrations 4.0 times higher than MPC, its content increased by 12.2%, 10.7%, 51.6%, 17.1% and 35.9%, respectively. The glycogen content in the cells grown in the medium without pollutants was 45.1 mg/g dry cell weight. Hydro- and dihydrophosphate, chloride and chlorate ions at concentrations 4.0 times higher than MPC stimulated glycogen synthesis in cells by 47.5%, 57.6%, 67.4% and 74.6%, respectively. The glycogen content in cells grown in the medium with Na2SO4 at concentrations 3.0 and 4.0 times higher than MPC increased by 102.9% and 107.5%, respectively. Therefore, it is established that pollutants of inorganic nature affect the physiologic properties of photosynthetic sulfur bacteria and thus change the course of biological processes of environment purification, in particular, from nitrite ions.

Keywords: phototrophic bacteria; nitrites; hydrophosphates; dihydrophosphates; sulfates; chlorides; chlorates.

Introduction

Phototrophic bacteria are a morphologically diverse group of gram-negative prokaryotes that are widespread in freshwater, marine sediments, and wastewater (Dahl, 2017). They are involved in the global biogeochemical cycles of nitrogen, sulfur and carbon (Middelburg et al., 2000). Phototrophic sulfur bacteria play an important role in restoring the balance of chemical elements in water bodies through the use of CO2 as a carbon source and reduced compounds of sulfur (sulfides, thiosulfates), nitrogen (nitrites), Fe(II), molecular hydrogen or organic compounds as exogenous electron donors in the process of anoxygenic photosynthesis (Kondratieva, 1989; Schott et al., 2010). This property of bacteria is due to the presence in them of integrated into the cytoplasmic membrane and intracytoplasmic photosynthetic membrane systems light-collecting pigment-protein complexes (antennas), which include bacteriochlorophylls and carotenoids, which absorb photons and transfer excitation energy to photochemical reaction centers (Kondratieva, 1989; Dahl, 2017; Hallenbeck, 2017). The light-collecting system of purple bacteria consists of membrane proteins bound to bacteriochlorophyll and carotenoids in stoichiometric amounts. In green phototrophic bacteria this system is localized in chlorosomes, vesicle-like organelles attached to the cytoplasmic membrane from the cytoplasm side by a crystalline basal plate that contain bacteriochlorophyll aggregates in the form of rod-shaped elements surrounded by a lipid monolayer (Lengeler et al., 2005). Photosynthesis of carbon dioxide and some organic compounds through the reductive pentose phosphate cycle by green sulfur bacteria of the genus Chlorobium leads not only to the formation by cells of substances necessary for their growth. Sometimes a synthesis of reserve product in the form of glucose and a product of its polymerization – glycogen can occur (Gorishnyi et al., 2008).

In addition to the biological treatment of polluted natural, technogenic water bodies and industrial effluents from hydrogen sulfide, phototrophic green and purple sulfur bacteria play an important role in the formation and accumulation of sulfur deposits. Sulfur can accumulate in the form of intracellular globules outside the cells of green and inside the cells of purple sulfur bacteria (Garnity et al., 2001; Garnity et al., 2005; Rosenberg et al., 2014). Phototrophic sulfur bacteria are actively involved in the accumu-
mulation of organic substances in water bodies, and also enrich the environment with nitrogen compounds, carrying out fixation of molecular nitrogen (Kondratieva et al., 1989; Proct, 1999; Pimenov et al., 2003).

Anoxicogenic phototrophs use nitrogen compounds in assimilation or dissimilation processes. Although ammonium is usually the best nitrogen source for them, some species assimilate nitrate or nitrite ions if ammonium is absent (Otmo-Nira et al., 2006). In the dark, some purple non-sulfur bacteria, such as Rhodopseudomonas spp. and Rhodobacter spp., can use nitrate as an electron acceptor for respiratory ATP generation (Hougardy et al., 2000). Denitrification by purple sulfur bacteria has not been reported so far. Aerobic oxidation of nitrites (aerobic nitrification) is carried out by bacteria of the genera Nitrobacter, Nitrooccus, Nitropini, Nitrpsira (Lengeler et al., 2005), during which electrons from nitrite ions are transferred to oxygen, and CO2 acts only as the carbon source (NO2− + ½ O2 → NO.). Anaerobic oxidation of nitrite ions occurs only with the participation of phototrophs (Griffin et al., 2007). In the process of phototrophic nitrites’ oxidation, nitrite ions serve as electron donors for anoxicogenic photosynthesis, and the electrons are used for autotrophic CO2 fixation.

Nitrates are organic or inorganic compounds. Nitrite oxidation in the process of phototrophic sulfur bacteria (Schott et al., 2010) and by purple non-sulfur bacteria Rhodopseudomonas yarrowii is described (Tanaka et al., 2019). The use by these bacteria of nitrite ions as electron donors is analyzed in detail with respect to their potential role in nitrite oxidation in nature (Schott et al., 2010; Tanabas et al., 2019). The results of 16S rRNA gene analysis indicate that Thiothrix sp. strain KS1 is closely related to the aerobic nitrite oxidizer Nitroococcus mobilis (Schott et al., 2010). Intracytoplasmatic membrane systems of Nitroococcus are very similar to the same structures in phototrophic purple bacteria (Schott et al., 2010; Hemp et al., 2016). The genome of the nitrite-oxidizing phototrophic bacteria Thiothrix sp. KS1 was sequenced and analyzed. Genes associated with respiration, photosynthetic and nitrogen metabolism in these bacteria have been identified (Hemp et al., 2016). The diazotrophic strain Thiothrix KS1 has a complete set of *nif* genes whose products are involved in nitrogen fixation including molybdenum-iron nitrogenase (NiFDK) and nitrogenase reductase (NiFH). Bacteria Thiothrix KS1 can assimilate ammonium and also uses nitrite and nitrate ions as nitrogen sources (Schott et al., 2010; Hemp et al., 2016). Nitrite oxidation in Thiothrix KS1 occurs by the action of Mo-ksi-MGD-binding nitrite oxidoreductase (NXR), an enzyme that can catalyze nitrite oxidation and nitrate reduction: NO2− + H2O → NO− + 2e− + 2H+ (Tanaka et al., 1983). The NXR of Thiothrix KS1 was similar to the NXR forms found in the chemolithotrophic nitrite-oxidizing bacteria (Sorokin et al., 2012) and to the dissimilatory membrane-bound nitrate reductase (NAR) system found in many nitrate-reducing organisms. The NXR complex consisted of the α-subunit (NxaA), which contains the catalytic site, β-subunit (NxbB), which transmits electrons, with four cysteine-rich binding motifs for [Fe-S] clusters and the γ-subunit (NxrC), a membrane protein that putatively binds two heme b groups. Electrons derived from nitrite flow from NxaA through NxbB to NxrC, which anchors NXR in the membrane and transfers the electrons to the downstream electron carriers. The NxrA and NxrB subunits are cytoplasmic and oriented similar to the NarGH subunits of bacterial nitrate reductases NARs (Hemp et al., 2016). Reduction of nitrites to nitrites can be carried out by periplasmic nitrate reductase NAR (NapDGHBB). The NXR can function as a membrane-bound NAR. The genome of Thiothrix KS1 contains encode proteins related to hydroxylamine dehydrogenase, which are involved in the nitrites reduction to NO. In addition, the strain Thiothrix KS1 contains NO and N2 oxidases, which sequentially reduce NO to N2 (Hemp et al., 2016).

Compared with other electron donors of anoxygenic photosynthesis, such as organic compounds, H2, H2S, and Fe2+, the nitrite ion is the electron donor with the highest standard redox potential (E0′ = NO2−/NO− = +0.43 V) (Lengeler et al., 2005). Electrons released during the exogenous electron donors’ oxidation enter the photosynthetic apparatus of purple bacteria via a cytochrome c2 or other electron carrier redox potential (+0.49 V), close to the redox potential of the reaction center primary electron donor – dimer of bacteriochlorophyll (α or b), reaction center II quinone type (Kozlova et al., 2008). The reaction centers of Chlorobioic family members with Fe-S proteins as final electron acceptors have substantially lower redox potentials (+0.24 V) (Madigan et al., 2006), and nitrite oxidation by these bacteria would require reversed electron transport. It is known that pollutants of inorganic nature change the course of biological processes of environmental purification (Kuznetsov et al., 2015; Tarabas et al., 2017), but their influence on the physiological properties of photosynthetic sulfur bacteria has not been studied enough. Therefore, the aim of the study was to investigate the usage of nitrite ions as an electron donor of anoxicogenic photosynthesis by cells of phototrophic green and purple sulfur bacteria isolated from the water of Yavorivske Lake under the influence of the most widespread inorganic pollutants – hydro- and dihydrophosphates, sulfates, chlorides and chlorates.

Materials and methods

Phototrophic green and purple sulfur bacteria Chlorobium limicola IMV K-8, Thiothrix sp. Ya-2003 and Lampropyxis sp. Ya-2003, isolated by us earlier from Yavorivske Lake, were identified at Microbiology Department of Ivan Franko National University of Lviv (Ká & Grádz, 2007; Gorishnyi et al., 2008). The strain C. limicola IMV K-8 has been stored in the depository of D. K. Zabolotny Institute of Microbiology and Virology of the NAS of Ukraine since 2010.

Bacteria were cultivated under anaerobic conditions and constant lighting for 10 days at temperature ~25...28 °C in van Niel medium (Grádz et al., 2014) of the following composition (g/L): NH4Cl (0.4), MgSO4·7H2O (0.33), KH2PO4 (0.04), CaCl2·2H2O (0.05), CH3COONa (2.55), C6H5O2Na·Ni (1.0), NaNO3 (0.29) (4.2 mM – concentration of electron donor in the medium of standard composition), NaHCO3 (6.0), inositol (1.0), vitamin B12 (0.000005), microelements solution – 2 mL. Solutions of CH3COONa, C6H5O2Na, inositol, NaHCO3, NaNO3, vitamin B3 and microelements of the following composition (g/L): FeC2O4·2H2O (2.0), diluted in 25% HCl, CoCl2·6H2O (0.19), MnCl2·4H2O (0.1), ZnCl2 (0.07), Na2MoO4·2H2O (0.036), NiCl2·6H2O (0.024), H2BO3 (0.006), CuCl2·2H2O (0.002), were sterilized separately and placed into the medium before seeding of the cells. The pH of the medium was adjusted to the optimum by phosphoric acid solution (10%). The pH value of the medium was slightly alkaline (pH – 7.5–8.0) for purple and neutral (pH – 7.0) – for green sulfur bacteria.

Bacteria were sown in the medium to initial cells concentration of 0.2 mg/mL. To create anaerobic conditions, 25 mL tubes were completely filled with the medium and closed with rubber stoppers. During the cultivation of the cultures the whole day lighting was provided by incandescent lamps with capacity 60–75 W. Purple sulfur bacteria were grown at an illumination of 150–200 lux using a red interference filter that transmits light with a wavelength of more than 800 nm. Green sulfur bacteria were illuminated by rays with a wavelength of 700–800 nm, the illumination was 40 lux. The illumination intensity was measured using a lux-meter U-116.

Table 1

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Maximum permissible concentrations (MPC) of pollutants, mg/L</th>
<th>Concentrations, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference between MPC, times</td>
<td>1</td>
</tr>
<tr>
<td>KC2H3O2</td>
<td>3.5*</td>
<td>0.019</td>
</tr>
<tr>
<td>K2HPO4</td>
<td>3.5*</td>
<td>0.019</td>
</tr>
<tr>
<td>Na2SO4</td>
<td>50*</td>
<td>2.604</td>
</tr>
<tr>
<td>KClO4</td>
<td>0.7*</td>
<td>0.004</td>
</tr>
</tbody>
</table>

To study the influence of inorganic pollutants on biomass accumulation, nitrite utilization, nitrate production, synthesis of intracellular carbohydrates, bacteria were sown in test tubes, grown until the middle of the exponential growth phase under anaerobic conditions and optimal illumination in medium with 4.2 mM NaNO₂ and inorganic pollutants: K₂HPO₄, KH₂PO₄, Na₂SO₄, NaCl, KClO₃, at concentrations that are 0.5, 1.0, 2.0, 3.0, 4.0 times different from the maximum permissible (Table 1). Since van Niel medium (excluding microelements) contains dihydrophosphate, sulfate and chloride ions, which are necessary for optimal growth of bacteria at concentrations of 2.094, 0.524 and 5.402 mM, respectively, the test compounds, in particular, KH₂PO₄, Na₂SO₄, NaCl, were added to the medium additionally. The control was a medium without pollutants. After 10 days, biomass, NO₂⁻ and NO₃⁻ content in the cultural liquid, glucose and glycogen content in cell-free extracts were determined. Biomass was determined by the turbidimetric method using the photoelectrocolorimeter KFK-3 by the optical density of the cell suspension (optical way l = 3 mm) by measuring it at wavelengths $\lambda = 450$ nm to green and 660 nm to purple sulfur bacteria and calculated using the formula: $C, g/L = (E \times n)/K$, where $E$ – extinction; $n$ – dilution factor, times; $K$ – coefficient of recalculation, obtained from the calibration curve of the dependence of extinction from the mass of dry cells, determined by the weight method, and equal 0.131 to green and 0.17 to purple sulfur bacteria (Gudz et al., 2014). In a cultural liquid, separated from the cells by centrifugation (4025 g, 15 min), we determined the concentrations of nitrate ions (after their reduction to nitrites in the presence of Zn:MnSO₄ (1:100) powder as a reducing agent) and nitrite ions by spectrophotometric method which relies on a diazotization reaction with a Griess reagent (n-(1-naphthyl)ethylenediamine dihydrochloride, sulfanil and acetic acid) (Granger, 1996; Gudz et al., 2014).

**Fig. 1.** The influence of KH₂PO₄ (**a**), K₂HPO₄ (**b**), Na₂SO₄ (**c**), NaCl (**d**) and KClO₃ (**e**) on biomass accumulation by phototrophic bacteria in the medium with 4.2 mM NaNO₂ on 10-th day of cultivation ($x \pm SD, n = 3$): control – the medium without pollutants; * – the data were statistically significant as compared with the control ($P < 0.05$)
The glucose and glycogen content was determined enzymatically in cell-free extracts of *C. limicola* IMV K-8, using the analytical kit “Diagluc-2” (Gonchar, 1998). To determine the concentrations of intracellular glucose and glycogen *C. limicola* IMV K-8 cells were precipitated at 4025 g for 30 min. The cultural liquid was drained, the cells were resuspended in 3 mL of extraction buffer (50 mM potassium phosphate buffer, pH 7.5; 10–5 M EDTA (ethylenediamine tetraacetate); 10–5 M PMSF (phenylmethylsulfonyl fluoride). Tubes with cells were frozen in a freezer chamber at –10 ºC and used for preparation of cell-free extracts. Cells were disrupted with an ultrasound disintegrator UZDN-2T at a frequency of 22 kHz for 5 min in tubes immersed in ice. Cell fragments were separated by centrifugation at 9000 g for 45 min at 4 ºC. The obtained cell-free extracts were immediately used to determine the content of glucose and glycogen. Glycogen concentration was calculated from the difference in glucose levels before and after acid hydrolysis. Glycogen hydrolysis was performed by boiling cell-free extracts in the presence of 1 N H2SO4 for 3 h with subsequent neutralization of Ba(OH)2 (Kondratieva et al., 1989). Experiments were repeated three times with three parallel formulations for each variant of experimental and control conditions. Data obtained were expressed as mean (x) ± standard deviation (SD) of three measurements. The ANOVA was applied for comparisons of means. Differences were considered significant at P < 0.05.

**Results**

After 10 days of bacteria growth in the medium with 4.2 mM NaNO2 and K2HPO4, KH2PO4, Na2SO4, NaCl or KClO3 at concentrations that were 0.5, 1.0, 2.0, 3.0, 4.0 times different from the maximum permissible, the inhibition in varying degrees of biomass accumulation by strains in all experimental variants was observed, compared with controls, which did not contain inorganic pollutants (Fig. 1).

![Fig. 2. The concentration of NO2– on 10-th day of cultivation of phototrophic bacteria in the medium with 4.2 mM NaNO2 and KH2PO4 (a), K2HPO4 (b), Na2SO4 (c), NaCl (d) and KClO3 (e) (x ± SD, n = 3): see Fig. 1](image-url)
In media with hydro- and dihydrophosphate ions at all concentrations inhibition of bacteria growth was negligible. The biomass accumulation by bacteria in the media with the highest studied concentration of these compounds – 4.0 times higher than the MPC, was only 1.5–1.7 times lower compared to the control. In media with sulfate, chloride and chlorate ions at concentrations 2.0–4.0 times higher than MPC, the biomass accumulation by all strains was significantly reduced. The biomass accumulation by bacteria in media with chloride and chlorate ions at concentrations 3.0–4.0 times higher than MPC was 2.0–2.8 times lower compared to the control. The greatest growth inhibition was observed in the medium with Na$_2$SO$_4$ at concentrations 2.0–4.0 times higher than MPC, and on day 10 the biomass was 2.0–4.0 times lower than in the control. Oxidation of nitrites by all strains in a medium with 4.2 mM NaNO$_2$ and the investigated pollutants was slowed down (Fig. 2). The residual content of nitrite ions in media with hydro- and dihydrophosphate, chloride and chlorate ions (at their concentrations 4.0 times higher than MPC) for 10 days slightly exceeded the content of NO$_2^–$ in the control variants, by only 1.1–1.7 times. In the medium with sulfate ions at a concentration equal to the maximum permissible and 2.0–4.0 times higher than MPC, the NO$_2^–$ residual content was significantly higher and exceeded the control values by 2.0–2.6 times. If in a medium without pollutants, cells of *C. limicola IMV K-8*, *Thiocapsa* sp. Ya-2003 and *Lamprocystis* sp. Ya-2003 strains oxidized 72.7%, 72.2% and 71.4%, respectively, nitrite ions available in the medium, then in the medium with sulfate ions at concentration 4.0 times higher than the MPC bacteria oxidized nitrite ions only at 39.6%, 34.4% and 27.0%, respectively.

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

![Graph](image5)

**Fig. 3.** The concentration of NO$_3^–$ on 10-th day of cultivation of phototrophic bacteria in the medium with 4.2 mM NaNO$_2$ and KH$_2$PO$_4$ (*a*), K$_2$HPO$_4$ (*b*), Na$_2$SO$_4$ (*c*), NaCl (*d*) and KClO$_3$ (*e*) (x ± SD, n = 3); see Fig. 1
Oxidation of a lower quantity of nitrites by cells of all phototrophic bacteria strains in media with inorganic pollutants led to the formation of a lower quantity of nitrates detected in the cultural liquid (Fig. 3). In the medium without pollutants the content of nitrate ions was significantly lower (0.46–0.61 mM) than could theoretically be formed from nitrites, oxidized by cells (3.00–3.05 mM). The concentration of nitrate ions in media with all studied pollutants on day 10 was lower than in the control variants.

The content of NO$_3^-$ in media with hydro-, dihydrophosphate and chlorate ions at all concentrations slightly (only 1.2–1.9 times) differed from the control. In media with sulfate ions at concentrations 2.0–4.0 times higher than MPC and chloride ions at concentration 4.0 times higher than MPC, the content of nitrate ions was significantly lower than in the control variants (2.1–4.3 and 2.0 times, respectively). Inorganic pollutants stimulated the synthesis of intracellular carbohydrates in *C. limicola* IMV K-8 (Fig. 4). In cells of green phototrophic bacteria grown in media with all investigated toxicants at all concentrations, a slight increase of intracellular glucose content was observed. If the glucose content in cells grown in the medium without pollutants was 10.25 mg/g dry cell weight, then in cells grown in media with K$_2$HPO$_4$, KH$_2$PO$_4$, Na$_2$SO$_4$, NaCl and KClO$_3$ at concentrations 4.0 times higher than MPC, its content grew by 12.2%, 10.7%, 51.6%, 17.1% and 35.9%, respectively. The glycogen content in the cells grown in the medium without pollutants was 45.09 mg/g dry cell weight. Hydro- and dihydrophosphate, chloride and chlorate ions at concentrations 4.0 times higher than MPC added into the medium of bacteria cultivation stimulated glycogen synthesis in cells by 47.5%, 57.6%, 67.4% and 74.6%, respectively. The glycogen content in cells grown in the medium with Na$_2$SO$_4$ at concentrations 3.0 and 4.0 times higher than MPC increased almost twice, by 102.9% and 107.5%, respectively.

![Fig. 4. Intracellular glucose and glycogen content in bacteria *C. limicola* IMV K-8 after 10 days of cultivation in the medium with 4.2 mM NaNO$_2$ and KH$_2$PO$_4$ (a), K$_2$HPO$_4$ (b), Na$_2$SO$_4$ (c), NaCl (d) and KClO$_3$ (e) (x ± SD, n = 3): see Fig. 1](image-url)
Therefore, sulfate ions showed the greatest stimulating effect on the synthesis of intracellular carbohydrates by green phototrophic bacteria, compared with other studied pollutants.

**Discussion**

Release of chemical pollutants into the environment is primarily due to the anthropogenic pressure on ecosystems – the increase in industrial production, the use of environmentally hazardous technologies, the accumulation of fertilizers, pesticides, toxic waste and so on. Chemical water pollution occurs due to the inflow of harmful impurities with wastewater of inorganic (acids, alkalies, mineral salts of various composition, metals) and organic origin (oil and petroleum products, detergents, etc.) (Camargo & Alonso, 2006; Karabyn et al., 2019; Shurhyin et al., 2020). Due to physiological and genetic features, microorganisms respond faster than other organisms to changes in the environment quality and the action of stress factors.

Photolithotrophic sulfur bacteria carry out detoxification of water bodies not only from H2S, but also NO3⁻, using them as electron donors in the process of anaerobic respiration in microorganisms, damages the structure of metalloproteins and sulfur-containing proteins, disrupts the mitochondrial respiration in eukaryotes due to depolarization of mitochondrial membranes or inhibition of cytochrome oxidase – a key enzyme in the respiratory chain. Nitrites, nitrites and other oxidized nitrogen compounds (nitrogen oxides, peroxoacetyl nitrates) are among the most dangerous pollutants of the environment. The main toxic effect of nitrates and nitrites on eukaryotes is the conversion of hemoglobin to methemoglobin, which is unable to carry oxygen. In addition, nitrates in eu- and prokaryotic cells cause changes in extracellular and intracellular levels of CT and K⁺, which causes a strong electrolyte imbalance, as well as the formation of N-nitroso compounds (nitrosamines), which are mutagenic and carcinogenic (Camargo & Alonso, 2006; Kupyers et al., 2018). The efficiency of biological methods of environmental purification depends on the metabolic activity of selected strains of bacteria and their resistance to contaminants.

The inflow of large amounts of phosphorus-containing compounds (orthophosphates, pyro-, meta- and other polyphosphates) and organically bound phosphates into non-flowing water bodies leads to their eutrophication (Krishnaswamy et al., 2011). Active chlorine has a complex influence on various structures of microorganisms: the cytoplasmic membrane, cytoplasmic proteins, genome, as well as respiratory chain enzymes, with blocking SH-groups. Another function of CT is Na⁺ homeostasis: the efficiency of Na⁺ export might be enhanced by simultaneous export of Cl⁻. Toxic effects of chlorates might be reduced by simultaneous export of Cl⁻, because glycogen as a secondary metabolite is a reserve of inorganic (acids, alkalis, mineral salts of various composition, metals) and organic origin (oil and petroleum products, detergents, etc.) (Camargo & Alonso, 2006; Karabyn et al., 2019; Shurhyin et al., 2020). Due to physiological and genetic features, microorganisms respond faster than other organisms to changes in the environment quality and the action of stress factors.

**References**


