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# Phytoplankton communities of polar regions - diversity depending on environmental conditions and chemical anthropopressure

KLAUDIA KOSEK[a], ŻANETA POLKOWSKA[a*], BEATA ŻYSZKA[b], JACEK LIPOK[b]

*corresponding author

[a]Department of Analytical Chemistry, Faculty of Chemistry, Gdansk University of Technology, 11/12 Narutowicza St., Gdansk 80-233, Poland, klaudia_kosek@wp.pl, zanpolko@pg.gda.pl

[b]Department of Analytical and Ecological Chemistry, Faculty of Chemistry, Opole University, Oleska 48 St., Opole 45-052, Poland, bzyszka@uni.opole.pl, jalip@uni.opole.pl

## Abstract

The polar regions (Arctic and Antarctic) constitute up to 14% of the biosphere and offer some of the coldest and most arid Earth's environments. Nevertheless several oxygenic phototrophs including some higher plants, mosses, lichens, various algal groups and cyanobacteria, survive that harsh climate and create the base of the trophic relationships in fragile ecosystems of polar environments. Ecosystems in polar regions are characterized by low primary productivity and slow growth rates, therefore they are more vulnerable to disturbance, than those in temperate regions. From this reason, chemical contaminants influencing the growth of photoautotrophic producers might induce serious disorders in the integrity of polar ecosystems. However, for a long time these areas were believed to be free of chemical contamination, and relatively protected from widespread anthropogenic pressure, due their remoteness and extreme climate conditions. Nowadays, there is a growing amount of data that prove that xenobiotics are transported thousands of kilometers by the air and ocean currents and then they are deposed in colder regions and accumulate in many environments, including the habitats of marine and freshwater cyanobacteria. Cyanobacteria (blue green algae), as a natural part of phytoplankton assemblages, are globally distributed, but in high polar ecosystems they represent the dominant primary producers. These microorganisms are continuously exposed to various concentration levels of the compounds that are present in their habitats and act as nourishment or the factors influencing the growth and development of cyanobacteria in other way. The most common group of contaminants in Arctic and Antarctic are persistent organic pollutants (POPs), characterized by durability and resistance to degradation. It is important to determine their concentrations in all phytoplankton species

cells and in their environment to get to know the possibility of contaminants to transfer to higher trophic levels, considering however that some strains of microalgae are capable of metabolizing xenobiotics, make them less toxic or even remove them from the environment.

**Keywords:** Arctic environment, cyanobacteria, persistent organic pollutants (POPs), phytoplankton communities

## 1. Introduction

Phytoplankton is a taxonomically diverse group of photosynthetic aquatic microorganisms, mostly single-celled, that sometimes join together into colonies, drifting with the currents (Fig. 1). Phytoplankton plays a crucial role in primary production, nutrient cycling, and food webs and makes up a significant proportion of the primary production in aquatic ecosystems (Dawes 1998). This group of organisms consists of approximately 20 000 species distributed among at least eight taxonomic divisions. In contrast, higher plants are comprised of more than 250 000 species, almost all of which are contained with one class in division.

**Fig. 1.** Simplified taxonomic classification of phytoplankton

Phytoplankton communities are phylogenetically diverse, which is reflected in their ecological function. Within this diverse group of organisms, there are some basic evolved species (Delwiche 2000), for instance - all strains of prokaryotic oxygenic phytoplankton that belong to one class of bacteria, named cyanobacteria (Falkowski et al. 2003). Cyanobacteria (blue green algae) are one of the largest, extremely diverse morphologically and metabolically, and phylogenic unique group of Gram-negative, photosynthetic prokaryotes. For the sake of that, they show a wide range of tolerance to multiple environmental factors, they can be found in almost all ecological niches. These organisms were initially described as algae in the eighteenth century and the first classification system was based on the International Code of Botanical Nomenclature. In the botanical taxonomy, two major works may be noted: the first one described by Geitler in 1932 including 150 genera and 1500 species of cyanobacteria and the second one described by Anagnostidis and Komárek (e.g. Komárek and Anagnostidis, 2005) aimed at defining more genera, both based on the morphology. After the prokaryotic nature of cyanobacteria became more obvious on the basis

of ultrastructural and molecular studies, it was proposed that their nomenclature should be governed by the International Code for Nomenclature of Bacteria (Stanier et al. 1978).

Cyanobacteria differ from other types of bacteria in that they have chlorophyll *a* and free oxygen is given off during the process of blue green algae photosynthesis. Many bacteria split $H_2S$ instead of $H_2O$ as a source of electrons during their photosynthesis - this is why they do not produce free $O_2$. Those other bacteria contain bacteriochlorophyll instead of chlorophyll *a* as their main photosynthetic pigment (Bold and Wynne 1985). Cyanobacteria are prokaryotic microorganisms, which have only a haploid life cycle (while all algae life cycles have an alteration of generations), they reproduce through simple fission, since their DNA is not associated with histone proteins (Clark et al. 1998).

Cyanobacteria are commonly thought to be microbial phototrophs that are characteristic of warm water environments such as hot springs, stratified lakes during summer or tropical oceans (Steunou et al. 2006; Vazquez et al. 2005; Johnson et al. 2006). It is less known that cyanobacteria exist also in low-temperature habitats including permafrost, cryconites, rock surfaces, glacier pools, rivers and coastal areas, and offshore waters represent probably the largest untouched biological resource on our planet (Zakhia et al. 2008, Lyon and Mock 2014). Microorganisms inhabiting cryoenvironments have to face the challenges of subzero temperatures, low water activity, and, often, high solute concentrations to sustain their viability (Lay et al. 2013). There are some unique characteristics of blue green algae that are responsible for this wide variety of habitats for example: the climate-resistant spores that may form when environmental conditions become harsh (Bold and Wynne 1985). Cyanobacteria play a key role in Arctic ecosystems as primary producers and are well adapted to prolonged freezing, exhibiting activity even at temperatures as low as -20°C (Sabacká and Elster, 2006; Vincent et al. 2004). They are often the predominant oxygenic phototrophs of such ecosystems because of the ability to tolerate the abiotic stresses that prevail in these perennially cold environments (Zakhia et al. 2008). Their presence was observed even during the early explorations of the polar regions at the end of the nineteenth century (Vincent 2007). These microbial communities are potential analogues for biotopes present during the major glaciation events of the Precambrian and also suggest that cyanobacteria would have been present throughout Proterozoic events and earlier periods of global cooling (Schopf 2000; Zakhia et al. 2008).

The focus of this review is to describe the environmental conditions that allow the photoautotrophs, especially cyanobacteria, to growth, develop and proliferate, but also these

ones that may influence or even limit their existence in polar regions. Furthermore, many mechanisms that let the phytoplankton species to survive in harsh polar conditions are emphasized in the context of the presence of chemical pollutants (with respect to their determination) in cyanobacterial habitats and in cells, due to the disquieting transfer of these substances to upper trophic levels.

## 2. Problem of eutrophication as the promoting factor of cyanobacterial proliferation

Eutrophication of the water ecosystems seems to be the most crucial factor that dramatically elevates the role and position of cyanobacteria in the consortia of water micro photoautotrophs. This problem became acute more than 40 years ago and still remains unresolved (Moiseenko et al. 2001).

There was a lot of uncertainty about the physical, chemical and ecological details of the eutrophication process and hot debates raged about the relative roles of different mineral nutrients as constraints on or regulators of, primary productivity especially the macronutrients nitrogen (N), phosphorus (P) and carbon (C) with the consequent increase in the growth of algae and higher plants (Smith 2006). Eutrophication is facilitated by external and internal sources of nutrients. Input of nutrients may be from one point or diffuse sources (Shaw 2003) (Table 1).

**Table 1.** Examples of some point and diffuse sources of nutrients that lead to water eutrophication (Shaw 2003)

In freshwater environments, anthropogenic input of nutrients (called cultural eutrophication) has been demonstrated to be a major contributing factor to eutrophication and consequently algal bloom. High concentrations of nutrients promote excessive growth of algae. As the algae die and decompose, high levels of organic matter and decomposing organisms deplete the water of available oxygen causing the death of other organisms (Fig. 2). While relatively common in lower-latitude ecosystems, cultural eutrophication has been limited in scope in the polar regions as a result of the lesser effects of human activities at high latitudes. However, as growth and development continue around the Arctic, the freshwaters of the region will be increasingly subject to human-induced eutrophication (Schindler and Smol 2006). Increased nutrient influx to lakes and higher trophic status may be also the predicted effects of climate warming in arctic aquatic ecosystems independent of point-source pollution

and therefore it is possible that eutrophication process may occur in many arctic lakes in the future (Prowse et al. 2006). There have not been many comprehensive studies of Arctic limnology but one of the lakes that was examined is Meretta Lake in the 1970s. The limnological interest in Meretta Lake is driven by the inputs of human sewage that it has been receiving for nearly four decades. Some studies of this lake have included photosynthesis pigments, stable isotopes of carbon, nitrogen, phosphorus and organic matter content (Antoniades et al. 2011). Definitely it must be said that nutrient enrichment causes an intensification of all biological activity and typically leads to dramatic changes in the composition and structure of aquatic food webs. Two of the most consistent eutrophication effects include a shift in algal species composition and an increase in the frequency and intensity of inconvenient algal blooms which in eutrophic freshwater lakes are typically dominated by harmful cyanobacteria (Downing et al. 2001; Huisman et al. 2005).

**Fig. 2.** The process of eutrophication

As well as nutrient contributions, the input of contaminants into arctic freshwaters can also have a detrimental effect on photoautrotrophs and on natural processes appearing in these aquatic ecosystems. For instance herbicides and other pollutants may inhibit self-purification processes involving all phytoplankton species (Shaw 2003).

## 3. Phytoplankton communities: taxonomic diversity and morphological advantages

Genetic diversity at the population level of species plays an important role in the interactions of species with the environment and also the environment has a big impact on a species variety (Medlin et al. 2000). There is growing appreciation that the composition, abundance, and trophic efficiency of phytoplankton communities are tightly linked to water temperature and the latitude of water reservoirs (Richardson 2008). The phytoplankton of lakes located in the temperate zones is characterized by the dominance of diatoms, especially in winter and fall and Chlorophyta, Cyanophyta and Phytoflagellates in summer. Diatoms during summer stratification frequently are excluded by silica limitation in particular when high availability of other nutrients (phosphorus and nitrogen) allows the build-up of large diatom populations, which leads to the depletion of silica within the euphotic zone. In lakes that have been affected by eutrophication, cyanobacterial communities have become very abundant, to the point of forming water blooms. However, cyanobacterial abundance in such

lakes is restricted to periods of thermal stratification and hence of low water turbulence and elevated temperatures. Cyanophytes may be abundant in the relatively shallow large-lakes but massive blooms at least are absent in deep large lakes. Even in the low-latitudes reservoirs, cyanobacteria appear to be restricted to periods of stable stratification (Pollingher 1990). On the other hand, there are many species of phytoplankton living in high-latitude lakes, however diatoms and chrysophytes are the dominant groups. The polar region environment is particularly interesting for studies on the adaptation of phytoplankton to extreme environmental conditions: water temperature, day length, available light and water column stability (Harrison and Platt 1986).

Some studies of phytoplankton include consideration of cell/organism size and shape that affect the appearance in various aquatic reservoirs depending on the availability of nutrients (Peters 1983; Chisholm 1992; Brown et al. 1993; Marba et al. 2007; Naselli-Flores et al. 2007). Phytoplankton size spans several orders of magnitude (from 1 μm to 1 mm) or so for individual cells and even more for colonial organisms. Such diversity of sizes suggests that there is not a universal best size but that differences are selected for by diverse selective pressures (Litchman et al. 2009). Small sizes, for example less than 10-20 μm, are advantageous under nutrient-limiting conditions due to the high surface area to volume ratio. Phytoplankton cells are surrounded by a diffusive boundary layer, which imposes an additional constraint on cell size. Nutrient molecules are first transported across the boundary layer by molecular diffusion before they are taken up at the cell membrane. The two steps (transport and uptake) co-limit the nutrient flux (Yoshiyama and Klausmeier 2008). Smaller cell sizes are even more beneficial in competition for nutrients under nutrient-limited conditions than may be predicted based on the larger surface to volume ratio. Limitation of transport relative to uptake is more visible for larger cells. Nutrient flux can also be enhanced depending on the cell shape. In stagnant water, elongated cells may take up more nutrients than spherical cells of equivalent volume due to the larger surface to volume ratio. Alternating selective pressures (e.g. nutrient limitation, light availability or fluctuating nutrient supply) may be selected for different sizes and create diversity in size distributions in natural communities. It can be also possible to infer a dominant selective pressure on phytoplankton species by analyzing cell size distributions. If the range of optimal sizes selected by temporally varying drivers is greater than the intraspecific size variation, different optimal sizes would be represented by different species and consequently lead to diversity of species (Litchman et al. 2010).

## 4. Environmental and physiological conditions that allow cyanobacteria to grow, develop and proliferate in polar regions

Early studies on the limnology of the polar regions paid attention to the apparent lack of cyanobacteria in the plankton despite the eutrophic conditions which would favor blooms of cyanobacteria in waters of temperate latitudes. More studies confirmed that the larger colonial and filamentous bloom-forming taxa were relatively rare in polar lakes (Kalff and Welch, 1974; Kalff et al. 1975). Despite that, the advent of fluorescence microscopy revealed that picoplanktonic species of cyanobacteria are abundant and may be even dominant in the phytoplankton community of lakes in both polar regions (Vincent 2002). Moreover, the growth of cyanobacteria has increased markedly over the last five years mostly in ice-free areas and in the shallow waters that ring the Arctic Ocean. In these areas algal growth rates increased because the sea ice cover melted sooner and froze later in the year, giving the algae increasingly more time to growth. Physical and chemical properties of these waters influence the survival strategies of phototrophic organisms therefore knowledge of them is an integrative step to understand microbial photoadaptation (Morgan-Kiss et al. 2006).

### 4.1. Polar cyanobacterial mats

Cyanobacterial mats are dominant features of polar lake, pond, and river ecosystems, with some of the most luxuriant communities growing on the thick ice shelves that float on Arctic and Antarctic seas. The stresses encountered by organisms on polar ice shelves include sparse nutrients, freeze-thaw cycles, bright sunlight exposure during summer, prolonged darkness during winter, salinity fluctuations, desiccation, and persistent low temperatures. Extreme cold is an overarching stress in the polar regions because it drastically modifies the physical-chemical environment of living cells, with effects on biochemical reaction rates, substrate transport, membrane fluidity, and conformation of macromolecules, such as DNA and proteins. Once the freezing point is crossed, there are additional physical and chemical stresses imposed by ice crystal formation, water loss, and increasing solute concentrations. Various physiological adaptations, such as increased membrane fluidity, synthesis of cold-adapted enzymes and production of cold shock and antifreeze proteins enable bacteria to survive under cold conditions, and bacterial activity has been detected at subzero temperatures in sea ice and snow (Møller et al. 2013).

Although polar ice shelf mats are visually dominated by cyanobacteria, other microorganisms, including *Bacteria*, *Archaea*, and protists, live within these mats, supporting microinvertebrates, such as nematodes, rotifers, and tardigrades. Previous studies on the mats have shown that they contain much higher concentrations of nutrients than the overlying ultraoligotrophic water. Furthermore, proteins involved in diverse scavenging and recycling processes are coded for within the mat metagenome, suggesting that the cyanobacteria profit, in terms of the recycled nutrient supply, from the close proximity to other microorganisms. However, cyanobacteria isolated from both the Arctic and Antarctica are psychrotolerant rather than psychrophilic, with growth optima at temperatures that are well above those of the ambient environment. Consistent with these observations, *in situ* measurements of Arctic ice shelf mats have shown that photosynthesis increases with rising temperatures up to the limit tested (20°C, well above the maximum ambient water temperature of 1.7°C), while bacterial production showed no such trend, with rates at 2.6°C that were as high as or higher than those at warmer temperatures (Varin et al. 2012).

### 4.2. Planktonic and benthic communities of cyanobacteria

Cyanobacteria in polar freshwater can be found as benthic and planktonic communities. Benthic communities are the richest biomass accumulation that occur in the habitats of lakes and ponds (Zakhia et al. 2008) and the most common groups are Oscillatoriales, Nostocales and some Chroococcales (Bonilla et al. 2005). Plankton communities are mostly comprised of Synechococcus morphotypes. Figure 3 presents the most common species of occurring groups of cyanobacteria in polar freshwaters. Bacteria in cold-habitats are mostly pigmented and it is well known that pigment production is important in cold-adaptation (Prasad et al. 2012).

The abundance of cyanobacteria seems to be correlated with nutrient availability - particularly nitrogen and phosphorus. The main source of nitrogen (N) for pristine, unpolluted ecosystems is the fixation of atmospheric $N_2$ performed by symbiotic, associative and free-living $N_2$ fixers (diazotrophs). Polar ecosystems generally receive low amounts of atmospheric N deposition, thus, the primary input of N in these ecosystems is the fixation of $N_2$ performed by free-living as well as by diazotrophs living in association or symbiosis with mosses (cyanobacteria, methanotrophs), legumes (rhizobia) and lichens (cyanobacteria) (Rousk et al. 2014).

**Fig. 3.** The most common groups of cyanobacteria that appear in polar freshwaters (photographs from the authors' own collection)

Both types play an important role in Arctic water environment as the first organisms in aquatic food chain. Many of benthic taxa have extremely thin trichomes (ca. 1 μm in diameter) and because of these morphological characteristics their light absorbing properties are as efficient as small coccoid (Vincent 2002). Cyanobacteria form highly pigmented layers over the bottom substrata and may gradually accumulate as mucilaginous films and mats up to several centimeters or even several tens of centimeters in thickness. Five types of benthic mats may be observed among blue green algae communities in both polar regions (Table 2) (Vincent 2002).

**Table 2.** Types of benthic mats among blue green algae communities (Vincent 2002)

As elsewhere, the Arctic and Antarctic mats are multilayered three-dimensional structures, where exo-polymer-producing cyanobacteria create an environment than can be colonized by other microorganisms (Zakhia et al. 2007). Cyanobacterial mats could be refuge for diverse communities of organisms in the polar environment. The mats at these sites are in close contact with soils and sediments, which would provide an additional source of biota, as well as organic matter and nutrients. The functionally more complex diversity of taxa found in the Arctic may potentially be attributed to milder conditions found at some parts, as well the greater connectivity to temperate continental regions relative to Antarctica (Jungblut et al. 2012).

### 4.3. Nutrient supply

Polar and alpine freshwater reservoirs are typically thought of as low-resources ecosystems in which the photosynthetic communities are severely constrained by nutrient supply (Bonilla 2005). Shallow water environments such as streams, ponds and lakes are intimately linked with dissolved inorganic nutrient sources from surrounding terrestrial environments. Wetland and lake sediments and the water surface of stream hyporheic zones or groundwater can also supply nutrients to benthic photoautotrophs. Nutrient availability is determined by the physical and chemical phenomena that control nutrient flux from these environments (Whitton 2012). It has been observed that inorganic nutrients are bound to small soil particles in lake sediments and a considerable amount of them can be leached. In studies described by Priscu (Priscu et al. 2005), it is claimed that the average amounts of ammonium and phosphorus that can be leached from lake sediments are 7.1 μgN/g and 4.1 μgP/g,

respectively. The ratio of leachable N:P is 1.7 which is below what is required for balanced cyanobacterial growth (Singh and Elster 2007). These nutrients tend to be one or more orders of magnitude higher in the interstitial waters of polar mat communities than in the overlying water column (Vincent et al. 1993; Villeneuve et al. 2001) and there is also molecular evidence of that these mats are active sites of nutrient regeneration and scavenging (Varin et al. 2010). Nutrient scavenging systems including genes for transport proteins and enzymes converting larger molecules into more readily assimilated inorganic forms. This analysis underscored the capacity of polar microbial mat consortia to retain and recycle nutrients in an otherwise oligotrophic environment (Varin et al. 2010). In many Arctic mat communities (e.g. Bergmann and Welch 1990), nitrogen supply is supplemented by nitrogen fixation. Nitrogenase activity is strongly regulated by temperature and moisture availability with maximum activity in December and January when the $N_2$-fixing mats are well supplied with meltwater and when ground temperatures rise to 8-10 °C (Davey and Marchant 1983). Fixation of dinitrogen by cyanobacteria may be an important contribution to the nitrogen budget of polar lakes, ponds and streams (Vincent 2002).

If one considers marine species of polar cyanobacteria and also those living in temperate regions, they are in a relatively small amount but there are obviously some exceptions. Chroococcoid forms of cyanobacteria generally ascribed to the genus Synechococcus are widely distributed throughout the world oceans and in many temperate and tropical regions they constitute a major, sometimes dominant, fraction of total phytoplankton biomass and productivity (Waterbury et al. 1986). The polar oceans are a notable exception. In the Arctic as well as Antarctic, concentrations of this genus fall to low values, often below $10^2$ cells/mL. Higher concentrations occur in sea ice, although such populations may represent cells which were trapped in the ice during freezing (Walker and Marchant 1989). Two types of picocyanobacteria were also distinguished in the Southern Ocean, on the basis of their cell wall ultrastructure, indicating the presence of genetically different strains (Marchant et al. 1987). Furthermore, there are some records of picocyanobacteria in the seas of the north polar regions however they are not major components of the phytoplankton. Mishistina et al. (1994) reported that Synechococcus occurred as an epiphyte on the blades of brown algal macrophytes in the littoral zone of the Barents Sea. In another study of northern waters (Gradinger and Lenz 1995), there were measured strong seasonal, spatial and depth variations in the abundance of picocyanobacteria in the Greenland Sea with the highest concentrations (up to 5470 cells/mL) in Arctic

Intermediate Water. However, they were virtually absent from water collected inside the central Arctic Ocean what may suggest that their appearance in the Greenland Sea was due to a high survival ability during the advection from the North Atlantic (Vincent 2002).

## 5. Non optimal conditions that may influence, or even limit the life of cyanobacteria in polar regions

Cyanobacteria have to contend with many harsh conditions that occur in polar regions therefore they had to develop the range of physiological strategies to deal with such conditions (Vincent 2007) (Fig. 4)

**Fig. 4.** Main adaptation strategies developed by cyanobacteria to survive in harsh polar conditions (Vincent 2007)

The strong seasonality of solar irradiance is the major factor that influences the availability of light for photoautotrophic organisms at high latitudes (Mock and Thomas 2008). Polar cyanobacterial mats live under two extremes of high and low irradiance conditions and they are capable of acclimating to both extremes. Many of them inhabit surface or shallow-water environments in which the exposure to continuous radiation in summer may play a role in limiting microbial colonization and growth (Vincent 2002). The polar mat communities cope with harsh conditions typical of cryo-ecosystems, including persistent low temperatures, variable freeze-thaw cycles, prolonged winter darkness, continuous solar irradiance in summer, and rapidly fluctuating osmotic regimes. The phototrophic communities in these mats rely on internal nutrient recycling and scavenging systems to cope with the low allochthonous input of nutrients that is typical of ultra-oligotrophic freshwater ecosystems in the polar desert environment. (Varin et al. 2010). Cyanobacteria-dominated microbial mats provide microhabitats in the polar environment that are shielded from many of the stresses that characterize their surroundings. For example, cyanobacteria produce UV (ultraviolet) screening pigments, enzymes, and carotenoids that quench reactive oxygen species, solute-binding materials, water absorbing gels, antifreeze compounds, and ice-nucleating substances (Zakhia et al., 2007), which will reduce oxidative, osmotic, freeze-thaw, and dehydration stresses for all organisms embedded within the microbial mat matrix. In contrast with their overlying ultra-oligotrophic waters, the mats are also rich in inorganic nutrients (Bonilla et al., 2005), recycled organic matter and bacteria

(Varin et al., 2010) that may provide food for eukaryotic heterotrophs such as ciliates and the metazoan microfauna. The presence of saprophytic, phagotrophic, parasitic and predatory eukaryotes would increase the number of links within the mat for nutrient and energy transfer, thereby increasing trophic complexity and potential resilience to environmental change (Duffy and Stachowicz, 2006). In addition, the inhospitable environmental conditions outside the mats and resulting microbe crowding provide an environment where chemical signaling and species interactions linked to predation, parasitism, mutualism, and symbiosis are likely important (Pernthaler, 2005; Martinez-Garcia et al., 2012). Bacteria within mats could also produce chemical grazing deterrents, limiting some grazers that would otherwise destroy mat integrity, as suggested for temperate regions (Stal, 2000).

Cyanobacteria are able to avoid ultraviolet radiation (UVR) by their choice of habitat such as beneath rock surfaces or deep within microbial mats, the bottom of perennially ice-covered lakes as well as by migration up and down the mat profiles. The consequence of adopting such a strategy is that only low photosynthetically active radiation (PAR) is available for growth. However in some environments this strategy may be more closely linked to water supply and desiccation tolerance than UVR avoidance (Davey and Clarke 1991). Another type of avoidance strategy is production of light-screening pigments. Cyanobacteria of the cold regions show two classes of such compounds: lipid-soluble sheath pigments (gloeocapsin and scytonemin) and the former one which forms rust-coloured crust over rocks in streams. The sheath pigment scytonemin that is found in several cyanobacteria absorbs maximally in the UV-A end of the spectrum (Garcia-Pichel and Castenholz 1991; Proteau et al. 1993) and may be in such high concentrations (e.g. in Nostoc colonies that the cyanobacterial mats or crusts are black). High concentrations of this pigment occur in mat-forming communities in many types of arctic, antarctic and alpine communities (Vincent and Quesada 1993). Another class of screening pigments is water-soluble mycosporine-like amino acids (MAAs) that may be found within the cells and absorb maximally at the UV-B end of the incident solar spectrum (Cockell and Knowland 1999). Some studies on a High Arctic cyanobacterial mat showed that these compounds were four times higher per unit chlorophyll *a* (Chl*a*) in the surface relative to the bottom layer (Quesada et al. 1999). One of the most grave damaging effects of exposure to high solar radiation is the production of reactive oxygen species (ROS) such as singlet oxygen, superoxide and hydrogen peroxide. Cyanobacteria have a variety of enzymatic and pigment strategies for quenching these highly toxic substances including production of ROS-quenching carotenoids which appear in

cyanobacterial mats in streams, lakes, ice shelf ponds and other shallow, brightly lit habitats that are often pigmented pink or orange with high carotenoid pigmentation (Vincent 2007).

Other important factors that contributes to the success of polar cyanobacteria in adopting to harsh conditions include coping with the cold and low water activity, withstanding freeze-thaw conditions and related stresses of high salinity. Cyanobacterial communities developed a variety of mechanisms to deal with these conditions. For example, to maintain membrane fluidity at low temperatures, polyunsaturated fatty acids with decreased chain-lengths are incorporated into the membrane. In addition, the production of compatible solutes helps to reduce the freezing point of the intracellular fluid. This strategy also reduces cell desiccation as less water is needed to retain the osmotic equilibrium (Welsh 2000). Furthermore, extracellular compounds such as polymeric substances may reduce ice nucleation around the cells (Vincent 2007). Regarding this, it is worth to note that cyanobacteria produce large amounts of extracellular polymeric substances (EPS) and were the primary source of EPS genes in the mats from both Arctic and Antarctica. These substances play an important role in buffering and cryoprotection for diverse microorganisms against ice crystal damage and high salinity. EPS allow bacterial aggregate formation, which in turn provides opportunities for close biogeochemical interactions. It is known that there exists significant correlation between concentrations of local bacteria and EPS in Arctic winter sea ice. In harsh environments, such as the polar regions, it is likely that EPS contributes to the physical stability of microbial communities (Varin et al. 2012).

The streams and shallow ponds may dry completely in late summer of freeze solid and then ablate to leave dry frozen communities. These later experience elevated salinities as the remaining solutes are redissolved and mobilized at the onset of the thaw of the next season. Such freeze-concentration effects may be extremely severe for the microbial mats living at the bottom of high latitude ponds that freeze completely in winter (Vincent 2002). Some conducted studies show correlation between freezing of ponds and their salinity variations (e.g. Schmidt et al. 1991). These waters have a relatively low conductivity in summer but the dissolved salts are excluded from the ice during winter freezing and there is a gradual concentration of solutes in the remaining water (Oren 2000; Vincent 2002). The cyanobacteria that live in polar streams are capable of maintaining huge populations of viable cells on the dry frozen stream bed throughout winter. These populations provide a large inoculum that may contribute a substantial percentage of the total standing stock during the next growing season. These overwintering assemblages begin photosynthesis, respiration and nutrient

uptake within 30 minutes to a few hours of rehydration (Vincent and Howard-Williams 1986). It is known that the presence of cyanobacteria in polar freshwaters is bigger than in marine habitats what may simply reflect their limits of tolerance to salinity. Wright and Burton (1981) noted that the combined extreme of salinity and low temperatures exerted a severe physiological stress on organisms and can account for the absence of cyanobacteria from some of the hypersaline lake environments (Vincent 2002).

Cyanobacterial communities are also able to tolerate very low water potentials what is connected with their extreme tolerance to osmotic stress and desiccation conditions (Wynn-Williams 2000). Recovery from desiccation conditions appears to vary among species and polar communities. Metagenomic studies have revealed a broad spectrum of stress genes in both polar cyanobacterial mats, including sigma B genes that may be involved in acclimating to freeze-up and osmotic stress (Varin et al. 2012).

One of the characteristic features of the polar cyanobacteria is their low growth rate in culture as well as in the natural environment. This may be an effect of very low temperatures that they have to deal with, perhaps compounded by osmotic stress in some habitats. In polar oceans these temperature-depressed growth rates can be slowed light-limitation in deep mixed layers. On the other hand, cyanobacterial assemblages are able to achieve net growth over a broad range of pH, nutrient concentrations, UV radiation and PAR. These physiological tolerances are likely to be important in highly variable freshwater habitats but may be less useful in oceanic environments (Vincent 2002).

## 6. The determination of chemical pollutants in phytoplankton, especially in cyanobacterial habitats and cells

In the aquatic ecosystems, phytoplankton is the foundation of the food web in providing a nutritional base for zooplankton and subsequently to other invertebrates (Emmanuel and Onyema 2007). For many bioaccumulative compounds, the principal route of movement into and through aquatic food webs is via dietary ingestion rather than via bioconcentration from water. This is apparently because these compounds mainly exhibit low water solubility and tend to concentrate in the lipid fractions of biological tissues such that the principal group of these compounds that is available to upper-trophic-level consumers is from dietary items rather than from abiotic media (Suedel et al. 1994). Once the contaminants are

bioaccumulated, organism lipids become the dominant force that control the dynamics of distribution and the manifestation of toxic effects. The interaction of xenobiotics with lipids mainly depends on the ability of the contaminant to dissolve in the lipid and not crossing the cell membrane except through facilitated or active transport sites.

Therefore, it is important to determine pollutants in all phytoplankton species cells and in their environment to get to know the possibility of contaminants to transfer to higher trophic levels (Walsh 1978; Wang and Wang 2005). Figure 5 shows a possible arctic food chain and consequently transfer of contaminants through all organisms.

**Fig. 5.** An example of arctic food chain (Wang and Wang 2005; Kozak et al. 2013)

### 6.1. Contaminants bioaccumulation in the cells of selected phytoplankton species

There are a lot of countries and regions in which the scientists have studied phytoplankton samples. Due to selected literature, the greatest amount of research was conducted in United States and Great Britain, a little less in China and India. The rest of research on temperate regions was conducted in Vietnam, Sweden, Russia, Poland, Kuwait, Brazil and Australia. If one considers Arctic and Antarctic, there was the same amount of studies conducted in both polar regions in presented literature (Fig.6).

**Fig. 6.** Countries and regions in which phytoplankton samples were studied

The majority of studies on the toxicity and pollutant accumulation in phytoplankton cells have focused on the temperate areas communities - 74,0%, less on the ones present in cold areas - 26,0% (Fig. 7). It may be caused by the remoteness of these species which avoids an easy and economically affordable testing. Moreover, polar communities are difficult to cultivate, decreasing drastically their survival after isolation. Despite this, the amount of polar studies is still increasing (Echeveste et al. 2014).

**Fig. 7.** Percentage amount of studies of phytoplankton samples collected from polar and temperate regions

Due to important issue of xenobiotics transfer and consequently bioaccumulation in the cells of the organisms of each trophic level, table 3 presents some examples of contaminants accumulated in selected phytoplankton cells (e.g. some types of cyanobacteria, snow and ice algae, diatoms, flagellates, dinoflagellates, green algae, microalgae, macroalgae) and also few environmental samples analyses (e.g. snow and ice of the glacier surface).

**Table 3.** Literature information about determined contaminants in phytoplankton and their environment

It has been observed that the most common groups of compounds that were detected in phytoplankton species and the environment are metals: 35,0% (e.g. Ca, Mg, Zn, Cu, Cd, Pb, Al, Ti, Fe, Mn, Mo, Co, Ni, V, Hg, As) and also polychlorinated biphenyls: 30,0%. Other compound that was detected in a large scale is dissolved organic carbon: 25,0% (Fig. 8).

**Fig. 8.** Percentage amount of determined xenobiotics in selected samples presented in the literature

In table 4, there are shown some examples of contaminants determination (with concentration ranges) in selected phytoplankton species and in the aquatic environment where they live. Phytoplankton samples are usually collected using nets of synthetic gauze, water bottles and pumps. Net samples cannot be used for quantitative studies because they do not retain all the organisms quantitatively. However, they may be very useful in providing material for morphological and taxonomic work. Pumps and water bottles sample the entire spectrum of planktonic algae. Furthermore, the sample volume may be accurately determined and several depths can be sampled at the same time with water bottles. A negative aspect is that they do not concentrate the organisms as the nets do. This must be done after collection, most often after preservation with buffered formalin or an iodine fixative. The purpose of the fixative is to stabilize the cells well enough to permit identification at some later time (Heimdal 1989).

Many biological parameters have been used to define pollutant levels in phytoplankton (Shaw 1990), such as reduction of photosynthetic electron transport, inhibition of respiratory oxygen consumption or disruption of nutrient uptake processes, which may inhibit the primary production in aquatic ecosystems (Davies 1978; Thomas et al. 1980).

**Table 4.** Literature information about contaminants determination in selected phytoplankton species and their environment all over the world

Remote sites, such as Polar regions were previously regarded as pristine environments where there were no significant sources of pollutants. However, there has been increasing evidence that these areas are contaminated with certain chemicals, particularly Persistent Organic Pollutants (POPs). Even though there are no significant local sources of POPs, considerable concentrations of POPs have been detected in these areas. Atmospheric transport processes such as global cold-trapping, fractionation, and long-range atmospheric transport

are believed to be an important and rapid route of transport for POPs to these otherwise pristine locations (Table 5).

### 6.2. The most common xenobiotics that appear in arctic environment

- *Polycyclic aromatic hydrocarbons:*

Polycyclic aromatic hydrocarbons (PAHs) are biologically toxic, biopersistent chemical components accounting for about 20% of crude oil and include the range of compounds with two or more condensed aromatic rings either with or without alkyl groups substituent (Neff 1990). They are natural constituents of crude oil but they are also released as a result of the combustion of petroleum-based fuels (Boehm et al. 2004). PAHs have low vapor pressures and therefore they are rapidly absorbed by particulate matter and living organisms. The Integrated Risk Information System (IRIS) of the U.S. Environment Protection Agency (EPA) contains assessments of over 540 individual chemicals with potential human health effects (Torres et al. 2008). The EPA has identified 16 unsubstituted PAHs as priority pollutants (Rodríguez and Sanz 2000).

- *Polychlorinated biphenyls:*

Polychlorinated biphenyls (PCBs) are a class of chlorinated derivatives of aromatic organic compounds with 1 to 10 chlorine atoms attached to biphenyl which is a molecule composed of two benzene rings. The empirical formula of PCBs is $C_{12}H_{10}$-$xCl_x$. They are also referred to different trade names such as Aroclor, Pheonclor, Askarel, Clophen, Therminol and Kanechlor (Subashchandrabose et al. 2013). PCBs comprise mixtures of 209 possible synthetic organic chemicals (congeners), ranging from oily liquids to waxy solids. Due to their non-inflammable nature, chemical stability and insulating properties, commercial PCB mixtures have been used in many industrial applications, for example in transformers and other electrical equipment (Torres et al. 2008). Biodegradation processes including dechlorination may transform PCBs effectively altering their potential toxicity but these reactions are usually slow while altered PCB mixtures can persist in the environment for many years (Borja et al. 2005; Doick et al. 2005).

- *Pesticides:*

Intensive agriculture with dependence on agrochemicals such as fertilizers and pesticides (herbicides and insecticides) has increased global food production but at the same

time polluted environment considerably (Subashchandrabose et al. 2013). The safest pesticides should not affect non-target species usually in the soil zone and not persist in the environment. In practice, most pesticides are often not rapidly degraded (rapid degradation might reduce their applicability). Therefore, it is likely that a large volume of pesticide residues accumulates in the environment. Moreover, pesticides do not always remain in the soil but they find their way into sedimentary systems through leaching, surface run-off, spray drift, soil erosion and volatilization. A complex range of factors determines the fate of pesticides applied to agricultural soils including method of application, active ingredients, weather conditions, land topography, soil type etc. These factors all influence the persistence and extent of contamination of non-target sites (Warren et al. 2003; Torres et al. 2008). Finally, all pesticides may also be transported over long distances and can be trapped in cold arctic water reservoirs.

- *Dioxins:*

The terms "dioxin" or "dioxin-like" refers to a group of chemical compounds that share chemical similarities and mode-of-action (biological) characteristics. A total of 30 of these dioxin-like compounds belong to three closely related families: the polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and certain PCBs. PCDDs and PCDFs are generated as unwanted by-products of chemical syntheses but may also be produced inadvertently in nature. Other sources of these xenobiotics are: combustion, chlorine bleaching of pulp and paper and many industrial processes (Torres et al. 2008).

- *Phenols:*

Phenol and its derivatives which consist of a hydroxyl group (-OH) bonded directly to an aromatic hydrocarbon are categorized under alcohol and more of acidic in nature due to tight coupling of aromatic ring with oxygen and a relatively loose bond between oxygen and hydrogen. Phenols are group of dangerous organic pollutants that are toxic to all living organisms even at low concentrations. At higher concentration it is very difficult to remove them from the environment, even by using physical and chemical techniques. Phenolic compounds are synthesized industrially and they are also produced by plants and microorganisms with variation between and within species (Subashchandrabose et al. 2013).

- *Metals:*

Among the major groups of contaminants reaching Arctic, metals are of special interest due to their wide dispersal capacity and long-lived chemistry. Many metals are natural components of seawater and sediments. However, some of them have been transported and accumulated in the polar regions, presenting higher concentrations due to anthropogenic pollution (Echeveste et al. 2014). Metals are introduced into the atmosphere by human activities such as fossil fuel combustion, coal burning, metal production, waste incineration and redistributed in the environment through long-range transport and deposition. They can also be transported to polar regions by rivers and ocean currents (AMAP 2005). In the Arctic ecosystem, metals are accumulated by terrestrial, freshwater and marine organisms and biomagnified through successive trophic levels (Grotti et al. 2013).

**Table 5.** Literature information about determined contaminants in polar regions

Persistent organic pollutants (POPs) are chemicals that persist for long periods of time in the environment, bioaccumulate and biomagnify in living organisms, are toxic to humans and wildlife, and become widely distributed in the environment as a result of natural processes. Three types of natural processes are responsible for the transport of chemicals to locations far from their primary emission sources. These processes are atmospheric transport, transport in ocean currents and rivers, and transport as bioaccumulated chemicals in migratory animals (biovectors). Due to long-range transport, POPs have been found in some of the most remote regions on Earth, including Arctic and Antarctic (Hageman et al. 2015).

Although there are fewer studies conducted in both polar regions, the number of Arctic and Antarctic studies is still growing. Polar areas are rich in cyanobacteria and other phytoplankton communities even though the prevailing temperatures in these regions may be extremely low, which can influence a development of many species. Many scientists (e.g. Corsolini and Focardi 2000, Montone et al. 2001, Kelly et al. 2008, Uetake et al. 2010, Echeveste et al. 2014) have also determined a wide range of xenobiotics (metals, POPs) and other compounds in phytoplankton's cells and in the harsh, polar environment where they live (Table 6).

**Table 6.** Literature information about contaminants determination in selected phytoplankton species and their environment in polar regions

In presented literature, some phytoplankton species were obtained from various centers and cultured in laboratory conditions with exposure to high concentration of contaminants, other phytoplankton samples were taken directly from freshwater and marine

water reservoirs and then analyzed in laboratory. It has been observed that laboratory cultured species, which often grow in mono-specific flasks, do not compete for nutrient resources among species. Moreover, the long-term exposure to high levels of pollutants in laboratories gives cultured species a higher resistance to pollution than natural communities (Echeveste et al. 2010a). Sorption of persistent organic pollutants and metals on phytoplankton cell surface is known to be dependent on a number of factors ranging from the concentration of inorganic ions (e.g. cations), dissolved organic matter, pH and the nature and concentration of particulates (Rhee and Thompson 1992).

Present levels of anthropogenic contaminants including persistent organic pollutants (POPs) found in the polar environments cannot be related to known use and/or release from sources within the region. Based on continuous monitoring and surveillance, with the exception of restricted local contamination issues, atmospheric long–range transport from lower latitudes is known to be the most important reason for the presence of many persistent organic and inorganic pollutants in the Arctic environment today (Kallenborn et al. 2012). Such statement seems to be coherent with the explanation of the global transport of chemical pollutants via two pathways: the atmospheric transport of volatile precursors followed by oxidizing degradation, and the marine current transport of ionic compounds in the oceans (Zhao et al. 2012).

## 7. Degradation of persistent organic pollutants and other contaminants by phytoplankton

In the Chemical Abstracts Service (CAS) Registry System, there are more than 66 million organic and inorganic substances with about 12 thousand new substances being added daily (CAS, 2012). Several millions of natural and synthetic compounds are formed with carbon as a constituent element. Human effort to synthesize many organic compounds may be a paradox of saving numerous lives and providing economic benefits while chronic toxicity of some of these chemical substances make other organisms (including plants and animals) suffer. Understanding the environmental fate of chemical substances, their effect on many living organisms and their transformation to less toxic structures, is a big challenge (Adeola 2004).

Recently, there has been a growing interest on the use of bioremediation as the most desirable technology for contaminants removal or detoxification to make them harmless (Cunningham and Berti 1993). Investigation on organic pollutants bioaccumulation or

biodegradation in blue green algae and green algae is of great importance from environmental point of view due to widespread distribution of these compounds in agricultural areas has become a huge problem in aquatic ecosystems (Jin et al. 2012). A lot of factors influence the uptake, bioconcentration and degradation of chemical pollutants, for example pH, temperature, structure and concentration of chemical substances, nutrient availability of the medium and cell size. It is certain that all contaminants influence the life of phytoplankton habitats differently and the degradation of these pollutants is also different. Variety of mechanisms used by algae species to make pollutants less toxic depend on type of contaminant and its form (Subashchandrabose et al. 2013). Some examples of selected contaminants biodegradation are described below.

- *Polychlorinated biphenyls:*

The algal bioconcentration of polychlorinated biphenyls (PCBs) depends on physico-chemical properties of the compounds and physiology, exudates and density of algae. Other factors that influence bioaccumulation are hydrophobicity and structure of PCBs congeners, variations in total lipids at different growth stages and restricted membrane permeability in algae (Subashchandrabose et al. 2013). Some organisms may degrade polychlorinated biphenyls aerobically or anaerobically (Borja et al. 2005; Pieper and Seeger 2008). PCBs degradation is complex as there are many different forms and it has been shown that orthochlorinated PCBs inhibit and inactivate a key enzyme in the degradation pathway, dehydroxybiphenyl oxygenase (Dai et al. 2002). Aerobic degradation of lower chlorinated PCBs is via co-metabolism by dioxygenases leading to ring split and possibly complete mineralization (Dhankher et al. 2012). It should be also assumed that certain factors such as bioconcentration factors (BCF), octanol-water partition coefficients ($K_{ow}$) and dissolved organic carbon (DOC) may play a crucial role in algal bioconcentration of polychlorinated biphenyls (Subashchandrabose et al. 2013).

- *Polycyclic aromatic hydrocarbons:*

If one considers polyaromatic hydrocarbons (PAHs), they are pollutants of serious concern because they are carcinogenic, mutagenic and teratogenic to humans and animals (Dejmek et al. 2000). The environmental pollution by PAHs and the scope for microbial remediation had been reviewed many times (Samanta et al. 2002; Haritash and Kaushik 2009; Thavamani et al. 2012). Although the bacterial and fungal degradation of PAHs has been known for a long time, algal utilization of these compounds has been established relatively

recently (Subashchandrabose et al. 2013). For instance, the accumulation and biodegradation has been studied of two typical polycyclic aromatic hydrocarbons: phenanthrene (PHE) and fluoranthene (FLA) by two algal species (Skeletonema costatum and Nitzschia sp.) from the Jiulong River Estuary Mangrove Nature Reserve in China. The authors (Hong et al. 2008) found that the accumulation and degradation abilities of Nitzschia sp. were higher than those of S. costatum. Degradation of FLA by two algae was slower indicating that FLA was a more recalcitrant PAH compound. Moreover, these organisms showed comparable or higher efficiency in the removal of the PHE-FLA mixture compared with both compounds alone and it may suggest that the presence of one PAH have stimulated the degradation of the other (Chekroun et al. 2014). Another example is the PAH phenanthrene (PHEN) which is highly toxic and commonly found in aquatic environments. Muñoz et al. (2003) described the PHEN degradation by an algal-bacterial consortium formed by Chlorella sorokiniana and phenanthrene-degrading Pseudomonas migulae strain that was able to biodegrade 200-500 mg/l of phenanthrene dissolved in silicone oil or tetradecane under photosynthetic conditions and without any external supply of oxygen. It may suggest that the microalgae release biosurfactants that could further enhance the phenanthrene degradation (Chekroun et al. 2014).

- *Pesticides:*

Pesticides, of various chemical nature and structures, comprise the next important group of chemicals, which are seriously involved in the contamination of aquatic environment. Multiple methods including incineration and land filling have been used to remove this class of pollutants however this methods turned out to be too expensive and inefficient (Chekroun et al. 2014) so many scientists have started to use algae species to eliminate or reduce pesticides from the environment (Singh and Walker 2006; Cáceres et al. 2010). Algal cell size, morphology, density and activities play an important role in the uptake and removal of these compounds. High surface area to biovolume ratio of algae provides greater sorption potential and subsequent interaction with pesticides. Generally, algae utilize pesticides when the concentrations of chemical substances are nontoxic (Subashchandrabose et al. 2013). An example may be accumulation and biodegradation of herbicide - prometryne by the green algae *Chlamydomonas reinhardtii* (Jin et al. 2012). The uptake and catabolism of prometryne described by the authors led to the rapid removal of the substance from the media and this process of degradation may be interpreted as an internal tolerance mechanism, suggesting that the green algae might be useful in bioremediation processes. The same species

were found to be able accumulate the herbicide – fluroxypyr, that is rapidly degraded in the cells, what may suggest that the accumulation and degradation of this compound occurred at the same time (Zhang et al. 2011). According to the results of the experiments reported by Forlani et al. (2008), it can be concluded that some strains of blue-green algae are tolerant up to millimolar concentrations of glyphosate (N-phosphonomethyl)glycine, the most worldwide used herbicide, which is believed to be persistent in water ecosystems. Moreover, two among six of tested strains of cyanobacteria: *Leptolyngbya boryana* and *Nostoc punctiforme* were able to degrade and metabolise this herbicide and use it as the nutrient.

- *Phenols:*

Algal strains are also capable of metabolizing phenol in the environment and the mechanistic dynamic energy budget model proposed by Lika and Papadakis (2009) for aerobic degradation suggests that inhibition may occur in the presence of growth-enhancing carbon source like glucose due to competition for oxygen. Report of Klekner and Kosaric (1992b) showed that Chlorella sp. metabolized 1000 mg/L of 2,4-dimethyl phenol to an isomer of dimethyl benzenodiol and with and algal cell concentration of 4 g/L complete degradation have been achieved (Subashchandrabose et al. 2013).

- *Metals:*

Algae also proved to be effective in heavy metals degradation (Suresh and Ravishanker 2004). Most of the currently used technologies for metals removal are based on physico-chemical reactions mainly precipitation and adsorption in ion-exchange resins. These processes face various problems such as lack of selectivity, intolerance to organic species, low efficiency in removing trace concentrations and generation of large secondary wastes with prohibitive disposal costs (Eccles 1999). Nevertheless, Matsunaga et al. (1999) have designed a marine screen where they were able to characterize a Chlorella strain capable of sustaining growth at 11.24 mg $Cd^{2+}$/L and 65% removal when exposed to 5.62 mg $Cd^{2+}$/L. Travieso et al. (1999) working with Chlorella and Scenedesmus strains in batch cultures at 20 mg $Cr^{6+}$/L they have found removal percentages of 48% and 31% respectively (Perales-Vela et al. 2006). Scenedesmus is a microalgae genus commonly used in heavy metal removal experiments. It has proven removal capacity for $U^{6+}$ (Zhang et al. 1997), $Zn^{2+}$ (Aksu et al. 1998; Travieso et al. 1999; Cañizares-Villanueva et al. 2001) and $Cu^{2+}$, $Cd^{2+}$ (Terry and Stone 2002). This information brings the hope that many phytoplankton species, which have shown appropriate

properties for metals removal, will be positively verified acting as a core elements of modern, algae-based, green technologies.

## 8. Conclusions

The arctic phytoplankton species differ in several aspects from those living in temperate regions. Biological and physical factors (e.g. low temperatures, limited nutrient availability and pronounced seasonality with short growing seasons) affect the ecosystem and also the fate of persistent organic pollutants (POPs). In spring, when the temperature increases and the sun light returns, primary production increases rapidly what means that in ice-free arctic waters about 60-70% of total annual primary production takes place during the spring bloom (AMAP 1998). Furthermore, polar phytoplankton communities have adapted to low UV-light levels and show higher photosynthetic efficiencies at lower UV-light levels, than phytoplankton in temperate waters (Sobek et al. 2010).

From about half of the last century we are living in a period of global disappearance of biodiversity, the consequence of human activities that alter the processes of homeostasis of the Earth biosphere on most of trophic levels. Phytoplankton populations are continuously exposed to by-products of human activities. Cyanobacteria and microalgae, especially phytoplankton species living in aquatic polar reservoirs that have to deal with harsh condition to survive, may adapt to novel environments through selection on spontaneous mutations or through individual responses and mechanisms (López-Rodas et al. 2006). Additionally, they have to cope with various pollutants that appear in their environment. In this review, we described xenobiotics commonly appearing in water ecosystems with the emphasis of those reported in polar environments and therefore in the cells phytoplankton organisms. In selected literature data, it may be observed that the most common groups of compounds that were detected in phytoplankton species and the environment are polychlorinated biphenyls: 31,25% and dissolved organic carbon: 31,25%. Other group of contaminants that was detected in a large scale are metals: 25,00%. It is worth noting that phytoplankton species are capable of degrading pollutants and remove them from the environment, or biotransform them into less toxic forms. Obtaining however more detailed knowledge on these aspects (absorption, accumulation and biodegradation) requires the study on different parameters of aquatic ecosystems such as e.g.: temperature, insolation, pH and nutrient availability, as well as the study on interactions between xenobiotics by phytoplankton.

Nowadays, the majority of related studies focus on phytoplankton communities living in temperate areas, and much less on these, which are present in cold areas of high latitudes. Even if the organisms living in polar regions are more difficult to cultivate, and their abundance is decreasing drastically after isolation from natural habitats, the focus on polar cyanobacteria and microalgae that are able to grow autotrophically, heterotrophically or mixotrophically, may provide the desired knowledge about the advantages in degrading organic pollutants and sustainable existence in harsh conditions.

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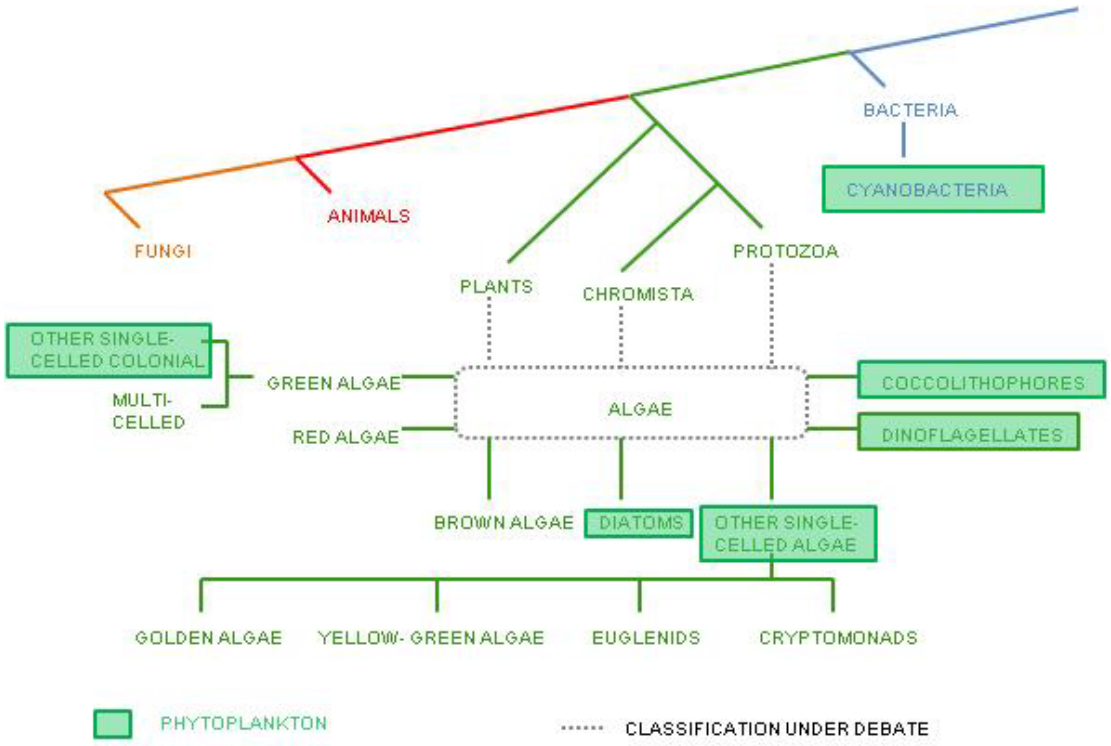


**Fig. 1.** Simplified taxonomic classification of phytoplankton

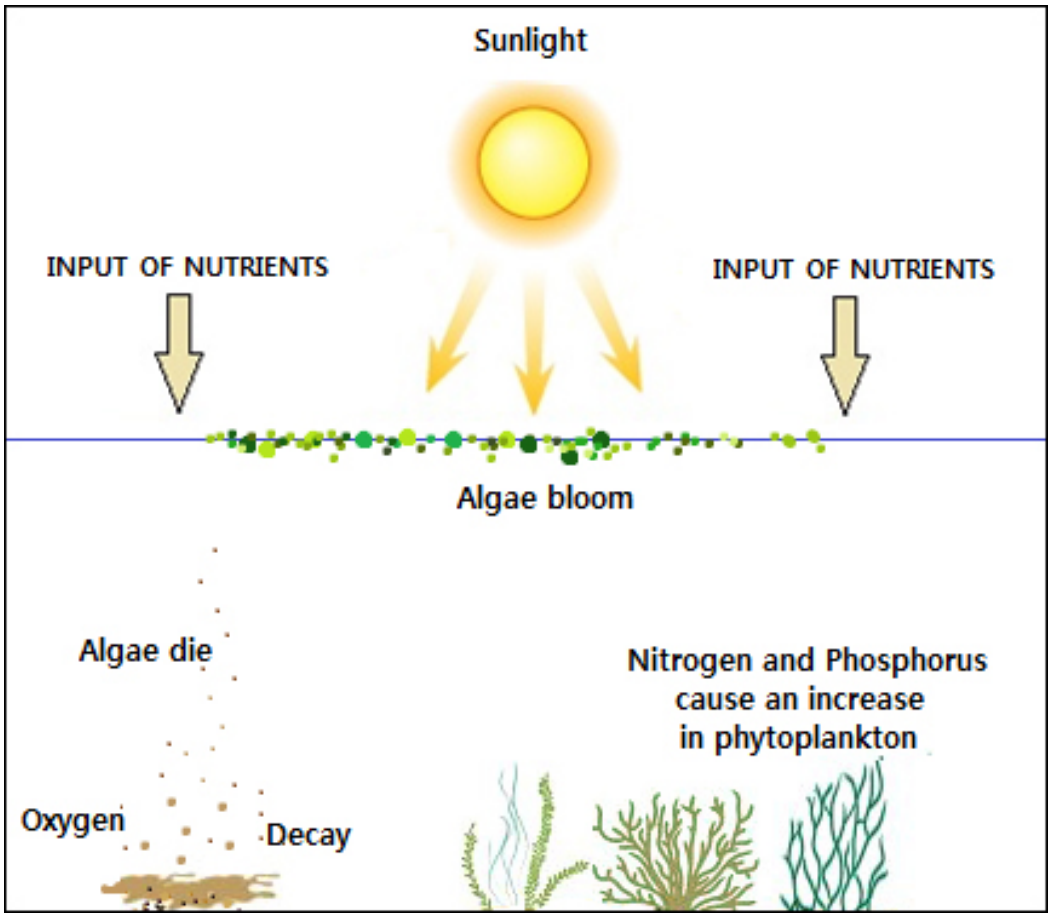


**Fig. 2.** The process of eutrophication

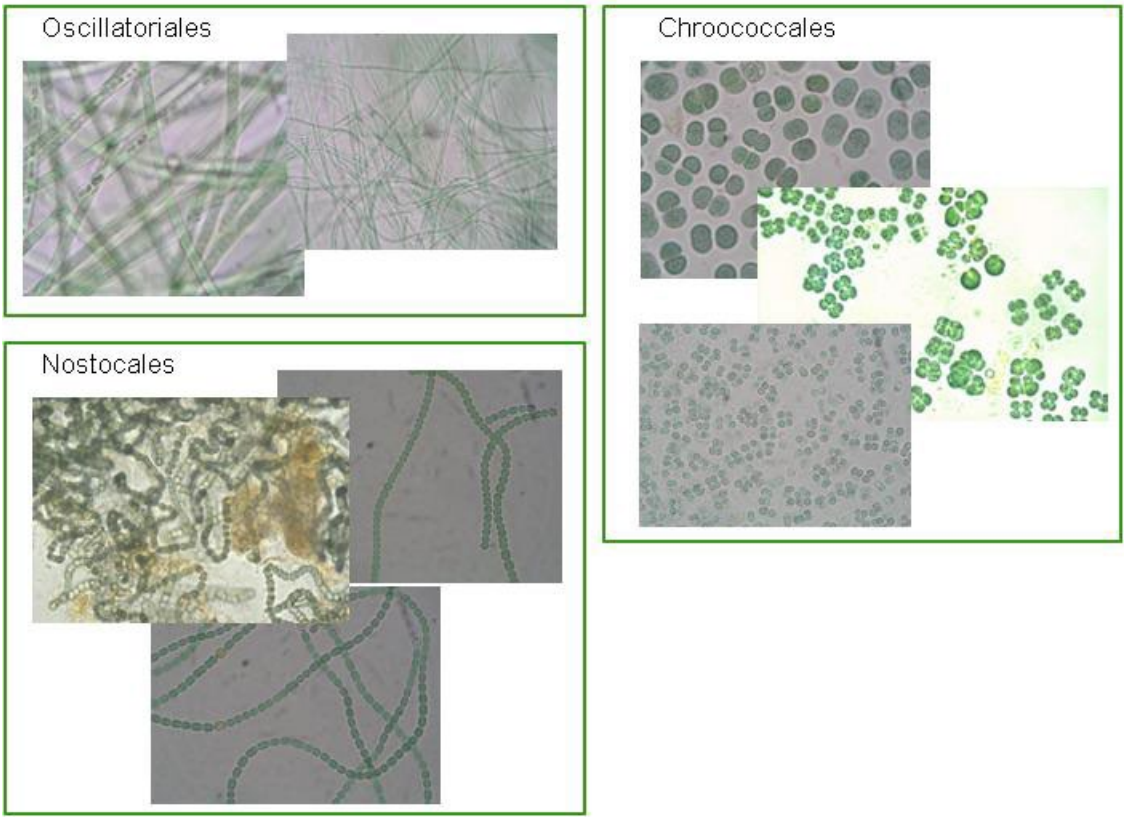


**Fig. 3.** The most common groups of cyanobacteria that appear in polar freshwaters (photographs from the authors' own collection)

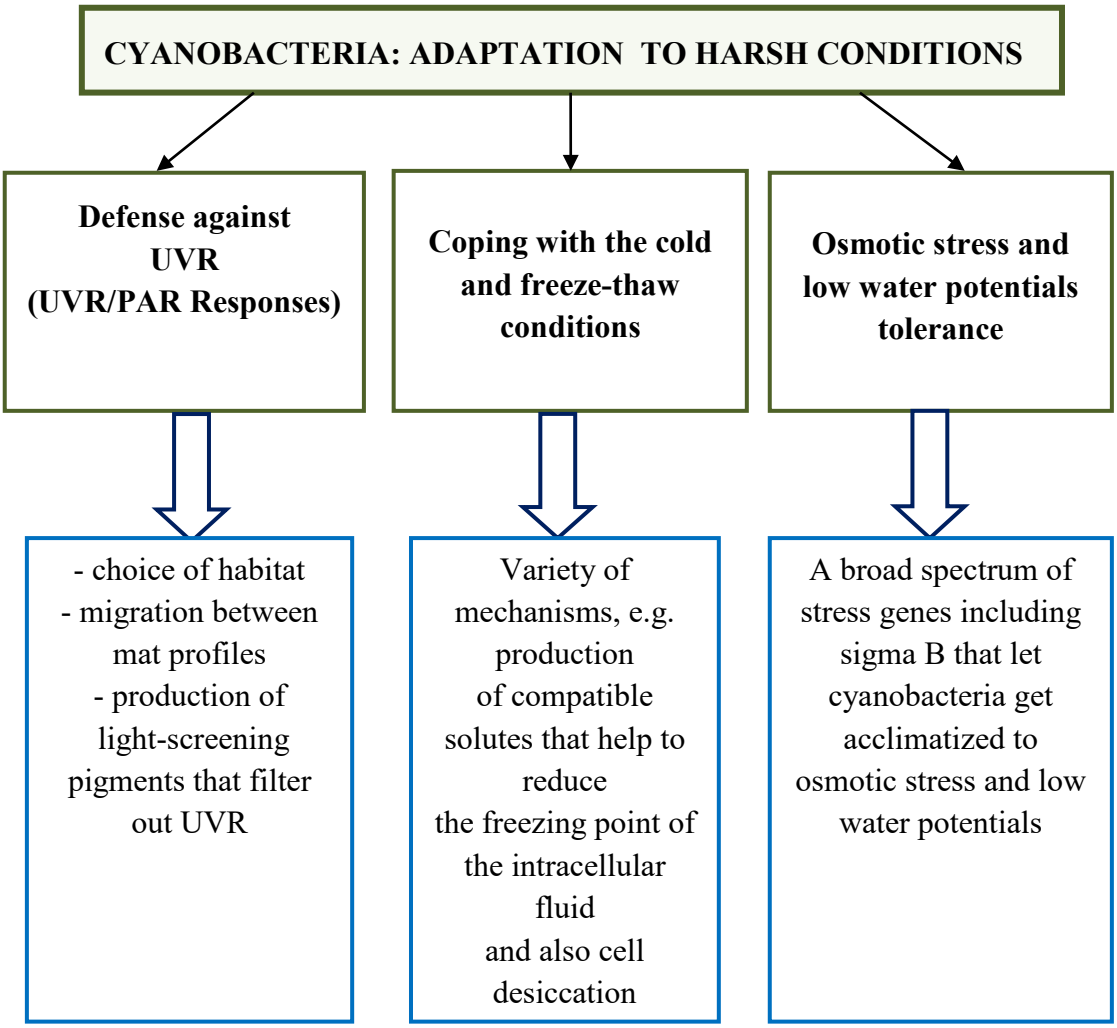


**Fig. 4.** Main adaptation strategies developed by cyanobacteria to survive in harsh polar conditions (Vincent 2007)

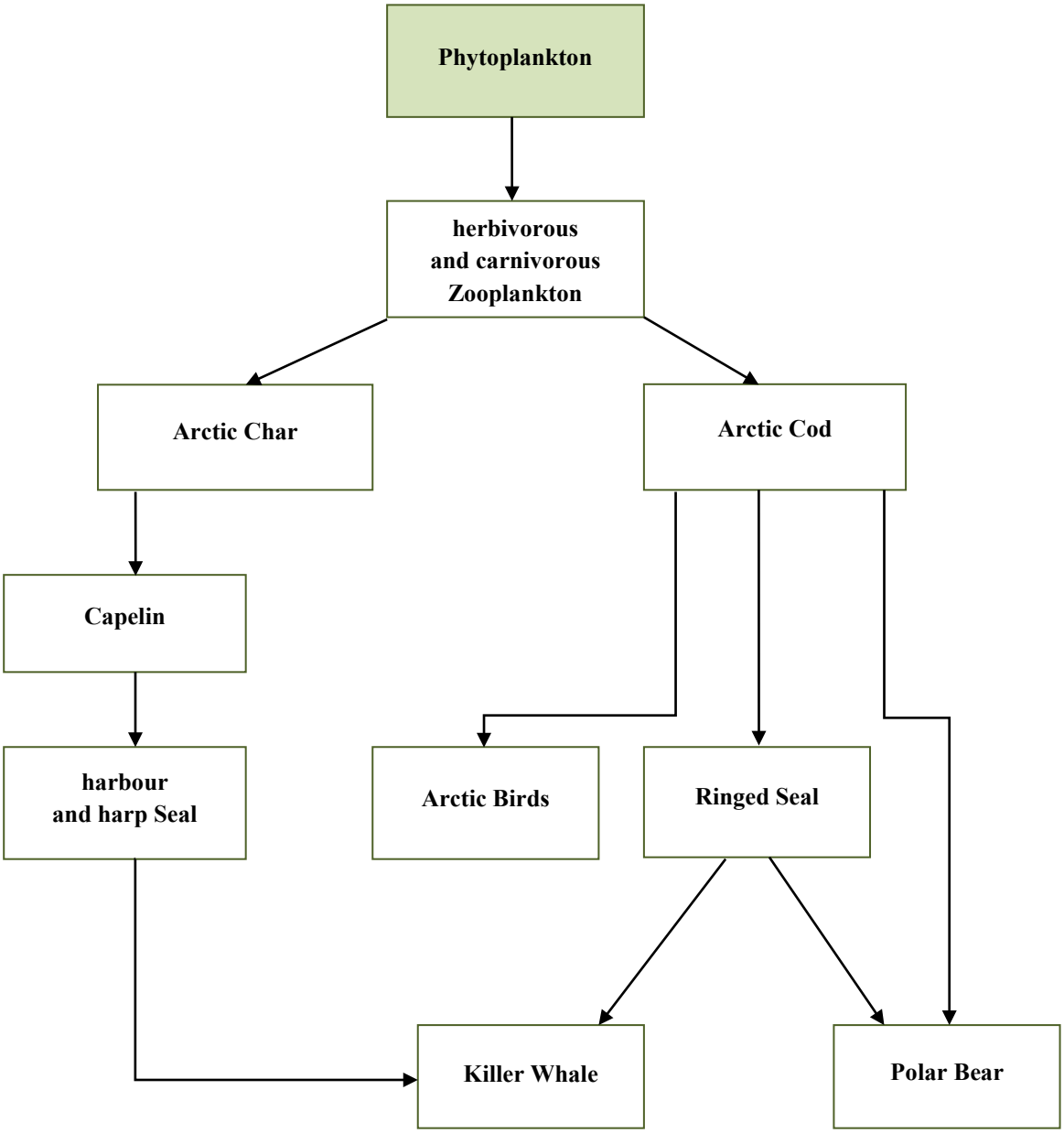


**Fig. 5.** An example of arctic food chain (Wang and Wang 2005; Kozak et al. 2013)

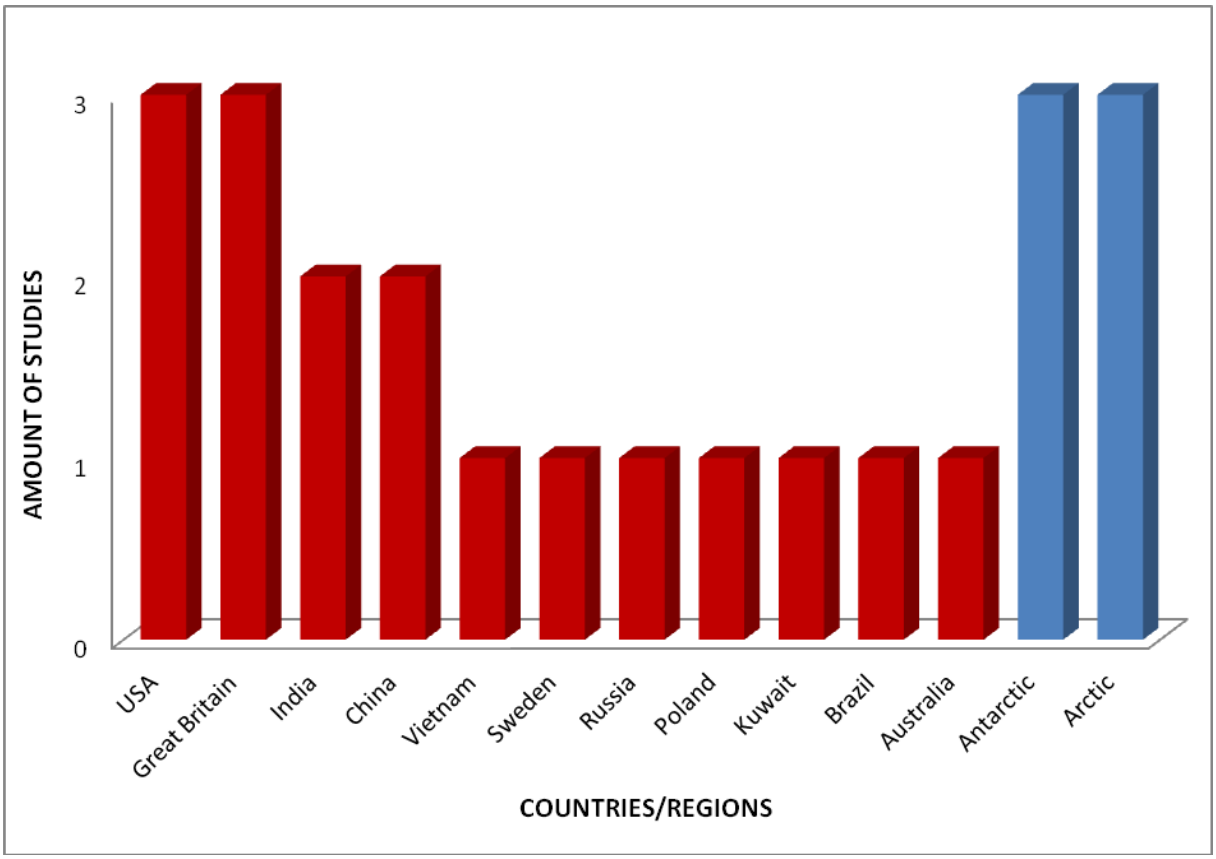


**Fig. 6.** Countries and regions in which phytoplankton samples were studied

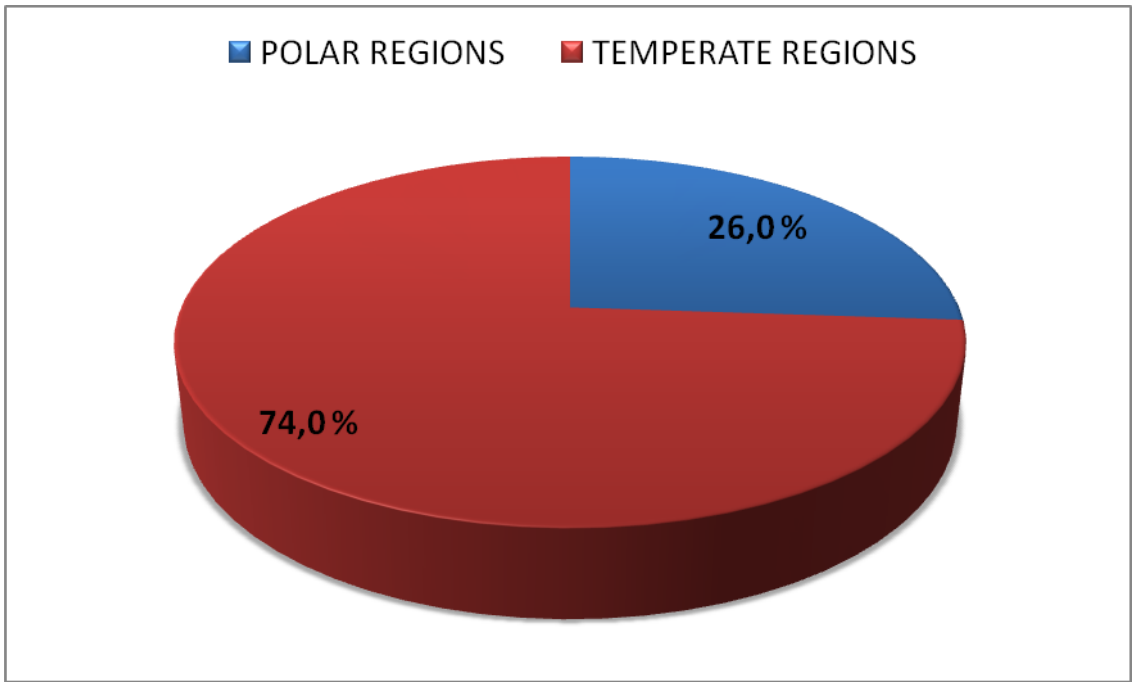


**Fig. 7.** Percentage amount of studies of phytoplankton samples collected from polar and temperate regions

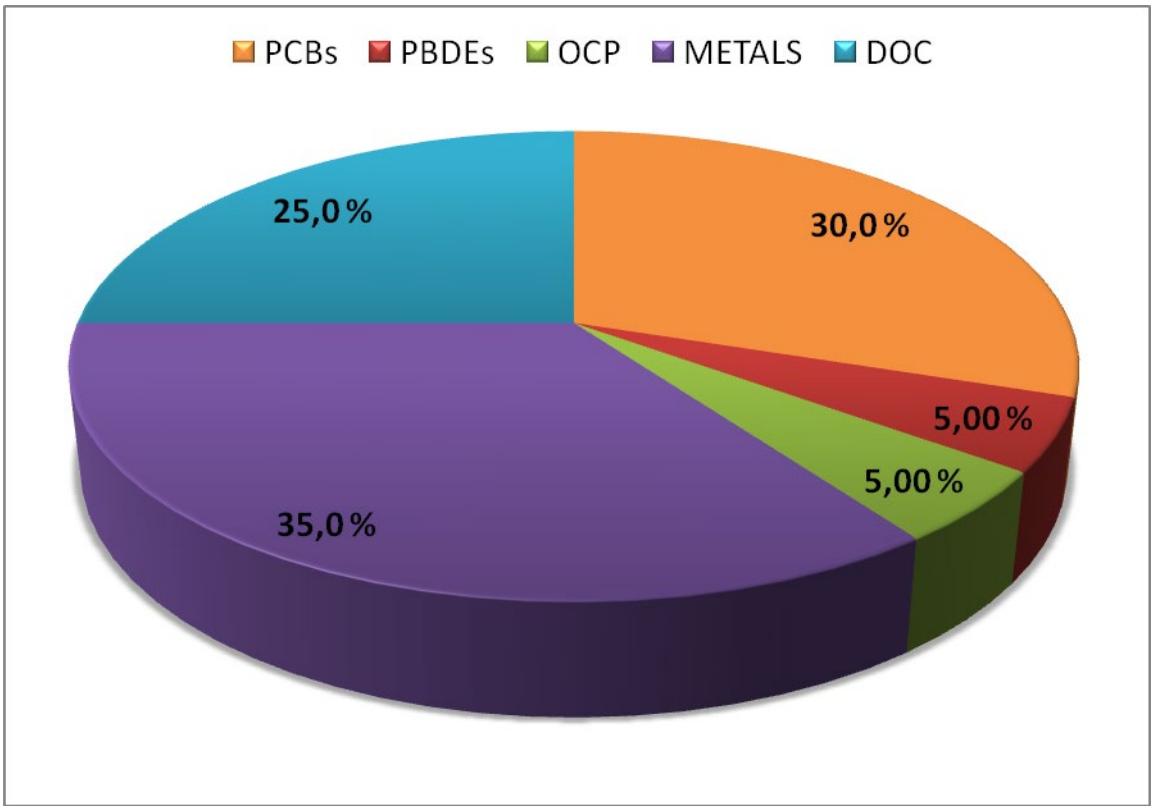


**Fig. 8.** Percentage amount of determined xenobiotics in selected samples presented in the literature

**Table 1.** Examples of some point and diffuse sources of nutrients that lead to water eutrophication (Shaw 2003)

| Point sources | Diffuse sources |
|---|---|
| • sewage treatment plants<br>• feedlots<br>• piggeries<br>• dairies<br>• industrial effluents<br>• irrigation drains | • urban runoff<br>• storm runoff from rural lands<br>• groundwater discharge<br>• grazing<br>• atmospheric fall-out |

**Table 2.** Types of benthic mats among blue green algae communities (Vincent 2002)

| | |
|---|---|
| **Moat mats** | These forms occur around the edge of the lake where the ice melts each season. They are often pigmented bright orange or brown and characterized by spongy, thick layers |
| **Columnar lift-off mats** | These forms are produced by the trapping of nitrogen and oxygen bubbles within the surface mat and they grow as upright columnar structures. Portions of the mat may break off and float up under the permanent ice cover of the lake so that they become incorporated into the ice when it freezes |
| **Pinnacle mats** | These structures occur to at least 30 m depth within the relatively well illuminated environment and incorporate sand grains and calcite crystals |
| **Aerobic prostrate mats** | These forms occur over the surface sediments at depth and precipitate calcite |
| **Anaerobic prostrate mats** | These ones may be found in deep anoxic basins of the lakes |

**Table 3.** Literature information about determined contaminants in phytoplankton and their environment

| Type of sample | OCP | | | PCBs | PBDEs | Metals | DOC | Lit. |
|---|---|---|---|---|---|---|---|---|
| | DDTs | HCHs | HCBs | | | | | |
| - cyanobacteria,<br>- toxic planktonic cyanobacteria<br>- nitrogen-fixing cyanobacteria | | | | | | x | x | (Garnham et al. 1993, Pokrovsky et al. 2008, Dwivedi et al. 2010, Chakraborty et al. 2011, Tonietto et al. 2014, Walve et al. 2014, Huang et al. 2014 ) |
| - freshwater algae cultures | | | | | | | x | (Henderson et al. 2008) |
| - surface seawater with phytoplankton<br>- phytoplankton (diatoms, flagellates, dinoflagellates) | x | x | x | x | | x | x | (Echeveste et al. 2014, Wang et al. 2009, Corsolini and Focardi 2000, Bu-Olayan et al. 2001, Cherrier et al. 2014, Satterberg et al. 2003, Ikemoto et al. 2008) |
| - macroalgae | | | | x | x | x | | (Montone et al. 2001, Kelly et al. 2008, Baumann et al. 2009, Cheney et al. 2014) |
| - microalgae | | | | x | | x | | (Wang et al. 1998, Foster et al. 2008) |
| - green algae | | | | | | x | | (Garnham et al. 1993, Dwivedi et al. 2010) |

**Table 4.** Literature information about contaminants determination in selected phytoplankton species and their environment all over the world

| Species | Determined parameters | Concentration ranges | Lit. |
|---|---|---|---|
| **BLUE GREEN ALGAE (CYANOBACTERIA)** | | | |
| - Synechococcus PCC 6301<br>- Synechocystis PCC 6803<br>- Plectonema boryanum | Zr | Total:<br>18.2-19.9 µmol/g d.w.<br>1.80-2.20 µmol/g d.w.<br>16.0-17.0 µmol/g d.w. | (Garnham et al. 1993) |
| - Gloeocapsa sp. | DOC | 10-100 mg/L | (Pokrovsky et al. 2008) |
| | Metals (Ca, Mg, Zn, Cu, Cd, Pb) | 0.1-400 µM | |
| - Microcystis aeruginosa,<br>- Asterionella formosa,<br>- Melosira sp. | DOC | Total: 3.6-27 mg/L | (Henderson et al. 2008) |
| - Cylindrosper-mopsis raciborskii | DOC | 28.70-41.90 mg/g | (Tonietto et al. 2014) |
| - Nodularia,<br>- Aphanizomenon | Trace metals (Al, Ti, Fe, Mn, Mo, Cu, Co, Cd, Ni, V), Si, P | 0 < - > 369 µmol/mol C, except P:C which is in units of mmol/mol C | (Walve et al. 2014) |
| - Oscillatoria tenuisa,<br>- Anabaena affinis,<br>- Microcystis aeruginosa | As | n.d. - 67.31 ($10^{-2}$ ng/cell)<br>n.d. - 52.20 ($10^{-2}$ ng/cell)<br>n.d.- 56.67 ($10^{-2}$ ng/cell) | (Huang et al. 2014) |
| Cyanobacterial species | PCB | Σ 0.017 ng/g w.w. | (Ikemoto et al. 2008) |
| | DDT | Σ 0.058 ng/g w.w. | |
| | CHL | Σ 0.0043 ng/g w.w. | |
| | HCH | Σ 0.00055 ng/g w.w. | |
| | HCB | Σ 0.0021 ng/g w.w. | |
| - Spirulina subsalsa<br>- Lyngbya majuscula | Pb | - 0.49-1.32 mg/g d.w.<br>- 0.88-13.5 mg/g d.w. | (Chakraborty et al. 2011) |
| - Oscillatoria tenuis,<br>- Oscillatoria nigra,<br>- Phormedium bohneri | Metals (Cr, Cu, Fe, Mn, Ni, Zn, As) | Cr: 1863-8550 µg/g d.w.<br>Cu: 18.44-44.64 µg/g d.w.<br>Fe: 480-1192 µg/g d.w.<br>Mn:21.73-66.08 µg/g d.w.<br>Ni: 7.22-28.61 µg/g d.w.<br>Zn: 59.91-227 µg/g d.w.<br>As: 0.86-3.44 µg/g d.w. | (Dwivedi et al. 2010) |

| OTHER SPECIES OF PHYTOPLANKTON (DIATOMS, FLAGELLATES, DINOFLAGELLATES, MICROALGAE, MACROALGAE, GREEN ALGAE, SNOW ALGAE) | | | |
|---|---|---|---|
| - Chlorella emersonii,<br>- Scenedesmus obliquus,<br>- C. reinhardtii | Zr | Total:<br>23.0-25.6 µmol/g d.w.<br>21.0-22.0 µmol/g d.w.<br><br>7.50-11.2 µmol/g d.w. | (Garnham et al. 1993) |
| - the diatom Thalassiosira pseudonana,<br>- the dinoflagellate Prorocentrum minimum | $Cd^{2+}$ | Total: 0.07-11.1 µmol/L | (Wang et al. 2009) |
| - Asterionella sp.,<br>- Bidulphia sp.,<br>- Ceratium sp.,<br>- Chaetoceros sp.,<br>- Coscinodiscus sp.,<br>- Ludigia sp.,<br>- Melosira sp.,<br>- Rhizosolenia sp.,<br>- Thalassionema sp.,<br>- Eucampia sp.,<br>- Triceratium sp. | Trace metals (Cu, Fe, Zn, Ni, Pb, Co) | Cu: 5.00-59.17 µg/g d.w.<br>Fe: 4.90-61.25 µg/g d.w.<br>Zn: 10.40-63.12 µg/g d.w.<br>Ni: 2.45-41.01 µg/g d.w.<br>Pb: 4.73-49.10 µg/g d.w.<br>Co: 1.40-22.82 µg/g d.w. | (Bu-Olayan et al. 2001) |
| - the diatom Thalassiosira weissflogii (from the surface seawater) | DOC | 0.5-16 µM C | (Cherrier et al. 2014) |
| - Phaeocystis globosa,<br>- Gymnodinium sanguineum,<br>- Scrippsiella trochoidea,<br>- Ditylum brightwellii | DOC | ranged from 47% to 85% of the total organic carbon | (Satterberg et al. 2003) |
| -Nannochloro-psis oculata,<br>- Isochrysis galbana | PCB | 0.26-257.52 ppm d.w.<br>0.08-64.22 ppm d.w. | (Wang et al. 1998) |
| - Dunaliella tertiolecta,<br>- Phaeodactylum tricornutum | As | 13.3-14.5 µg/g d.w.<br>1.62-2.08 µg/g d.w. | (Foster et al. 2008) |
| - Chlorella vulgaris | DOC | Total: 3.6-27 mg/L | (Henderson et al. 2008) |
| - the green alga Chlorella autotrophica | $Cd^{2+}$ | Total: 0.07-11.1 µmol/L | (Wang et al. 2009) |
| -Chlamydomo-nas angulosa<br>- Chlorococcum vitiosum,<br>-Hydrodictyon reticulatum<br>- Rhizoclonium hieroglaphicum,<br>- Ulothrix tenuissima,<br>- Oedogonium sp. I,<br>- Oedogonium sp. II,<br>- Spirogyra adenata, sp. I | Metals (Cr, Cu, Fe, Mn, Ni, Zn, As) | Cr: 10.61-5325 µg/g d.w.<br>Cu: 5.74-182 µg/g d.w.<br>Fe: 22.45-3583 µg/g d.w.<br>Mn: 66.44-372 µg/g d.w.<br>Ni: 1.35-32.82 µg/g d.w.<br>Zn: 28.44-390 µg/g d.w.<br>As: BDL-3.71 µg/g d.w.<br><br>BDL - below detection limit | (Dwivedi et al. 2010) |
| - Ulva rigida | PCB | 0 < - 2500 µg/kg d.w. | (Cheney et al. 2014) |
| - A. nodosum,<br>- F. vesiculosus,<br>- P. lanosa,<br>- P. palmata,<br>- C. crispus, | Metals (Cu, Cr, Zn, Cd, Pb) | Cu: 0.046-0.217 µmol/g<br>Cr: 0.004-0.200 µmol/g<br>Zn: 0.254-0.786 µmol/g<br>Cd: BDL-0.005 µmol/g<br>Pb: 0.002-0.079 µmol/g | (Baumann et al. 2009) |

| | | | |
|---|---|---|---|
| - U. intestinalis,<br>- C. rupestris | | | |

**Table 5.** Literature information about determined contaminants in polar regions

| Place | | Determined parameters | Lit. |
|---|---|---|---|
| **Arctic** | seawater from Arctic and air massess | dechlorane plus (DP, $C_{18}H_{12}Cl_{12}$) | Möller et al. 2010 |
| | Ny-Ålesund | organochlorine pesticides (OCPs):<br>- hexachlorocyclohexane (HCH): α-HCH, β-HCH, γ-HCH<br>- dieldrin<br>- endosulfans – endosulfan-I<br>- chlordanes: trans-chlordane (TC), cis-chlordane (CC), trans-nonachlor (TN) and heptachlor (HEPT)<br>- dichlorodiphenyltrichloroethanes (DDTs)<br><br>polychlorinated biphenyls (PCBs):<br>- DiCB, TrCB, TeCB, PeCB, HxCB, HpCB, OcCB, NoCB<br><br>metals: Pb | Baek et al. 2011; Bazzano et al. 2015 |
| | Canadian Arctic water | polyfluoroalkyl substances (PFASs): PFOA, | Zhao et al. 2012 |
| | soil from Ny-Ålesund | polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) | Jia et al. 2014 |
| | Arctic biota, snow and sediments | Trace metals (Pb, Cd, Hg, Cu, Zn) | Echeveste et al. 2014; Pederson et al. 2015, Clayden et al. 2015 |
| **Antarctic** | Antarctic air masses and coast | dechlorane plus (DP, $C_{18}H_{12}Cl_{12}$) | Möller et al. 2010 |
| | King George Island | organochlorine pesticides (OCPs):<br>- hexachlocyclohexane (HCH): α-HCH, γ-HCH<br>- endosulfans – endosulfan-I<br>- chlordanes: trans-chlordane (TC), cis-chlordane (CC), trans-nonachlor (TN) and heptachlor (HEPT)<br><br>polychlorinated biphenyls (PCBs):<br>- DiCB, TrCB, TeCB, PeCB, HxCB, HpCB, OcCB, NoCB, DeCB | Baek et al. 2011 |
| | Antarctic Peninsula coast | polyfluoroalkyl substances (PFASs): PFOA, PFOS | Zhao et al. 2012 |
| | Antarctic Peninsula coast | hexachlorobenzene (HCB) and HCHs | Galbán-Malagón et al. 2013 |
| | Adélie Land, Antarctica | PCB, HCB, pentachlorobenzene (PeCB), polybrominated diphenylethers (PBDE) | Goutte et al. 2013 |
| | soil from Fildes Peninsula in Antarctic | polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) | Jia et al. 2014 |
| | Antarctic snow and other Antarctic locations | Trace metals (Pb, Cd, Hg, Zn, Cu, Fe, Mn, Mo, Ni, Sr, Ti, V), Al, Ba, Ca, Mg | Echeveste et al. 2014; Witherow et al. 2010; White et al. 2012; Santos et al. 2005 |

**Table 6.** Literature information about contaminants determination in selected phytoplankton species and their environment in polar regions

| Species | Determined parameters | Concentration ranges | Lit. |
|---|---|---|---|
| **PHYTOPLANKTON (DIATOMS, FLAGELLATES, DINOFLAGELLATES, MICROALGAE, MACROALGAE, GREEN ALGAE, SNOW ALGAE)** | | | |
| - Flagellates,<br>- small diatoms,<br>- medium diatoms,<br>- large diatoms,<br>- nano-plankton,<br>- Phaeocystis pouchetii,<br>- Picoeukaryotes | Trace metals (Pb, Cd, Hg) | Arctic: average: Cd: 0.034 µg/L, Pb: 0.006 µg/L, Hg: <0.001-0.004 µg/L<br>Antarctica:<br>Cd: 0.058 µg/L Pb: 0.016 µg/L | (Echeveste et al. 2014) |
| - Desmarestia sp. | PCB | Total PCB concentration: 0.46-3.86 ng/g d.w. | (Montone et al. 2001) |
| - diatoms | PCB | Total PCB concentrations: 1 ng/g d.w. | (Corsolini and Focardi 2000) |
| - Fucus gardneri | PBDE | Σ 324 (34–3.100) ng/g l.e.w. | (Kelly et al. 2008) |