Universidade de Aveiro
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SAMUEL AUGUSTO LOBO PEREIRA DE CASTRO

Panorama biogeográfico de cianobactérias potencialmente tóxicas na Europa

Biogeographic overview of potentially toxic bloom-forming cyanobacteria across Europe

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Biogeographic overview of potentially toxic bloom-forming cyanobacteria across Europe

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Biologia Aplicada, realizada sob a orientação científica da Doutora Daniela Rebelo de Figueiredo, Investigadora Auxiliar do Departamento de Biologia da Universidade de Aveiro.

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palavras-chave

Cianobactérias, *Blooms*, Distribuição geográfica, Europa

resumo

As alterações climáticas têm um efeito catalisador na ocorrência de *blooms* de cianobactérias potencialmente tóxicas nos sistemas de água doce, conduzindo ao seu aumento de frequência e intensidade, colocando em risco o ambiente e a saúde humana. As espécies de cianobactérias formadoras de *blooms* mais comuns nos sistemas aquáticos dulçaquícolas Europeus incluem: *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, *Aphanizomenon gracile*, *Chrysosporum bergii*, *Cylindrospermopsis raciborskii / Raphidiopsis raciborskii*, *Dolichospermum lemmermannii* e *Planktothrix agardhii*. No entanto, *Raphidiopsis raciborskii* tem mostrado uma grande dispersão por toda a Europa nos últimos anos, particularmente na Europa Central. Devido ao facto de muitos dos sistemas de água doce se encontrarem perto ou dentro de áreas urbanas, a monitorização é um factor chave no que toca a registar eventos de blooms e salvaguardar a saúde animal e humana. Para tal, a compilação de informação histórica feita neste trabalho também contribui para futuras bases de dados georeferenciadas, que permitam integrar e analisar tendências para reocorrência de blooms potencialmente tóxicos em toda a Europa.

keywords

Cyanobacteria, Blooms, Geographical distribution, Europe

abstract

Climate change has a bolstering effect on the occurrence of potentially toxic cyanobacterial blooms in freshwater systems, leading to their increased frequency and intensity, and putting at risk the environment and human health. The most common bloom-forming cyanobacterial species in European freshwater aquatic systems include: *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, *Aphanizomenon gracile*, *Chrysosporum bergii*, *Cylindrospermopsis raciborskii / Raphidiopsis raciborskii*, *Dolichospermum lemmermannii* and *Planktothrix agardhii*. However, *Raphidiopsis raciborskii* has shown a wide dispersal throughout Europe in recent years, particularly in Central Europe. Because many freshwater systems are located near or within urban areas, monitoring is a key factor to predict and anticipate bloom events and safeguarding animal and human health. For this purpose, the compilation of historical information made in this work also contributes to future geo-referenced databases that allow the integration and analysis of trends in the re-occurrence of potentially toxic blooms across all Europe.

List of publications from the present work

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Index

List of Figures

List of Tables

Annexes

Introduction

1.1. General Introduction

Cyanobacteria are photosynthetic microorganisms that presently can be found in virtually any aquatic ecosystem and are considered to have played a pivotal role in the possibility of life on Earth, because of their contribution towards building a liveable environment with a breathable oxygenated atmosphere as we presently have (Merel et al., 2013). These microorganisms were responsible for the oxygenation of the atmosphere as well as enabling the formation of the ozone layer (Mur et al.,1999), which in turn shielded Earth's surface from dangerous radiation and thus allowing a safer haven for evolution to blossom.

Over the past decades, cyanobacteria have been explored for numerous applications in several industries and can offer profitable opportunities if the right species are selected and managed for specific purposes. For example, the aquaculture of cyanobacteria can bring many advantages like the production of biofuels, as a valuable source of inorganic nitrogen, and as a natural source of high-protein nutrition for the food industry (Haberle et al., 2020). The production and usage of biofuels derived from cyanobacteria can help reduce the dependency on fossil fuels and thus reduce harmful emissions of greenhouse gases such as carbon dioxide (Upendar et al., 2018), thus boosting the achievement of de-carbonization objectives and fighting climate uncertainty.

However, despite all the excellent features of cyanobacteria, they can also be a cause of nuisance in water bodies across the globe. The World Health Organization (WHO) offers a general but clear definition of a *cyanobacterial bloom*: a high average cyanobacteria cell density in a waterbody (Ibelings et al., 2021; Chorus and Welker, 2021). Freshwaters are increasingly vulnerable to the increase in incidence and intensity of harmful cyanobacterial blooms due to anthropogenic eutrophication and climate change contributions (Burford et al., 2020). Many species of cyanobacteria are associated with the eutrophication of ecosystems, resulting in bad quality of drinking water, and, most impactfully, the occurrence of harmful blooms and dangerous toxicity events (Svircev et al., 2019). Old references pointed out that toxic blooms account for 40–70% of blooms around the world (Lawton et al., 1991), while slightly more recent ones stipulate that estimate to be 25 to 75% (Chorus, 2001; Bláhová *et al*., 2007; 2008). The most frequent cyanobacteria and their commonly associated respective toxins are shown summarized in Table 1.

Table 1. Cyanotoxins, their effect and corresponding cyanobacteria strains. *So far only detected in marine water – adapted from Merel et al. (2013).

Toxin Type	Cyanotoxin	Producing Cyanobacteria	References
Hepatotoxin	MCs	*Microcystis* sp. *Oscillatoria* sp. *Nostoc* sp. *Anabaena* sp. *Anabaenopsis* sp.	(Kaebernick and Neilan, 2001; Merel et al., 2013)
Hepatotoxin	NODs	*Nodularia spumigena*	(Kaebernick and Neilan, 2001)
Hepatotoxin	CYL	*R. raciborskii, Raphidiopsis curvata, Umezakia natans*	(Merel et al., 2013; Banker et al., 1997; Fristachi and Sinclair, 2008)
Neurotoxin	Homoanatoxin-a	*Phormidium* sp. *Anabaena* sp.	(Wood et al., 2007; Furey et al., 2003)
Neurotoxin	ANTX-a	*Anabaena* sp. *Aphanizomenon* sp. *Planktothrix* sp.	(Osswald et al., 2007; van Apeldoorn et al.,2007; Merel et al., 2013)
Neurotoxin	ANTX-a(s)	*Anabaena* sp.	(Molica et al.,2005; Ondera et al., 1997; Sivonen and Jones, 1999; Merel et al., 2013)
Neurotoxin	STXs	*Dolichospermum circinale, Aphanizomenon flos-aquae, Lyngbya wollei, C. raciborskii*	(Nicholson et al., 2003)
Neurotoxin	BMAA	(Possibly all groups of cyanobacteira)	(Cox et al., 2005; Mere et al. 2013)
Dermatotoxin	APTXs*	*Lyngbya majuscula*	(van Apeldoorn et al., 2007)
Dermatotoxin	LTX*	*Lyngbya majuscula*	(van Apeldoorn et al., 2007)

A great variety of toxins can be produced by cyanobacteria and fall under three main classes: hepatotoxins, neurotoxins and dermatotoxins. Hepatotoxins are chemical compounds that primarily attack the liver and include the famously widespread microcystins (MCs), nodularins (NODs) and cylindrospermopsin (CYL).

Neurotoxins can interfere with normal neuromuscular signal transmission, and they are homoanatoxin-a, anatoxin-a (ANTX-a), anatoxin-a(s) (ANTX-a(s)), saxitoxins (STXs) and β-N-methylamino-L-alanine (BMAA); further neurotoxic compounds are currently under debate and investigation among the scientific community. Among cyanobacterial dermatoxins there are listed the aplysiatoxins (APTXs) and lyngbyatoxins (LTX).

The presence of toxic cyanobacteria in water is a global health concern (Aguilera et al., 2018; Carmichael & Boyer, 2016; Chorus & Bartram, 1999; Falconer & Humpage, 2005; Lévesque et al., 2014; Poniedziałek et al., 2012; Scarlett et al., 2020). Farmers and veterinarians were the first to blow the alarm over the poisoning risks of cyanobacterial blooms, with the first scientifically documented case being reported from Australia in 1878 (Francis, 1878). Just before the turn of the century, in 1991, saxitoxins originated from a toxic bloom of *Dolichospermum circinale* in the Darling River and killed 1600 sheep in Australia (Humpage et al., 1994). Cases of cattle deaths attributed to cyanotoxins were also registered at higher latitudes, such as in Finland (Sivonen et al., 1990). Microcystins are the most commonly recorded cyanotoxins in freshwater bodies used for recreational purposes and for drinking water, which has led WHO to set toxicity threshold guideline values for microcystin MC-LR at 1 µg/L for lifetime drinking water ingestion and 12 µg/L for short-term drinking water ingestion (WHO, 2020), whereas for the other cyanotoxins (cylindrospermopsin, anatoxin-a, and saxitoxins) those threshold values can be slightly higher: 3,30 µg/L for non-drinking water and 3 µg/L for drinking water (WHO, 2020). Impacts on human health by cyanotoxins can be short-term or long-term (Table 2); the contact with microcystins may, for example, induce symptoms as light as tingling or burning sensations or, in extreme cases, reach the severity of organ failure leading to death.

Table 2. Cyanotoxin types and their corresponding short- and long-term health effects - adapted from Carmichael et al. (2013).

Toxin	Short-term health effects	Long-term health effects
Microcystins	Gastrointestinal discomfort; Liver problems (inflammation and haemorrhage, fatal liver failure); Pneumonia; Dermatitis.	Tumour catalyst and inciter of deadly liver failure.
Nodularins		
Saxitoxins	Tingling and burning sensations; Numbness, speech difficulties; Deadly respiratory paralysis.	Growing numbness in mouth & digestive tract; symptoms spreading towards extremities. Muscle and respiratory paralysis.
Anatoxins	Tingling and burning sensations; Deadly respiratory paralysis.	Ultimately fatal Cardiac arrhythmia.
β-N-methylamino-Lalanine (BMAA)	Language problems and general disorientation; Unstable mood, behaviour changes, loss of motivation.	Cancer development. Lytico-bodig (neurotangle disease).
Cylindrospermopsin	Similar to Microcystins	Anorexia, malaise and liver failure leading to death.
Lipopolysaccharide	Gastrointestinal pain and dermatitis.	Fever, leucopoenia, hypo-tension, cardiopulmonary dysfunction, disseminated intravascular coagulation and multi-system failure.
Lyngbyatoxins	Skin tumours and Dermatitis.	Severe dermatitis and damage to the kidneys.

Cyanobacterial blooms can modify the structure and interactions of a food web (Briland et al., 2020); the 2020 study on Canadian Lake Eire concluded that prey-fish continued actively foraging in cyanobacterial blooms but showed a change in diet by increasing preferences for small cladocerans and benthic prey. The authors (Briland et al., 2020) highlighted that since both prey and predator fish were found in bloom-affected waters, there is the risk of human intoxication by bio-accumulated microcystins due to recreational and commercial fishing. The toll from these blooms affects the whole community not only health-wise but also financially - for Lake Erie communities, the losses are about $142 M / year from un-mitigated HABs (DeRose et al., 2021).

Shellfish aquaculture, for instance, is an industry deeply affected by Harmful Algal Blooms (HABs) that produce saxitoxins (Bilbao et al., 2020), similarly to cyanobacteria, leading to economic losses of £ 1.37 M / year in shellfish production (Martino et al., 2020). Tourism is also affected. Recreational razor clam fishery contributes towards the economies of Grays Harbor and Pacific counties in the US state of Washington. However, the occurrence of HABs have forced beach and fishery closures since 1991. The total estimated negative economic damage for both USA and Canada were a loss of 339 full-time jobs and $10.6 M of labour income, a study concluded (Dyson & Huppert, 2010). Furthermore, a 2022 study by the University of Wisconsin and the US Environmental Protection Agency proved that cyanobacterial blooms influence property values (Zhang et al., 2022); by analysing over 2000 large lakes from the year 2008 to year 2011, they concluded that a 10 percent increase in annual algal bloom occurrence caused a decline in average home values for near-shore properties up to 4.3% in North-eastern USA.

Without a doubt, cyanobacteria were and still are vital for life on planet Earth. Nonetheless, they can pose a serious threat to various dimensions of human life, from health to economy and social fabric of entire communities. Climate change acts as an enhancer for cyanobacteria proliferation and bloom occurrence throughout the world.

1.2. Climate Change and Cyanobacterial Blooms

Climate Change can catalyse the proliferation of cyanobacterial blooms (Paerl & Huisman, 2009; Paerl & Otten, 2013; Paerl & Paul, 2012; Wells et al., 2020). In addition to over-nutritive conditions, factors such as temperature and hydrologic changes have an effect on blooms' occurrence, frequency, composition and dynamics. The tendency of increased temperatures facilitates cyanobacteria to attain an optimal growth on surface water layers, allowing their multiplication and formation of large blooms that absorb heat and shield deeper layers below and cutting off other species from sunlight intake. Both the accumulation of sunlight energy by the bloom and the shading of lower layers in the water column from the sun creates ideal conditions for surface cyanobacteria to dominate and ultimately outcompete their eukaryotic phytoplankton rivals. Thus, rising temperatures can start a positive- feedback cycle favouring cyanobacterial blooms (Jöhnk et al, 2008). The wide- spread nature of the presence of toxic blooms all over Europe, a continent suffering from unusually high temperatures (such as in summer of 2022), is known to scientists at least since the mid 80's (Skulberg et al., 1984). An example of how temperature influences cyanotoxic events in Europe is the case of the eutrophic and urban Lake Pamvotis, in Greece, where a correlation was found between high temperature and a high amount of cyanotoxins produced by cyanobacterial blooms (Gkelis et al., 2014)—a situation that is believed to be aggravated by anthropogenic influence and climate change.

Alterations in precipitation and drought patterns, caused by climate change, can also contribute to the development of Harmful Cyanobacterial Blooms (HCBs). Intense precipitation can mobilize nutrients from the soil to waterways, leading to nutrient-enriched conditions (King et al., 2007). When it comes to droughts, added to the rise of sea level, with diminished freshwater sources, they not only may poison valuable water sources but also contribute to the increase of salinization in available freshwater. Cyanobacteria are not particularly fond of extreme salinity. However, not only cyanobacteria have evolved to resist under the environmental pressure of high salinity conditions while keeping a positive growth rate—as such is evident in *Nodularia spumigena*'s with a 20g/L salinity tolerance (Mazur-Marzec et al., 2005)—but also take advantage of the subsequently more stratified water column as buoyant cyanobacteria species take over the surface layer to harvest energy from the Sun and multiply.

Cyanobacteria also have an important role in the carbon cycle. Carbon is an element at the very genesis and centre of the climate change conundrum but it is also related to nuisance microalgal events, in which cyanobacteria play their part. Nourished dense blooms demand high quantities of CO_2 to fuel their photosynthetic processes. The water in which the bloom grows is depleted of its free CO_2, which alters the chemistry dynamics and alkalinizes the water up to pH 10 or higher; CO_2 intake levels being, in some cases, a limiting factor for growth (Paerl & Paul et al., 2011).

In summary, climate change plays a role on the proliferation of harmful and potentially toxic cyanobacterial blooms. Increased temperatures and water stratification offer cyanobacteria optimal conditions to growth and to outcompete their rivals for the same resources. Moreover, long and heavy rainstorms that dislodge nutrients from the soil and send them to a receiving water system, cause nutrient enrichment which subsequently may enhance the cyanobacterial growth. In conclusion, CHBs have much to gain from the aggravating conditions from climate change.

1.3. Framework and Structure of the Thesis' research

Harmful Cyanobacterial Blooms (HCBs) present a worldwide threat to aquatic ecosystems and to public health. In light of the increasing frequency of blooms, this work aims to review and compile data related to bloom-forming *taxa* of cyanobacteria affecting Europe, including the Portuguese territory. The type of data varies and can range from ecological to toxicological as well as molecular data. Once the necessary data is gathered, encapsulating the past fifty years but focusing more on the past two decades, an analysis is carried out as well as of discussion to draw final conclusions. As a long-term objective, beyond the scope of this work, the resulting compiled data is expected to feed online databases.

2. Biogeography of potentially toxic and bloom-forming cyanobacteria in Europe

The following section aims to offer a panoramic view over Europe and its nations regarding cyanobacterial records through a compilation of data from several countries. The search was mainly based in records from the scientific database Scopus although additional information was added from other sources. For some countries, unfortunately, no source of peer-reviewed information regarding cyanobacterial blooms in freshwater bodies was found; those countries include Albania, Andorra, Azerbaijan, Bosnia and Herzegovina, Cyprus, Kosovo, Liechtenstein, Malta, Moldova, Monaco, North Macedonia, San Marino and the Vatican City (Holy See).

2.1. A general overview

Using data gathered from the articles used for every country in this thesis, Figure 1 was built to showcase the confirmed locations of *R. raciborskii* dispersion in Europe. This species of cyanobacteria enjoys a vast dispersion throughout Mainland Europe and its accurate documentation of cases makes it possible to make a map of confirmed occurrences with confidence.

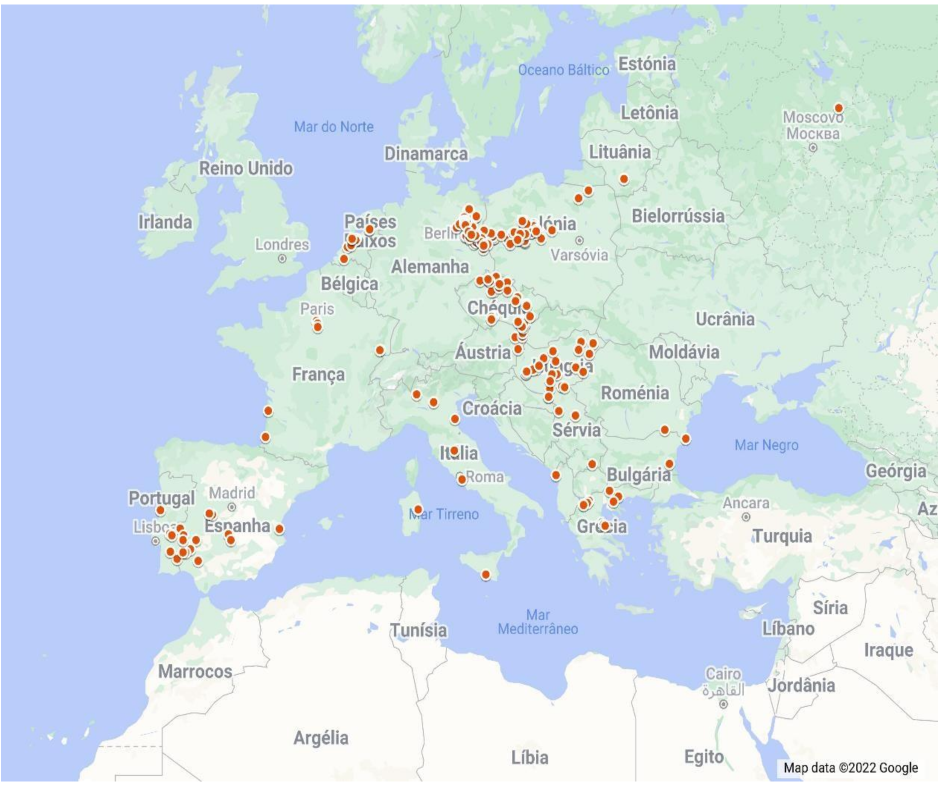

Figure 1. Confirmed cases of *R. raciborskii* in Europe in the available scientific literature.

R. raciborskii is a well spread-out invasive species that has colonized water bodies throughout mainland Europe, where reports essentially are registered from mainland/continental Europe. It has noticeable clusters in southwest Iberia and in central Europe between Warsaw and Berlin but also throughout Hungary and Czechia. The absence of data in other mainland countries or other parts of affected countries is probably due to a lack of testing more than the cyanobacterium's absence. Cases are marked with red dots (several references, identified throughout this thesis). A Table list of occurrences of *M. aeruginosa*, *A. flos-aquae* and *R. raciborskii* is attached as Annex I.

2.2. Northern Europe

In Denmark, eutrophication has been a major problem for the Danes. More than 60% of the country is farmland, and despite successful efforts to cut overall excessive nutrient discharges, out of which still high loads of inorganic nitrogen leak into Denmark's waterbodies (Christoffersen & Perlt, 2012). Cyanobacteral blooms appear annually not just in Danish coastal waters but also in inland waters. Blooms are prolific especially when the weather is warmer. Such periods in July and August have been reported to bolster harmful ecological events such anoxia and release of cyanotoxins (Christoffersen & Perlt, 2012). Fatalities are counted among animals, pets and livestock because many of them rely on surface water, which is vulnerable to cyano-contamination. In a notable event, cyanobacterial blooms were implicated in bird kills at lakes in Denmark in July 1993 and June-July 1994. Dead birds collected from Lake Knud sø during the neurotoxic 1993 *Anabaena* bloom were suspected to have succumbed to cyanobacterial toxicosis (Henriksen et al., 1997). Suspicions were later unmasked: *Dolichospermum lemmermannii* was the dominant species in the blooms and the presence of neurotoxin anatoxin-a(s) was confirmed (Onodera et al., 1997). Plus, in a recent study, several lakes were found to contain neurotoxin Saxitocin (STX); the Arresø, Bagsværd Sø, and Lyngby Sø lakes holstering *Dolichospermum* as the most abundant genus (Podduturi et al., 2021), the species likely being *D. lemmermannii* (already flagged in previous study (Kaas and Henriksen, 2000)). Today, severe threat to public health is not yet presently reflected in reality, mostly due to frequently monitored high quality water in bathing areas, the fact that nearly all of the drinking water comes from unaffected ground water. Despite almost all lakes being open for recreational activities, cyanotoxin-originated disease is rare and there is no record of human deaths to date. Frequent potentially cyanotoxic species occurring in Danish lakes and coastal areas belong to the following genera: *Microcystis*, *Anabaena*, *Aphanizomenon*, *Planktothrix*, and *Nodularia* (Christoffersen & Perlt, 2012).

In Iceland, Lake Mývatn is a thermal waterbody that has suffered blooms of *Dolichospermum flos-aquae* and *Dolichospermum circinale* (Einarsson et al., 2004; Jasser et al., 2022); *Symploca thermalis* and *Mastigocladus laminosus* have been also registered in Iceland (Castenholz 1969).

Finland is one of the best countries when it comes to cyanobacteria and cyanotoxin monitoring scheme. A nationwide observation system has been in force since 1998. These efforts encompass a joint venture of local authorities and national institutes such as the Finnish Environment institute SKYE and formulate a report every Summer. Plus, volunteers receive training from SYKE in order to correctly identify and report algae blooms. In samples dated between 1986 and 1987, various *Anabaena* sp. strains were found in the lakes Yla-Keyritty, Kiikkara and Vesijarvi (Sivonen et al., 1992). Plus, *Oscillatoria agardhii* has been identified and isolated from samples of Langsjon, Valkjarvi, Maarianallas, Haukkajarvi, Koylionjarvi, Ostra Kyrksundet, Kotojarvi and Vesijairvi (Sivonen et al., 1993). For Lake Pyhäjärvi, on the border between Finland and Russia in Karelia, during the study period 1998-2002, it was observed that algal blooms were caused by *Anabaena* species, mainly by *Dolichospermum lemmermannii* (Niinioja et al., 2004). Finnish water treatment plants perform regular screening tests for toxins and have been doubled-down following events such as high cell count of *Planktothrix agardhii* leading to problems like clogged filters on the plants, cyanobacteria numbers peaking in the end of September 2008 (Rapala et al., 2012). Samples with high MC toxin concentrations from a cyanobacterial bloom occurring in autumns 2015/2017 and original from the eastern part of the Gulf of Finland, were subjected to genetic analysis and the responsibility for the high MC level was attributed to *Apanizomenon flos-aquae* (Chernova et al., 2019). Currently, the occurrence of cyanobacterial blooms is mostly registered from the central inland down to the south parts of the country, where more people live, and also in coastal and open sea areas such as the Baltic Sea. SYKE's services recorded in 2010 two peaks of cyanobacterial abundance in the Baltic Sea, in the end of July and another in the first part of September (Rapala et al., 2012) and it could be arguably seen an overall increase in comparison with 1989 - 2009 period. A summary report on June-August 2021 bloom monitoring highlighted a peak in cyanobacterial growth mid-July, prompted by high temperatures (SYKE 2021).

In Sweden, blooms on lake Mälaren were dominated by *Microcystis flos-aquae* while also containing a strong presence of *Microcystis aeruginosa* (Pekar et al., 2016), with microcystins being detected in this lake and in others: Ulmiste, Långasjön, Vombsjön, Immeln and Sydvatten. In addition, other cyanobacteria were recorded, namely from *Dolichospermum*. Furthermore, *Microcystis botrys* and *Woronichinia naegeliana* were found to be abundant at Lake Immeln, with *M. botrys* dominating the blooms.

For Norway, *A. flos-aquae* was detected In a sample collected from Lake Edlandsvatn in 1981 (Sivonen et al., 1992). The presence of *Gonyostomum semen*s has been known in northern Europe (Lebret et al., 2012), and has significantly affected the southeast lakes of Norway, namely Gjølsjøen, Isesjø, Langen, Longumvannet, Lundebyvannet, Rokosjøen, Skjeklesjøen, Storsjøen, Øyeren (Hagman et al., 2015). Since its first detection in 1975 (Hongve et al., 1988),

In Estonia, historical record peaks of cyanobacterial mass occurred under the Soviet Union period, due to the soviet policy being strongly bent on vast agriculture. The turn of the century brought three major reforms in Estonian agriculture: from redistribution in 1919 and collectivization in 1949 to reprivatisation starting in 1989 (Hansen 2008). By the end of the 20th century, blooms were recorded to bolster increased frequency, biomass and duration (Ott & Kõiv, 1999). The fall of Soviet agricultural reforms allowed a decrease in registered cyanobacterial biomass, and these values have been decreasing in lakes ever since (Ott et al., 2002; Rakko et al., 2008). An explanation for the noted decline in biomass can be the fall of externally sourced nutrient load flowing into water bodies and the growing replacement of once-dominant algal colonies in favour of the lighter filamental species of Nostocales (Rakko et al., 2008); dominant species include *Limnothrix planctonica*, *Aphanizomenon yezoense*, *A. gracile* and *Planktolyngbya limnetica, M. botrys* and *Gonyostomum semen* (Tanner et al, 2005; Rakko et al., 2008). In a context of scarce work on cyanobacterial blooms in Estonia, there are several reports of allergic reactions and skin irritation suffered by swimmers.

In Latvia, Balode et al., 2006 studied cyanobacterial blooms in several lakes near Riga, Latvia's capital, during the period of 1998 to 2004 (the risk of cyanobacterial blooms in the region of Riga was already noted by Eynard et al., 2000). Lake Lielais Baltezers suffered from most high concentration of microcystins. Dominant species in the blooms were *Anabaena* spp., *Aphanizomenon flos-aquae* and *Microcystis* spp.. In 2002, after a period of rainy weather, *Aphanizomenon flos-aquae* dominated Lakes Lielais and Mazais Baltezers. *Microcystis* spp. have increased their presence at Lake Lielais Baltezers. *Planktothrix spp*. became more frequent in Lake Langstini, during the study period (Balode et al., 2006).

In Lithuania, toxic blooms of *Microcystis aeruginosa* were reported in 2006, on the Curonian lagoon (Paldaviciene et al., 2009). *A. flos-aquae* has also been detected frequently in the Curonian lagoon (Vybernaite-Lubiene, 2017). After intrusion of water from the Baltic Sea*, Nodularia spumigena* was detected in the northern part of the lagoon; this marked the first time that a nodularin-producing species was detected in the Curonian Lagoon in record, a water body that has recurrent hotspots for cyanobacterial blooms (Vaiciute et al., 2021). Jiezno ež has been registered to suffer blooms with significant pesence of *Raphidiopsis raciborskii* (Kokociński et al., 2017). Also, *G. Semen* was detected in Lakes Pabezninkai and Slabada (Karosienė et al., 2016). Eutrophication and climate change were appointed as probable culprits of the appearance of novel species of cyanobacteria *Anabaena bergii* var. *limnetica* (now *Anabaena minderi*) in lake hypertrophic Lake Gineitiskes (Koreiviene and Kasperoviciene, 2011), detected in the period of July-August of 2008.

For the United Kingdom, the cyanobacterial genera *Microcystis*, *Oscillatoria*, *Plantothrix*, *Anabaeana*, *Pseudoanabaena*, *Aphanizomenon*, *Snowella* and *Gomphospaeria* have been detected on across the country (Howard et al., 1996; Krokowski et al., 2002); and there have been reports of serious human intoxication following exposure to blooms. Two 16-years-old army recruits, in 1989, were hospitalized for a week after performing canoeing exercises for hours in Rudyard reservoir, in Staffordshire, England. They had swallowed water and developed severe symptoms that included vomiting, blistered mouth, dry cough, left basal pneumonia, abdominal pain and fevers of 38.4 ºC and 39.2ºC (the first one suffered from periodic hallucinations for two days). The doctors managed to apply medication and cure the fever in 24h. However, due to the multiple symptoms and observation necessities, the young recruits were only discharged after a week. Testing revealed that, at the time these recruits were canoeing, there was a *Microcystis aeruginosa* affecting Rudyard reservoir (Turner et al., 1990). In the fallout of these hospitalizations, 16 more recruits were admitted to the medical barracks with similar symptoms. Turner et al. (2018) analysed several samples from all over England dated from 2016 (Figure 1). The magnitude of microcystin concentrations recorded was higher during the months August-October, the south of the country being the most affected, but also big cities in the centre and north experienced clear hotspots.

In Ireland, the presence of *Oscillatoria* sp. was confirmed in lake Caragh, in Kerry, and *Anabaena* sp. in lakes Inniscarra, in Cork, and Corbally, in Roscommon (James et al., 1997).

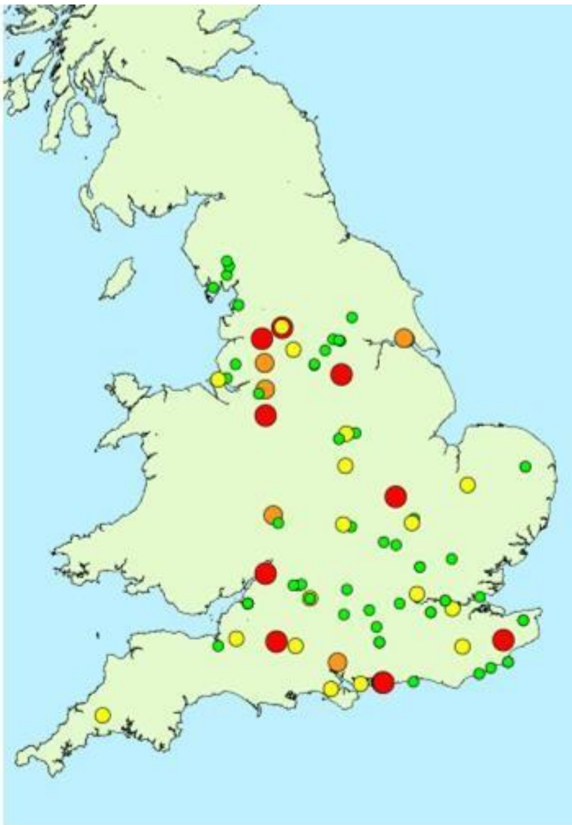

Figure 2. *Microcystis* occurrence in England (adapted from Turner et al., 2018). Colour scheme: red: >100 μg/L; orange: 20–100 μg/L; yellow: 2–20 μg/L; green: <2 μg/L).

2.3. Western Europe

Belgian scientists have alerted the need for a country-wide picture of the diversity of cyanotoxins and their corresponding *taxa* (Van Hassel et al., 2022), because such a view is needed to correctly understand and deal with the bloom's dynamics. Important water sources for drinking and recreational activities remain exposed to bloom risk. Aquifers provide most of Belgium's drinking water, along with a small reliance on reservoirs and inter-regional water imports (Brussels, Flanders, and Wallonia regions) as well as from other countries. The composition of the freshwater supply varies from region to region and according to circumstances. Pressure on the use of recreational waters rises in summertime as, in the other hand, these remain, as many others across Europe, exposed to eutrophication due to fertilizer run-offs from agriculture and untreated sewage discharges. Despite the known risk to human health that contact with cyanotoxins poses, no conclusive evidence is yet to be officially recorded in Belgium. *Microcystis aeruginosa* was singled out as the likely culprit for the death of thirty birds during the summer of 1995 in Jehay (Wirsing et al.,1997). This event of mass mortality occurred at the same time that a bloom dominated by *M. aeruginosa* plagued three adjacent ponds at Jehay, where the birds were found. Autopsy by the Liege-located "Centre Provincial de Depistage des Maladies Infectieuses" revealed that ingested hepatoxins probably caused blood to accumulate in the entrails, leading to the birds' death. Occurences listed by Willame et al., 2005 show that species of *Microcystis sp.* have been detected and dominant in blooms at various water bodies in Belgium: Etangs de Robaiwé I and Etangs de Robaiwé II (both located at Saint-Hubert), pond Fourbechies (a hypereutrophic livestock reservoir at Froid-Chapelle), Louvain-la-Neuve (hypereutrophic pond at Ottignies), Serinchamps (hypereutrophic pond at Ciney) and at Weillin (hypereutrophic pond at Saint Hubert). Particularly, *M. aerugionsa* was dominant in blooms registered at Jehay étang moyen (pond for nature conservation use), Neufchâteau (pond commonly used for fishery), and Robertville (drinking-water reservoir) (Willame et al., 2005). Furthermore, *Aphanizomenon flos-aquae* was dominant in a bloom at a pre-dam lake in Féronval (Willame et al., 2005), classified as hypereutrophic. *Planktothrix agardhii* was one of the most common species detected during the study, having been found at ponds

Pêcherie du Poisson rouge, Tharoul (Clavier), Gomzé-Andoumont (Sprimont), Ftêre (Serville), La carpe bocqueuse (Hamois), Féronval, Bomerée (Mont-sur-Marchienne), Château de Graaf (Montzen-Plombières), Château de Jehai (Amay), and at Etang Michaux in Charleroi. Other species found in Belgian waters are further specified in the mentioned paper. The occurrences mentioned in this sub-section on Belgium are represented in Figure 3.

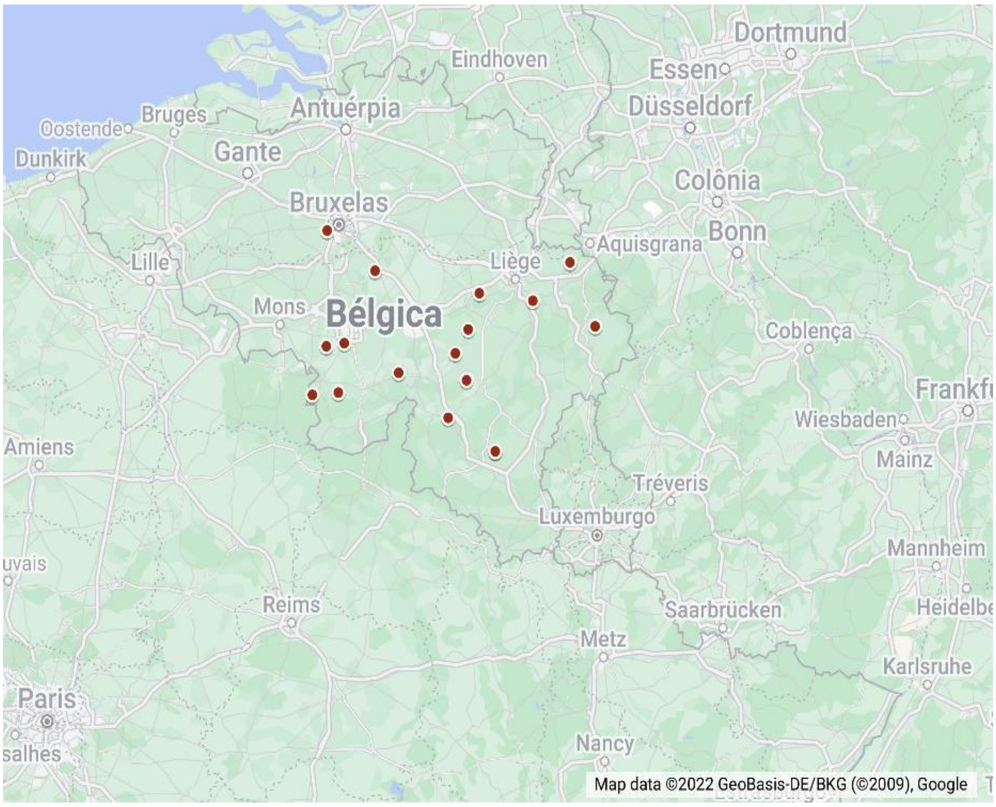

Figure 3. Geographical records of cyanobacterial blooms in Belgium.

In Austria, Alte Donau is a popular destiny for recreational activities, having a valuable ecological habitat area and being home to numerous leisure businesses. Blooms at the urban lake of Alte Donau have been composed mainly by *Raphidiopsis raciborskii*, while registered blooms at the Mondsee lake (Salzkammergut), to where thousands of people pay a visit each year, have been dominated by *Planktothrix rubescens* (Dokulil et al., 2000).

In France, samples taken in 1994 from Lake Grand-Lieu, southwest of Nantes, revealed the presence of the toxic species *M. aeruginosa* and *Dolichospermum circinale* (Vezie et al., 1998). *M. aeruginosa* as also been found at the Lac de

Grangent, Loire (Latour & Giraudet, 2004). The study Willame et al., 2005 detected several cyanobacteria species dominating blooms in northern France near the border with Luxemburg and Belgium. In the referred study, *Microcystis aerugiosa* was found dominating blooms at Etang rouge eutrophic pond (Insviller-Moselle), while *Planktothrix rubescens* dominated blooms ate Givet pond in the French Ardennes region. Moreover, *Planktothrix agardhii* and *Aphanizomenon* sp. dominated blooms in the hypereutrophic pond of Lindre, designated for Nature conservation. *Planktothrix agardii* was found again in a pond at Niederstinzel (Moselle), together with co-dominating *Anabaena spiroides*. Plus, *Planktothrix agardhii* was also found dominant in blooms at ponds Nolweilher (Moselle) and Parroy (Meurthe et Moselle). In recent studies, *M. aeruginosa* was found at Lake Place (Pobel et al., 2011) and Rivière de Saint-Eloi, Muzzilac (Lance et al., 2021). Furthermore, *Raphidiopsis raciborskii* has been recorded in Francs Pêcheurs (Briand et al., 2002; Coute et al., 1997), Lacanau (Cellamare et al., 2010), Soustons (Cellamare et al., 2010), River Seine a Ivry (Druart & Briand, 2002), Malsaucy ponds, Étang Léchir and Lake Chanteraines (Cellamare et al., 2010).

For Germany, the presence of *R. raciborskii* in waterbodies has been documented for the past decades, with the first observation being registered in 1990 at Lake Lieps, Brandenburg (Krienitz and Hegewald, 1996), spreading to other Brandernburg lakes since (Wiedner et al., 2002; Mischke; 2003), including Melangsee and Langer See (Fastner et al., 2003). Furthermore, according to GBIF (Botanic Garden and Botanical Museum Berlin), this cyanobacterium was also found present in Eichenteich, Falkenhagener See, Neuer See, Kleiner Schwielochsee and Schwielochsee. Stüken et al., 2006 also gives a long list of occurences of *R. raciborskii* in Germany's water bodies: Bützsee, Ruppiner See, Molchowsee, Zermützelsee, Buckwitzer See, Vielitzsee, Werbellinsee, Braminsee, Großer Zernsee, Rahmer See, Fauler See, Lieps, Petersdorfer See, Scharmützelsee, Großer Glubigsee, Springsee, Großer Kossenblatter See, Lebbiner See, Großer Storkower See, Schaplowsee, Großer Schauener See, Wolziger See, Kutzingsee, Zemmin-See, Pätzer Vordersee, Motzener See, Rangsdorfer See, Croisensee, Zeuthener See, Großer Zeschsee, Siethener See, Flakensee, Großer Krampe, Kietzersee, Oder-Spree, Spree, Byhleguhrer See, Gülper See, Wirchensee and Petznicksee. It was also detected at Großer Plessower See (Wiedner et al., 2007) and Zierker See (Mehnert et al., 2010). *Aphanizomenon flos-aquae* has been detected in lakes Müggelsee (and *Microcystis* sp.) (Dokulil et al., 2000), Melangsee and Heiliger See (Potsdam) (Preußel et al., 2006), while the occurrence of *Microcystis aeruginosa* has been confirmed in lake Bareleber (Ronicke et al., 2021), where *Anabaena* and *Aphanizomenon* cyanobacteria has also been detected (Ronicke et al., 2021). Furthermore, *Raphidiopsis raciborskii*, *Chrysosporum bergii* and *Sphaerospermopsis aphanizomenoides* have been detected in numerous water bodies in lowlands in and near Berlin (Stuken et al., 2006). The Bleiloch reservoir (Thuringia), once an important freshwater reservoir for drinking-water storage, was confirmed to harbour toxic cyanobacteria by the detection of hepatoxic microcystins (Hummert et al., 2001).

In Luxemburg, Willame et al. (2005) reported cyanobacterial species dominating blooms in different waterbodies. The locations are highlighted on Figure 4. At a mesoeutrophic, drinking-water reservoir at Esch-sure-Sûre, a bloom was found to be dominated by *Planktothrix agardhii*. *Anabena planctonica* dominated blooms in a pre-dam, mesoeutrophic waterbody in Bavigne-Beivenrbaach. At Mettendall eutrophic pond, without official use, showed bloom dominance by *Aphanizomenon* cyanobacteria. Lastly, *Microcystis* sp. dominated blooms at Weiswampach recreational pond, classified as mesoeutrophic.

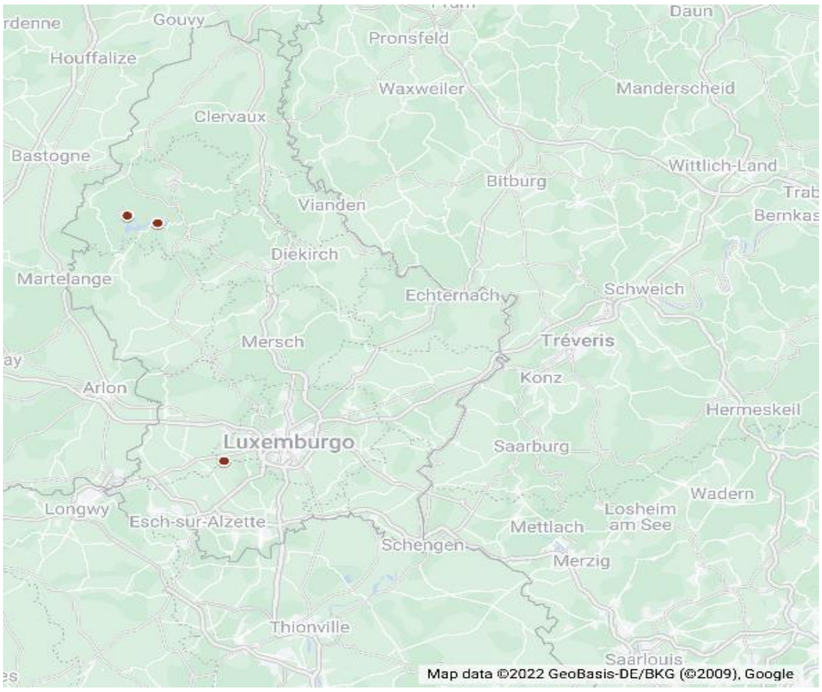

Figure 4. The three locations (Esch-sure-Sûre, Bavigne-Beivenrbaach, Mettendall) of studied blooms by Willame et al., 2005 in Luxemburg.

In the Netherlands, **"**God made the world, and the Dutch made the Netherlands"; that's a Dutch saying that encapsulates a lot of Dutch water bodies. Most of the lakes are man-made and are close to potential sources of nutrients such as densely populated areas. However, natural conditions are now at odds with that land use development. The exposure risk to toxic cyanobacterial blooms is high in the Netherlands. Despite great efforts to reduce nutrient loads in lakes, a large number remain highly eutrophic. Cyanobacterial blooms affect many Dutch lakes; figure 5, a map created by Kardinaal & van der Wielen 2011, shows the spatial distribution of lakes dominated by cyanobacteria. The most frequent type of blooms consists of year-round filamentous cyanobacteria (such as *Planktothrix* and *Limnothrix*) and *Mycrocystis* blooms during the summer (Ibelings et al., 2005). In addition to regional waters, *Mycrocystis* blooms ranging from tens to hundreds of square kilometres spread over big lakes such as IJsselmeer (1136 km2) and Volkerak Zoommeer (61.5 km2). According to occurrence data available by the Dutch Foundation for Applied Water Research the on the Global Biodiversity Information Facility (GBIF), *Raphidiopsis raciborskii* has marked presence in the following water bodies: De Poel (Amstelveense), Kleine Poel (Amstelveense), Sluipwyk (Plas sgravenkoop), Binnenschelde (Bergen op Zoom), Kortenhoefse Plassen (Kortenhoef), Naarden, Schutsloterwijde, Bergschenhoek, Wijde Gat (Kortenhoef), canal in Uithoorn and at an agricultural canal in Sint Jansklooster. In the summer of 1999, an inquiry was established to get a grasp of health incidents related to water bodies and recreational activities. Registered incidents counted 15 gastro-intestinal complaints, 22 for skin complaints, and 4 related to dogs' health (Ibelings et al., 2005; Leenen, 2000). The study is old and had a relatively small number of participants but illustrates the type of impacts on health derived from cyano-contamination of surface waters. A recent bloom at banks of river Maas can be seen in Figure 5.

Figure 5. A cyanobacterial bloom affecting the south bank of the river Maas in Bokhoven, 's-Hertogenbosch, North Brabant province (August 12th, 2022). The morning's low tide waves leave vibrant green marks and covered objects with scum. Local authorities issued advice against swimming in the river. Photo taken by the author of this thesis.

From a quick view of data plotting via a google maps chart of the *R. raciborskii* occurrences in the Netherlands (Figure 6), it is possible to view that most of the registered occurrences happened in the Randstad region, where most of the people live. The southernmost occurrence was registered in Bergen op Zoom and the northernmost in the northern suburbs of Zwolle, an important transportation node in the country's north. There can be seen a concentration of cyanobacterial blooms in the "Randstad" region—the most densely populated in the Kingdom of the Netherlands. The main cities of the Randstad are Almere, Amsterdam, Delft, Den Haag, Leiden, Dordrecht, Haarlem, Zoetmermeer, Rotterdam and Utrecht. A concentration of blooms can also be seen in the north, spread over areas east of Groningen.

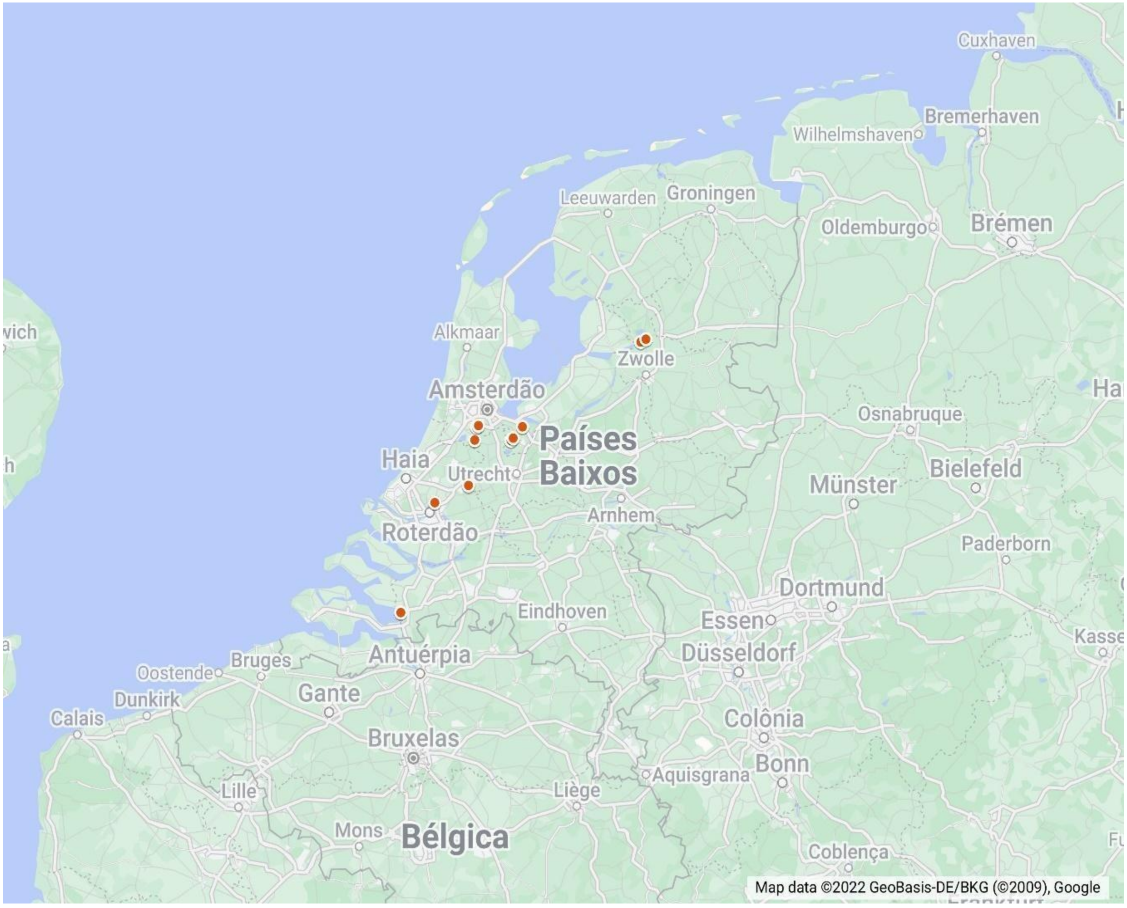

Figure 6. Plotted chart of *R. raciborskii*'s occurrence in the Netherlands (data from various references mentioned in the main text).

In Switzerland, *Microcystis aeruginosa* was found at Lake Zurich and at Greifensee (Monchamp et al., 2016)*. Anabaena minderi* has been detected at Lake Greifen (Greifensee) (Huber-Pestalozzi, 1938), Flaach, Andelfingen and Altikon (Couté and Preisig, 1978).

2.4. Eastern Europe

In Armenia, a 2018 study on the Lake Yerevan, South Caucasus region, reported a total of 27 cyanobacterial species identified (Minasyan et al., 2018). Important species were detected, such as *Microcytis aeruginosa*, *Microcytis ichthyoblabe*, *Dolichospermum circinalis*, *Dolichospermum flos-aquae*, *Dolichospermum planktonica*, and *Planktothrix agardhii*. Futhermore, large quantities of *Aphanothece* spp. and *Aphanocapsa* spp., and *Nostoc linckia* were also detected in the lake.

For Belarus, only two studies on Belarus relevant for this study were found: Mikheyeva et al., 2012 & Mikheyeva 2021. The most recent analysed the status of 50 recreational water bodies in the country but, unfortunately, it was not accessible. Nonetheless, the earlier study of 2012 focused on important findings in waters that passed through Belarus' capital—Minsk. Urban waters in Minsk suffer yearly from cyanobacterial blooms, where around 90% of phytoplankton biomass is composed by potentially toxic species (Mikheyeva et al., 2012). Dominant quantities of *Microcystis aeruginosa* were detected at the Svisloch river, along with other MC-producing species: *Planktothrix agardhii*, *M. wesenbergii*, *M. viridis, Dolichospermum lemmermannii*, *A. flos-aquae*, and *Aphanizomenon flos-aquae*. It is believed that the artificial alterations such as the building of the reservoirs Drozdy and Lake Komsomolskoye (increasing therefore the waters' surface area and exposure) and the inflows of untreated urban waste have contributed to the occurrence of such blooms and increased the health risk to the public.

Reports of cyanobacterial presence in Bulgarian wetlands date back to the end of the 19th century, although concrete data on harmful blooms began referring to it from the mid-20th century onwards (Stoyneva et al., 2007; Pavlova et al., 2013). In this data—further detailed in Michev et al., 2007 for Bulgarian wetlands—it is notable an increase in frequency of bloom events considered as potentially toxic at both coastal and inland water bodies. Serious studies on the occurrence of cyanotoxins started in 2004 (published Pavlova et al., 2006). In this work, water samples were taken and analysed. The locations were drinking water reservoirs (Iskur, Sofia; Yasna Polyana, Burgas; Studena, Pernik and reservoirs for fishing and

water sports: Pchelina, Pernik; Bistritsa, Sofia; Botunets, Sofia; Kutina, Sofia) and recreational lakes from Black Sea region (Shabla, Ezerets, Durankulak, Vaya and Mandra) and from Sofia (Dolni Bogrov, Druzhba, Choklyovo Blato and Pernik). Cyanobacterial blooms were detected in half of the studied water bodies—namely Shabla, Durankulak, Vaya, Mandra, Pchelina and Bistritsa lakes—, species of the *Microcystis* genus being dominant. As for the drinking water reservoirs, none of them showed signs of cyanobacterial blooms. The next year, the *Microcystis* genus asserted dominance in cyanobacterial blooms once again in lakes Shabla and Durankulak, in the Black Sea region (Pavlova et al., 2007). Nonetheless and fortunately, blooms were not detected in the reservoirs storing water meant for human consumption. Bulgaria is one of the many European countries in which *Raphidiopsis raciborskii* proliferates. In a 2020 study, potentially toxic cyanobacteria species were identified in various Bulgarian water bodies (Stefanova et. al, 2020). *Raphidiopsis raciborskii* was detected in lake Vaya, being especially abundant in the Poray reservoir and lake Uzunguren. Out of all the water bodies included in this study (lakes: Vaya, Durankulak and Uzungeren; reservoirs: Mandra, Poroy and Sinayta Reka), lake Vaya was by far the one which accused a higher number of cyanobacterial species being *Dolichospermum flos-aquae* and *Dolichospermum crissum* both abundant and *Dolichospermum pertubatum* dominant in the samples.
R. raciborskii occurred also in Srebarna Lake (Stoyneva, 2003), in Lake Burgas (Vaya) and Shabla (Durankulashko ezero Durankulak) (Stoyneva, 2016). The ecological monitoring of water bodies is evolving positively, and since 2010 the *Law for water* ensures that the protection of water resources stands inscribed into the national legislation of Bulgaria.

For Croatia, *Raphidiopsis raciborskii* has been detected in Sakadaš Lake, as well as in the Kopački Rit park—one of the best preserved in Europe which has suffered cyanobacterial blooms over the years with the following cyanobacteria being detected in significant quantities: *Anabaena solitaria*, *Dolichospermum circinale*, *A. planctonica*, *Aphanizomenon flos-aquae*, *Limnothrix redekei*, *Planktothrix agardhii*, *Pseudanabaena limnetica*, *Planktolyngbya limnetica*, *Merismopedia punctata*, and the previously mentioned *R. raciborskii* (Mihaljević & Stević, 2011).

In Czechia or Czech Republic, during the summertime of years 2012 – 2015, a study collected, and taxonomically analysed water samples various lakes affected by cyanobacterial blooms in southern region (Blahova et al., 2021). Major cyanobacterial species were identified. *Aphanizomenon gracile* cyanobacteria were found in lake Máchovo jezero. High quantities of *Cylindrospermopsis raciborskii (R. raciborskii)* (30% plankton composition biomass) and *Cuspidothrix issatschenkoi* in were detected in lake Písecenský, with *Microcystis aeruginosa* (25% of plankton composition biomass) being found to be present in Opatovický lake and at the Starý Kanclír lake. A previous study of 2009 identified notable quantities of cyanobacteria species *Raphidiopsis raciborskii* and *Aphanizomenon flos-aquae* in Svet and Ducibe reservoirs (Blahova et al., 2009). Kaštovský et al. (2010) compiled a list of the cyanobacterial species that are considered to be alien or "potentially expansive" in the Czech Republic: *Chrysosporum bergii*, *Cuspidothrix issatschenkoi*, *Raphidiopsis raciborskii*, *Dolichospermum compactum*, *Geitleribactron periphyticum*, *Gloeotrichia echinulata*, *Planktothrix rubescens*, *Raphidiopsis mediterranea*, *Sphaerospermopsis aphanizomenoides*, *Synechococcus capitatus*. Once again, invasive *R. raciborsii* is widely present in several Czech fresh water bodies: Nové Mlýny, Babice u Uherského Hradiště, Meadow poll south of Lány, Zámecký rybník, Dubice u České Lípy, Malhostický rybník u Rtyně nad Bílinou, Novozámecký rybník, Dvorský rybník, Morava, Olomouc (Mlýnský potok), Mlýnský rybník, Rybník Láska, Dobrá vůle, Koclířov, Rožmberk, Srálkovský rybník, Očko (Káraný), VN Harcov, Jezero Ostrá, Koupaliště Sedmihorky, Březina, Rybník Rosnička, Stříbrný rybník, Koupaliště Trutnov (Dolce park), Rybník Dlouhý u Lanškrouna (Jan Kaštovský personal communication). A plot chart from this data is in the Figure 7, below.

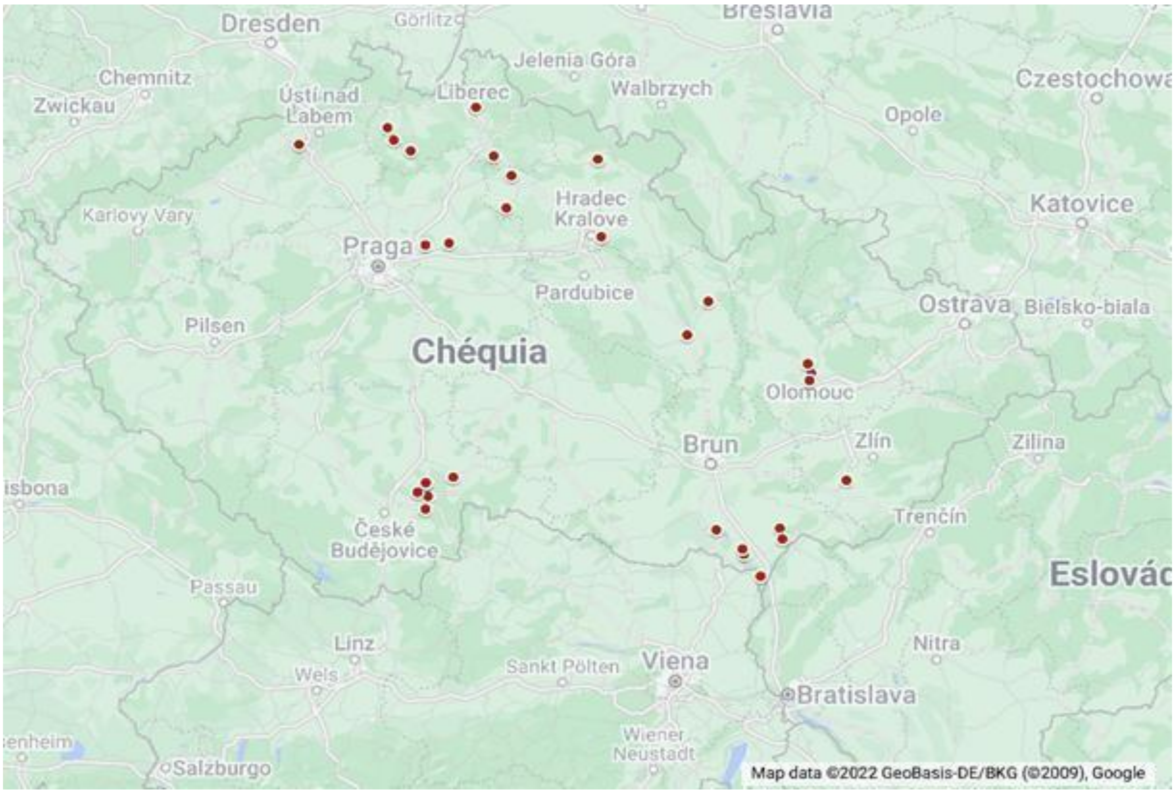

Figure 7. Occurrences of *R. raciborskii* on Czech freshwater bodies, marked by red dots (Jan Kaštovský personal communication).

Research on cyanobacteria in Kazakhstan focuses much more on the fuel-creating potential of these micro-organisms than on their potential toxicity. Nonetheless, a study with the objective of accessing the fitness of novel cyanobacteria for biofuel production retrieved filamentous cyanobacteria from rice paddies belonging to *Anabaena*, *Synechocystis*, *Oscillatoria*, *Phormidium* and *Nostoc* (Kossalbayev et al., 2022). This could indicate that cyanobacteria, including potentially toxic species, can proliferate in rice paddies. Rice farmers and workers run the risk of direct exposure to toxic blooms in the rice paddies.

Poland has a higher-than-average number of studies concerning cyanobacteria in freshwater in comparison with the overall European landscape. Various Polish rivers and lakes have been surveyed and studied. During the period months of June till October of 2005, *Microcystis aeruginosa* was present in large quantities at two eutrophic waterbodies in Central and Western Poland: Sulejów Reservoir (central Poland), and in the western Polish Bnińskie Lake (Western Poland) together with *Planktothrix agardhii* (Gagała et al., 2010). While there was a strong co-relation between total nitrogen quantities and biomass of *M. aeruginosa* for Sulejów, there was also a co-relation for temperature and *P. agardhii* in Bnińskie.

Pełechata et al. (2006) identified several species of cyanobacteria present in four lakes in Poland— Lake Jasne, Lake Złoty Potok, Lake Niesłysz and Lake Lednica. A summary of the cyanobacteria *taxa* found present in the studied lakes is organised in Table 3. Samples collected from May to September of 2010 and 2011 from the Polish lakes Mytycze and Tomaszne revealed the presence of cyanobacteria species *Aphanizomenon gracile*, *Dolichospermum planctonicum*, *Planktothrix agardhii*, *Planktolyngbya limnetica*, and *Microcystis* spp. (Solis et al., 2016). The table below summarises the results of the study in terms of presence or absence of cyanobacteria in the two polish lakes. Presence or absence of these cyanobacteria in the samples is laid out in Table 4. Napiórkowska-Krzebietke et al. 2021 identified a total of 23 species of cyanobacteria present at the Polish lake Warnołty. The dominant species were *Pseudanabaena limnetica*, *Aphanizomenon gracile*, *Planktothrix agardhii*, *Limnothrix sp.*, *Limnothrix redekei*, *Cuspidothrix issatschenkoi*, *Planktolyngbya limnetica*, *Dolichospermum affine*, *and Microcystis aeruginosa*. *R. raciborskii* (or *C. raciborskii*) has been found commonly throughout Europe and confirmed in numerous waterbodies in Poland: Kursko, Biskupieckie, Strykowskie, Kierskie Male, Żabiniec, Busko, Pniewskie, Chodzieskie, Kowalskie, Berzyńskie, Szydłowskie, Buszewskie, Niepruszewskie, Tomickie, Jelonek, Mogileńskie, Witobelskie, Rzepinko, Bnińskie, Bytyńskie, Lubosińskie, Pniewskie, Grylewskie, Świętokrzyskie, Boczowskie, Bnińskie, Biskupińskie, Zbąszyńskie, Kruchowskie, Lake Rusałka, Pątnowskie Lake, Jezioro Góreckie, Jezioro Łękno, Lake Malta and Jezioro Borusa (Kokociński & Soininen, 2012; Kokociński et al., 2009; Kokociński et al., 2013; Wilk-Woźniak & Najberek, 2013; Kobos et al., 2013; Budzyńska & Gołdyn, 2017). Overall bloom occurrence can be seen on Figure 8.

Table 3. Presence of cyanobacteria in four lakes in Poland— Lake Jasne, Lake Złoty Potok, Lake Niesłysz and Lake Lednica. The symbol means "present" and no symbol means that it was not present or detected. Adapted from Pełechata et al. (2006).

Taxa	Jasne	Złoty Potok	Niesłysz	Lednica
Aphanocapsa delicatissima		◆	◆	◆
Aphanocapsa holsatica	◆			◆
Aphanothece clathrata	◆	◆		
Aphanothece minutissima		◆	◆	
Aphanothece smithii		◆	◆	
Chroococcus limneticus		◆	◆	◆
Chroococcus microscopicus	◆	◆	◆	◆
Chroococcus minimus	◆	◆		
Chroococcus obliteratus	◆	◆	◆	◆
Cyanocatena planctonica	◆	◆		◆
Cyanodictyon planctonicum	◆		◆	◆
Merismopedia tenuissima	◆	◆	◆	◆
Radiocystis geminata	◆	◆	◆	◆
Limnothrix lauterbornii	◆		◆	◆
Planktothrix agardhii	◆	◆	◆	◆
Pseudanabaena limnetica		◆	◆	◆
Aphanizomenon gracile			◆	◆
Cuspidothrix issatschenkoi		◆	◆	
Dolichospermum lemmermannii	◆	◆	◆	◆
Dolichospermum mendotae			◆	

Table 4. Presence of *Aphanizomenon gracile*, *Dolichospermum planctonicum*, *Planktothrix agardhii*, *Planktolyngbya limnetica*, and *Microcystis* sp.. in lakes Mytycze and Tomaszne, adapted from Solis et al. (2016).

Taxa	Lake Mytycze	Lake Tomaszne
Aphanizomenon gracile	◆	◆
Dolichospermum planctonicum		◆
Planktothrix agardhii	◆	◆
Planktolyngbya limnetica	◆	
Microcystis spp.	◆	

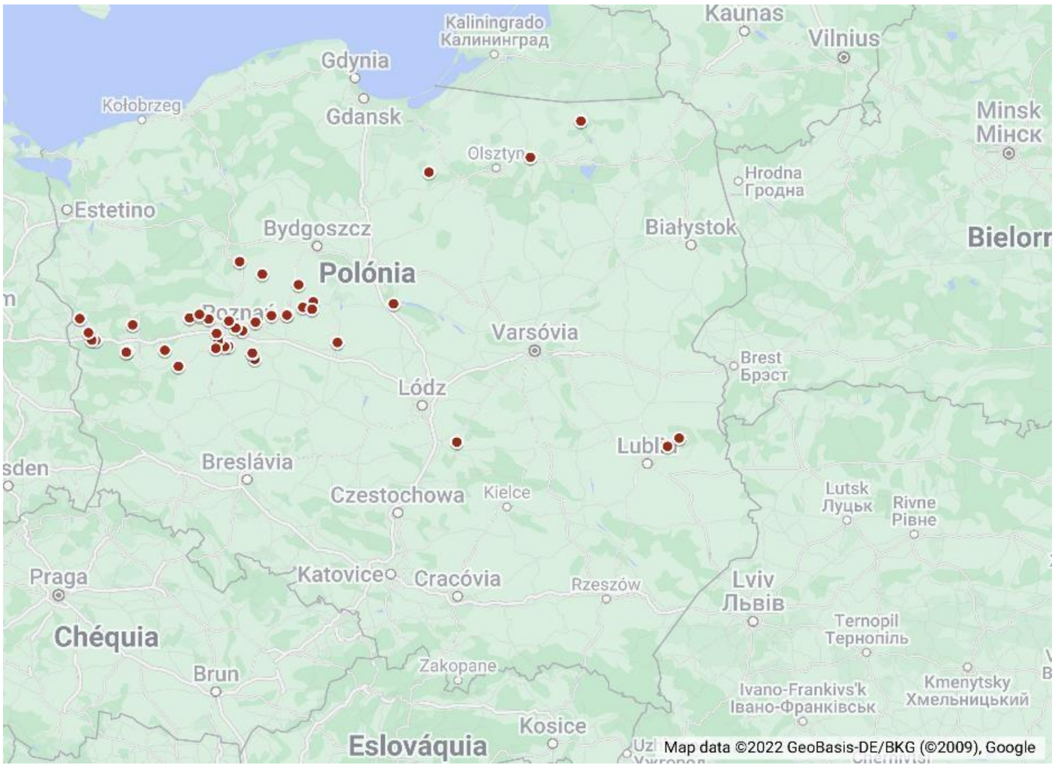

Figure 8. Overall occurrence of cyanobacterial blooms in Poland, marked by dots.

In Romania, cyanobacterial blooms in 2001 in the Gheorgheni recreational water body (Cluj-Napoca, Romania) were dominated by *Microcystis aeruginosa* and *M. viridis* (Boaru et al., 2006).

For Russia, toxic cyanobacterial blooms at the Curonian lagoon, a water body between Lithuanian and Russian land (Kalinigrad), have been noted (Vaiciute et al., 2021). *Chrysosporum bergii* has been detected in blooms at the Caspian Sea, and at saline lakes near Ural (Elenkin, 1938; Gollerbakh et al., 1953; Proshkina-Lavrenko and Makarova, 1968; Kondratjeva, 1968). Samples collected in 2009 from Lake Kotokel, located in the far e showed the presence of *Microcytis* spp. and *Anabaena lemmermannii*. Plus, phytoplanktonic dominance belonged to *Aphanocapsa holsatica* (Belykh et al., 2011). *R. raciborskii* has spread throughout Europe, reaching its northernmost point at Lake Nero, Russia (Babanazarova et al., 2015; Meriggi et al., 2022).

Since 1980, many Serbian waterbodies suffered cyanobacterial bloom events in Serbia: out of 83 water ecosystems examined, 58 have registered blooms (Svirčev et al., 2007). Frequently dominant and potentially toxic cyanobacteria in blooms were: *Microcystis aeruginosa*, *M. flos-aquae*, *A. spiroides*, *Anabaena flos-aquae*, *Aphanizomenon flos-aquae*, and *Planktothrix agardhii*. Central Serbia depends on around 20 drinking water reservoirs, out of which 9 have registered severe bloom events, showing that nearly half of the reservoir water supply has been affected and is very already vulnerable. *R. raciborskii* has been found in several Serbian freshwater bodies: Aleksandrovac Lake, Zasavica River, Ponjavica River, Kapetanski Rit fish farm, Palic and in Ludaš Lake (Svirčev et al., 2016; Predojević et al., 2015; Karadžić et al., 2013; Ćirić et al., 2015; Trbojevic, 2015; Tokodi et al., 2018). The agricultural part of the Vojvodina province has particularly been a frequent stage for cyanobacterial blooms. Seven Serbian lakes in the Vojvodina region were further studied by Svirčev et al., 2013, the results summarised in Table 5. Toxic species of cyanobacteria were dominant— *Aphanizomenon flos–aquae*, *Planktothrix agardhii*, *Pseudanabaena limnetica*, *Anabaena spiroides* and *Microcystis aeruginosa*. The locations of the mentioned blooms are displayed figure 9.

Table 5. Recorded dominance of cyanobacterial species in blooms in 7 Serbian lakes. Adapted from Svirčev et al. (2013).

Taxa	Mrtva Tisa	Provala	Zobnatica	Palić	Ludaš	Borkovac	Kudoš-Pavlovci
Aphanizomenon flos-aquae	◆					◆	◆
Microcystis aerugionsa				◆			
Planktothrix agardhii			◆				
Pseudanabaena limnetica			◆				
Merismopedia tennuissima				◆			
Coelastrum microporum							◆
Anabaena spiroides					◆		
Gomphosphaeria sp.		◆					
Pediastrum sp.						◆	
Microcystis sp.					◆		
Planktothrix sp.	◆						

For Slovakia, in the water bodies of Kopčany, Janíčkov dvor (gravel pit lake), Gajary (village lake), Devínske, and at the Castle-moat water in Holíč, *R. Raciborskii* was present (Horecká & Komárek, 1979; Marsâlek et al., 2000; Marsâlek et al., 2000; Hindáková & Hindák, 2012; Hindák & Hindáková, 2013).

In Slovenia, a ´97 study reported that *Microcystis aeruginosa* was detected in various, unspecified, waterbodies located in the north-east of the country’s territory (Sedmak & Kosi, 1997).

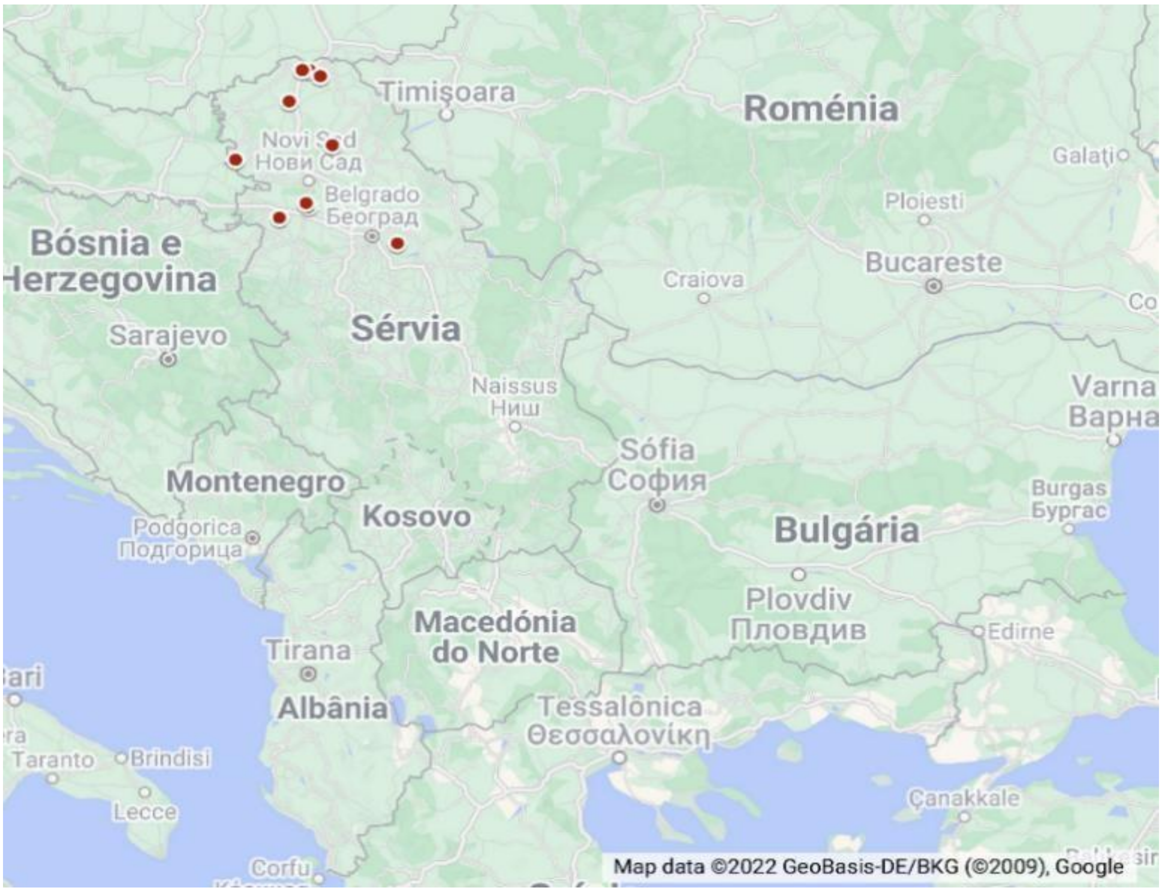

Figure 9. Bloom locations in Serbia. It is noticeable that the registered blooms took place from Belgrade to the north.

At Ukraine, cyanobacteria *Chrysosporum minus* (formerly *A. bergii* f. *minor*) has been found in the brackish Danube delta and at Beresanska estuary (Vladimirova and Danilova, 1968; Kondratjeva, 1968; Tsarenko et al., 2006) as well as at Lake Ostrovenskoe (Kondratjeva, 1968). In addition, *Chrysosporum bergii* was recorded at the delta and at the Tiligul lagoon (Vladimirova and Danilova, 1968; Terenko 2005; Tsarenko et al., 2006). The Russian invasion of Ukraine started a war that is having also severe consequences for the environment on the Ukrainian territory (Rawtani, et al., 2022; Pereira et al., 2022). While the UN already declared the Environment a casualty of war (UNEP, 2022), the Ministry of Environmental Protection and Natural Resources of Ukraine registered 254 Russian crimes against the environment during the first three months in the war, along with 1500 cases of ecosystem destruction, threatening 20% of protected areas in Ukraine (Ministry of Ecology and

Natural Resources of Ukraine, 2022; Eco Threat, 2022). The war has brought air, soil and water pollution, and damaging biodiversity and ecosystems. In terms of water quality, the war caused surface and groundwater pollution, water shortages, and poor sanitary conditions are (Pereira et al., 2022); shortage of water are already affecting cities such as Mariupol and Chernihiv. Decomposition of dead bodies is also a pressing and dormant danger, as they contaminate and make waters unsafe to drink, propagating disease. In addition, as the availability of drinkable water is uncertain, the more alarming are the consequences of a possible cyanobacterial bloom´s materialized risk on fresh water sources, making them undrinkable or dangerous to drink.

In Hungary, *R. raciborskii* was detected since 1970 in Lake Balaton (Padisák, 1997), and also in other water Hungarian fresh water bodies: Fancsika I. víztároló, Lake Balaton, Danube, Dunakeszi / Dead arm of the Danube, Levelek/fish pond, Zala river, Dabas stream, Lake Szelid, Tisza river, Tomalom, Vadkerti-to, Zámolyi-víztározó, Kis-Balaton, Zamardi, Doboz fish pond, Endrőd- Középső- Holt- Körös, Tiszadobi Holt-Tisza and Klágya-Duna (Horecká & Komárek, 1979; Padisák, 1997; Vasas et al., 2010; Vasas et al., 2010; Kidolgozása, 2004).

2.5. Southern Europe

Various Greek lakes suffered blooms dominated by *Microcystis aeruginosa*: Doirani, Kastoria, Pamvotis and Karla (Gkelis & Zaoutsos, 2014). Plus, *M. aeruginosa* was present at Polyphytos Reservoir (Cook et al., 2005). *Raphidiopsis raciborskii* was found at lake Volvi, Kerkini Reservoir, lake Doirani (Gkelis & Zaoutsos, 2014), and at lake Pamvotis (Gkelis et al. 2014). Furthermore, *R. raciborskii* was found in Lake Kastoria (Kormas et al., 2010), Lake Zazari (Vardaka et al., 2005), Lake Petron (Christophoridis et al., 2018), Lake Karla (Gkelis et al., 2017), Kalamaki reservoir (Gkelis et al., 2017), and in the river Struma (Padisák, 1997). *Cuspidothrix issatschenkoi* was found at lake Doirani (Gkelis & Zaoutsos, 2014), and at lake Pamvotis (Gkelis et al. 2014). Samples taken from Lake Marathonas in 2007-2010 revealed several kinds of cyanotoxins belonging to microcystins and nodularin (Kaloudis et al., 2013). A visualisation of these blooms referred in this section can be seen below in Figure 10.

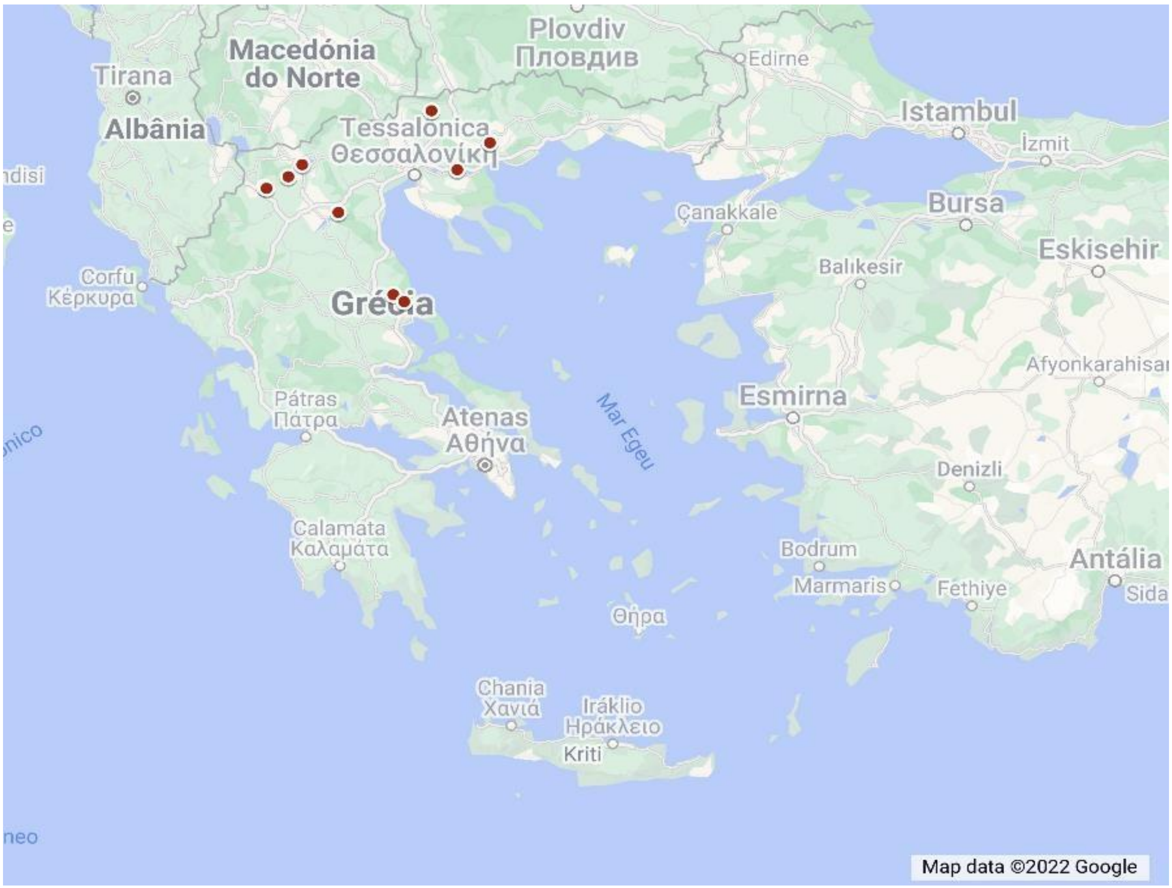

Figure 10. Overall cyanobacterial blooms in Greece.

For Italy, in the north of the country, south of the Italian Alps, cyanobacterial blooms are a motif for concern amid fears that such events may affect tourism and economic activity in the region (Salmaso et al., 2012; Comunita del Garda, 2013). Since the 1990s blooms of *Dolichospermum lemmermannii* have been registered in large lakes south of the Italian Alps: Como, Garda, Iseo, and Maggiore (Salmaso et al., 2015). In central Italy, a volcanic lake called Vico Lake, has been affected by the cyanobacteria *Planktothrix rubescens*; dominance often belonged to *P. rubescens* but alternated at times with *Limnothrix redekei* (Manganelli et al., 2016). Lake Vico is used for recreational purposes and as a source of water to drink. In the south, *Anabaena planctonica* blooms have been detected in Sardinia, Italy (Bruno et al., 1994), producing Anatoxin-a. *Raphidiopsis raciborskii* has been found in Lake Albano (Messineo et al., 2009), Lake Trasimeno (Manti & Mattei, 2005), Sartirana Lake (Manganelli, 2016), Il Bivieri di Gela (Barone et al., 2010), Lago di Castellaro

(Manganelli, 2016), Valle di Comacchio (Ghion et al., 2005), and in Lake Cedrino (Manti & Mattei, 2005).

The full inclusion of Turkey in geographical Europe is debatable but it is of European importance, nonetheless. Turkish freshwater waterbodies, such as lakes and reservoirs used as supplies of drinking water or recreational purposes have suffered from cyanobacterial blooms. National research output on cyanobacteria and cyanotoxins has increased since the 1990's numerous cyanobacterial blooms in Marmara region, southwest of Istanbul. In 1994, *Anabaena* spp. caused mass fish mortality in lake Iznik (Albay et al., 2003). In 1997, samples from Lakes Sapanca, Iznik and Taskisi (Calticak) revealed the presence of toxic cyanobacteria: cyanobacterial blooms in lake Sapanca consisted mostly of *Planktothrix rubescens*, *M. aeruginosa* in Taskisi and Iznik (along with other species: *Woronichinia compacta*, *Merismopedia tenuissima* and *Anabaena* spp.) (Albay et al., 2013). In other studies, *Chrysosporum bergii* was found to be present at lake Abant (Çelekli et al. 2007), and *Anabaena minderi* at Hirfanli dam lake (Baykal and Açikgöz, 2004). Furthermore, *Microcystins* were detected in 2000-2003 at Kucukcekmece Lagoon, a water body located at the west side of the city of Istanbul, where most blooms were dominated by *M. aeruginosa* (Albay et al., 2005). Significant levels of cylindrospermopsin (CYN) toxins were detected in 2013 at the Turkish Lake Iznik (Akcaalan et al., 2014), from *Dolichospermum mendotae* and *Chrysosporum ovalisporum*. Köker et al. (2017) ascertained the presence of various cyanobacteria species in waterbodies of the Marmara region; in Iznik lake (*Nodularia spumigena*, *Planktothrix rubescens*, *R. raciborskii*, *Dolichospermum sp.* and *Anabaenopsis sp.*), in Sapanca lake (*Planktothrix rubescens)*, Kucukcekmece Lagoon (*Microcystis aeruginosa*, *Planktothrix agardhii* and *Microcystis wesenbergii*), Manyas lake (*Microcystis aeruginosa*, *Microcystis wesenbergi, Sphaerospermopsis sp., Dolichospermum flos-aquae* and *Cuspidothrix issatschenkoi*), in Taskisi lake (*Microcystis* sp. and *Dolichospermum* sp.). A 2022 study analysed samples from several water bodies in the Küçük Menderes River Basin (Köker et al., 2022), and *Microcystis aeruginosa* was found dominant in most cases. Most of the toxic cyanobacteria blooms revealed dominance by *Microcystis aeruginosa*, *M. wesenbergii*, *Anabaenopsis* sp., *Dolichospermum* and *Aphanizomenon* sp.. The water bodies included in this study were Alaçatı Reservoir, Beydağ Reservoir, Tahtalı Reservoir, Seferihisar Reservoir, Kavakdere Reservoir, Çatal Lake and Gebekirse Lake. Tahtalı Reservoir suffered the highest content of Microcystins out of all the beforementioned water bodies at 9.1 µg/L in autumn. Despite microcystin not being detected. In the Beydağ Reservoir *D. mendotae* was dominant in spring and *M. wesenbergii* in autumn. In the Tahtalı Reservoir, *M. aeruginosa* was dominant. In the Alaçatı Reservoir, *A. flos-aquae* and *Microcystis* sp. comprised cyanobacterial biomass detected. Çatal Lake had *M. aeruginosa* as the dominant cyanobacterial species. In Gebekirse Lake, the dominant cyanobacteria were *Planktolyngbya* sp. and *Microcystis aeruginosa*. Figure 16 compiles the aforementioned occurrences into a map.

Figure 11. Overall blooms in Turkey.

Studies have also detected the presence of *Raphidiopsis raciborskii* in the Šasko Lake for Montenegro (Rakočević, 2018).

In Spain, *Microcystis aeruginosa* has been present at the reservoirs Trasona (Nieto et al., 2011; Nieto et al., 2015) and San Juan (Lezcano et al., 2016; Lezcano et al., 2017), where also *Aphanizomenon flos-gracile* has been detected in the same study, and at the albufeira of Valencia (Romo et al., 2011). Plus, *M. aeruginosa* was found at water bodies in El Vellón, Valmayor, El Atazar and Madrid (Rodas &Costas, 1999). Furthermore, *M. aeruginosa* was found at Doñana National Park, La Minilla and at El Gergal (D'ors et al., 2012; López-Róda et al.,2013). *R. Raciborskii* was found in Vega del Jabalón, Vicario, Albufeira de Valencia, Embalse de Valuengo, Embalse de Brovales, Embalse de Cala (Lagos del Serrano), Embalse de Rosarito, Embalse de Alange and Embalse de Navalcán (Cirés et al., 2014; Romo & Miracle, 1994; de Hoyos et al., 2004; Wörmer et al., 2011). Figure 17 shows the mentioned occurrences in the country's map.

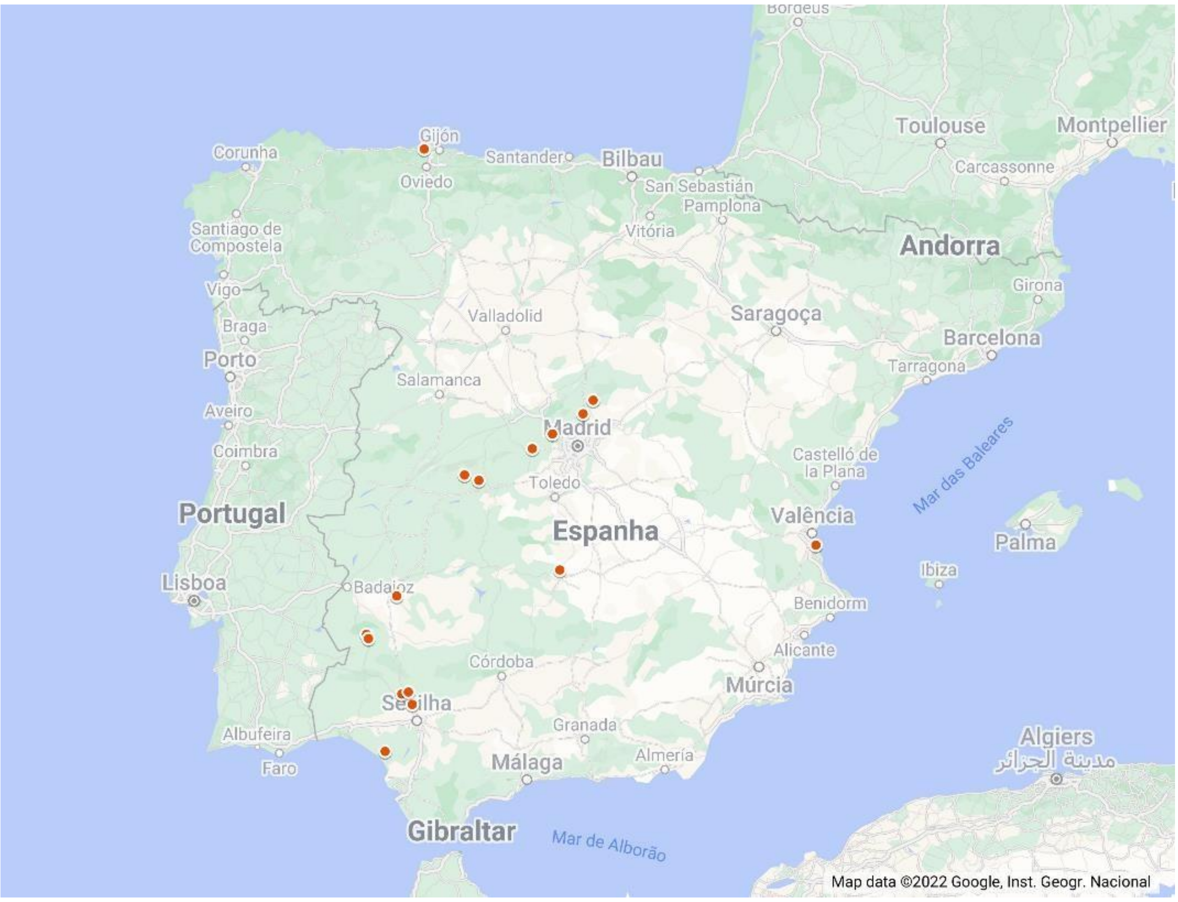

Figure 12. Bloom occurrences in mainland Spain.

For Portugal, despite a modest output of academic work studying cyanobacteria blooms on Portuguese waters in the past decades, by comparing to other European countries, the occurrence of such events is noted to be increasingly common (Vasconcelos et al., 1993; de Figueiredo et al., 2006; Moreira et al., 2020).

The occurrence of the three most prominent bloom-forming cyanobacterial species in mainland Portugal: *Microcystis aeruginosa*, *Raphidiopsis raciborskii* and *Aphanizomenon flos-aquae* is represented in Figure 18 and table 6.

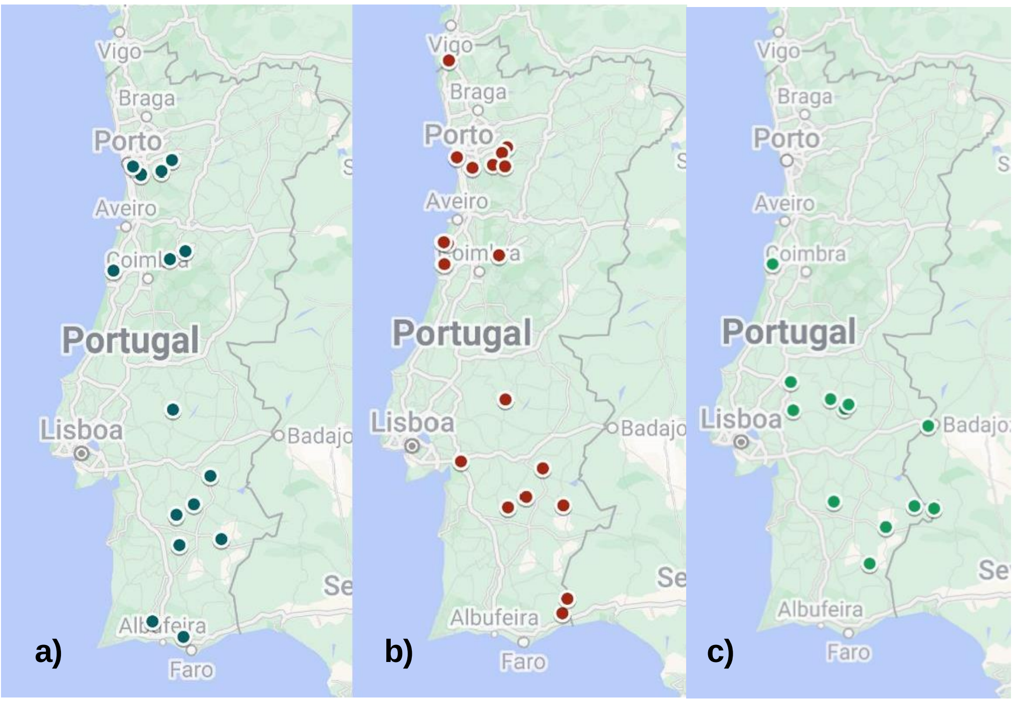

Figure 13. Geographical distribution records in Portugal for: a) *Microcystis aeruginosa; b) Raphidiopsis raciborskii;* and *Aphanizomenon flos-aquae.*

The warmer regions of Portugal are more affected by cyanobacterial blooms (as it can be seen at Table 6), with Algarve being the region where the cyanobacterial diversity was higher. Hotspots of bloom and cyanotoxin occurrence correspond to lentic water bodies such as reservoirs. Toxic and potentially toxic cyanobacteria species mark frequent presence in the blooms, with prominent *taxa* such as *Microcystis* spp. (Vasconcelos et al., 1993; de Figueiredo et al.,2006; Xavier et al., 2007; M.L. Saker et al., 2007), *Raphidiopsis raciborskii* (Saker et al., 2003; Valério et al., 2005; Moreira et al., 2011), *Aphanizomenon flos-aquae* (Vasconcelos, 1995; Ferreira et al., 2001; de Figueiredo et al., 2006; Saker et al., 2007; Vasconcelos et al., 2011) or *Aphanizomenon gracile* (de Figueiredo et al., 2009), *Anabaena flos-aquae* (Vasconcelos, 1995; Vasconcelos et al., 1996, 2011).

Table 6. Most common cyanobacteria registered in Portugal, assorted by regions. Selection of main species - adapted from Dias (2021) (2 pages).

Region	Cyanobacterial Species	References
North	*Microcystis aeruginosa* *Pseudanabaena mucicola* *Dactylococcopsis acicularis* *Aphanizomenon gracile* *Aphanizomenon flos-aquae*	(Vasconcelos et al., 1996; Vasconcelos, 1999; Ferreira et al., 2001; Saker et al., 2007; Oliva Teles et al., 2008)
Centre	*Microcystis aeruginosa* *Raphidiopsis raciborskii* *Aphanizomenon flos-aquae* *Chroococcus limneticus* *Aphanizomenon gracile*	(Vasconcelos & Pereira, 2001; Saker et al., 2007; Abrantes et al., 2006; 2009; de Figueiredo et al., 2006; Vasconcelos et al., 2011)
Lisbon's Metropolitan Area	*Entophysalis* sp. *Lyngbya* sp. *Merismopedia* sp. *Oscillatoria* sp. *Synechococcus* sp.	(Cannicci et al., 2002; Ribeiro et al., 2003; Martins et al., 2005)
Alentejo	*Microcystis aeruginosa* *Microcystis aeruginosa* *Microcystis wesenbergii* *Nostoc* sp. *Microcystis incerta* *Microcystis aeruginosa* *Dolichospermum circinale* *Aphanizomenon flos-aquae* *Aphanizomenon gracile* *Oscillatoria* sp. *Planktothrix agardhii* *Gomphosphaeria* sp.	(Galvão et al., 2008; Valério et al., 2008; Potes et al., 2011; Vasconcelos et al., 1996; Valério et al., 2008)
Algarve	*Anabaena flos-aquae* *Anabaena* sp. *Aphanizomenon flos-aquae* *Planktothrix rubescens* *Microcystis* sp. *Oscillatoria* sp. *Lyngbya* sp. *Chroococcus* sp. *Microcoleus* sp.	(Coelho et al., 2007; Galvão et al., 2008; Paulino et al., 2009; Cartaxana et al., 2009; Friend et al., 2003; Rocha et al., 2002; Osswald et al., 2009; Rosa et al., 2004; Edwards et al., 2005; Martins et al., 2005; Cannicci et al., 2002)

Algarve (cont.)	*Aphanizomenon* sp. *Planktothrix* sp. *Synechococcus* sp. *Synechocystis* sp. *Arthrospira* sp. *Coelosphaerium* sp. *Merismopedia* sp. *Gloeocapsopsis crepidinum*	
Azores	*Aphanizomenon flos-aquae* *Microcystis aeruginosa* *Microcystis flos-aquae* *Woronichinia naegeliana* *Prochlorococcus* sp. *Synechococcus* sp.	(Michelou et al., 2007; Martins et al., 2008; Cordeiro et al., 2020)

Since the 1930s, a list of occurring cyanobacterial species could be built for Portugal including *taxa* such as *Coelospherium kutzingianum, Pseudoanabaena catenata*, *Oscillatoria formosa*, *O. agardhii, O. rubescens*, *O. acutissima*, *Lyngbya majuscula*, *Schizothrix calcicola*, *Scytonema hofmanni*, *Nostoc paludosum* but also *Microcystis viridis, M. flos-aquae, M. aeruginosa*, *Anabaena flos-aquae*, *A. affinis, A. circinalis*, *A. variabilis* and *Aphanizomenon flos-aquae* (Vasconcelos,1995). However, a bloom of *Microcystis* sp. in the Douro River was the source of the first recorded cyanotoxins in Portugal (Vasconcelos et al., 1993). Since then, several potentially toxic species of cyanobacteria have been detected in Portugal (Castro et al., 2022; Moreira et al., 2020). Fortunately, since the limited knowledge of 1950's records there has been a significant evolution in research and data from the Portuguese freshwater bodies. Blooms of *Microcystis* spp. are spread across the country but *Aphanizomenon flos- aquae* has been recorded mainly in central and southern regions, suggesting a preference for warmer temperatures.

R. raciborskii is expanding throughout Europe as a whole, and in Portugal as well: Alqueva Reservoir, Ardila River, Odivelas Reservoir, Maranhão Reservoir, Caia Reservoir, Montargil Reservoir, Velas Lagoon, Mertola Reservoir, Ribeiro do Murtega or Bufo reservoir, Portalegre (Albufeira da Barragem da Apartadura) (Caetano, 2015, Saker et al., 2003, Valério et al., 2005). Notably, accounting for the spread of this phenomenon, the cyanotoxin CYN, associated with the *Aphanizomenon* genera was only found in 2017 present in Portugal for the first time (Moreira et al., 2017).

Several potentially toxic cyanobacteria have been also reported for Azores water bodies, namely *Microcystis aeruginosa* and *M. flos-aquae*, but also other taxa of Microcystis, *Dolichospermum*, *Planktolyngbya* and *Woronichinia* (Cordeiro et al., 2020). From Madeira Island, in spite of limited, there is information on the occurrence of potentially toxic cyanobacteria species such as *Aphanizomenon flos-aquae* and *Microcystis flos-aquae*.

3. Concluding remarks

1. Anthropogenic eutrophication of water bodies and Climate Change are a common justification for the occurrence of toxic cyanobacterial blooms in European freshwaters in general, with urban waters being particularly at risk. With more and more people choosing to live in cities, it is paramount that cyanobacterial blooms in urban waters is taken seriously. In some countries, like the Netherlands, local authorities have regularly issued warnings and recommendations in order to alert the public not to swim or get in contact with bloom-stricken waters.

2. Monitoring, public policy and health standards are three pillars that standing together can help safeguard human, animal and environmental health. When the bloom occurrence is inevitable (with or without prevention), early bloom detection is key to devise and deploy safeguarding measures; an exemplary story of success can be found in the Finland case, in which citizens are empowered to participate in the early detection of cyanobacterial blooms.

3. Uneven information coverage (temporally and geographically) and missing data on countries affect the panoramic understanding of the current situation in the European territory regarding cyanotoxins and toxic cyanobacterial blooms. While some countries present a sizable or well-covered output in literature on freshwater bodies (such as Belgium, Poland and Serbia), more studies that cover more geographical ground and that specify cyanobacterial species are needed in countries such as in the Balkans (with the exception of Bulgaria and Greece), on where there is a stark lack of literature output. Landlocked countries depend greatly on freshwater sources and would benefit from scientific studies on the occurrence of potentially toxic cyanobacteria in their freshwater.

4. The most common frequently identified cyanobacteria that occur in European freshwater bodies are *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, *Aphanizomenon gracile*, *Chrysosporum bergii*, *Raphidiopsis raciborskii*, *Dolichospermum lemmermannii* and *Planktothrix agardhii*.

5. Many of the cyanobacteria most commonly found in Portuguese freshwaters overlap with the general tendency throughout Europe. Reports of the occurrence of the most prevalent cyanotoxins—microcystins—in freshwater bodies date back from the 1980s, for example in lakes such as Mira Lake and reservoirs such as Torrão and Alvito reservoirs, among others. Despite *Microcystis taxa* such as *M. aeruginosa* being the main responsible for the majority of these events, other microcystin-producing species belonging to other genera such as *Aphanizomenon* and *Planktothrix* have been identified. Moreover, further toxic species were detected over the past 40 years, including *Aphanizomenon flos-aquae* (at Montargil and Crestuma reservoirs, for example) and *Raphidiopsis raciborskii* (a species vastly spread throughout Europe, and detected in Portugal since 2003).

6. *Raphidiopsis raciborskii* has proven to be one of the most successful cyanobacteria in terms of geographical expansion in mainland Europe, having been detected in the majority of European countries. Central Europe reports the highest density of occurrences of this cyanobacterium, especially in Poland and Germany.

7. The Russian invasion of Ukraine also threatens the Ukrainian environmental sphere, various types of contamination may have affected freshwater ecosystems and water bodies; the precise ecological consequences of which, is not yet known. Nonetheless, the Ministry of Environmental Protection and Natural Resources of Ukraine registered 254 Russian crimes against the environment only during the first three months in the war, along with 1500 cases of ecosystem destruction, threatening at least 20% of protected areas. Water pollution and the uncertainty of the availability of freshwater that is safe to drink (in places such as Mariupol), makes the risk of a cyanobacterial bloom on freshwater sources much graver than otherwise. The only solutions possible await after peace.

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Annexes

Annex I

Table X - Llist of occurrences of *M. aeruginosa*, *A. flos-aquae* and *R. raciborskii.*

Species	Country	Location	Reference
Microcystis Aeruginosa	Sweden	lake Mälaren	Pekar et al., 2016
	Lithuania	Curonian lagoon	Paldaviciene et al., 2009
	United Kingdom	Rudyard reservoir (Staffordshire)	Turner et al., 1990
	Belgium	Jehay	Wirsing et al.,1997
		étang moyen (Jehay)	Willame et al., 2005
		Neufchâteau	
		Robertville	
	Germany	lake Bareleber	Ronicke et al., 2021
	Switzerland	Lake Zurich	Monchamp et al., 2016
		Greifensee	
	Belarus	Svisloch river	Mikheyeva et al., 2012 & Mikheyeva 2021
	Czechia	Opatovický lake	Blahova et al., 2021
		Starý Kanclír lake	
	Poland	Sulejów Reservoir	Gagała et al., 2010
		Bnińskie Lake	
		Warnołty Lake	Napiórkowska-Krzebietke et al. 2021
	Romania	Gheorgheni recreational water body	Boaru et al., 2006
	Serbia	Palić	Svirčev et al., 2013
	France	Grangent, Loire	Latour & Giraudet, 2004
		Etang rouge (Insviller-Moselle)	Willame et al., 2005
	Greece	Doirani	Gkelis & Zaoutsos, 2014
		Kastoria	
		Pamvotis	
		Karla	
		Polyphytos Reservoir	Cook et al., 2005
	Turkey	Kucukcekmece Lagoon	Köker et al., 2017
		Manyas lake	
		Küçük Menderes River	Köker et al., 2022
		Tahtalı Reservoir	
		Gebekirse Lake	
		Taskisi	Albay et al., 2013
		Iznik	Albay et al., 2014
	Spain	Trasona reservoir	Nieto et al., 201 & Nieto et al., 2015
		San Juan	Lezcano et al., 2016 & Lezcano et al., 2017
	Portugal	Crestuma Reservoir	Vasconcelos et al., 1993, 1996; Ferreira et al., 2001
		Barrinha de Mira Lake	Vasconcelos et al., 1996

		Mira Lake	
		Vale Das Bicas Reservoir	
		Guadiana River	
		Minho River	
		Torrão Reservoir	Vasconcelos et al., 1996; Oliva Teles et al., 2008
		Carrapatelo Reservoir	Vasconcelos et al., 1996
		Aguieira Reservoir	Vasconcelos et al., 1996; Vasconcelos et al., 2011
		Montargil Reservoir	Pereira et al., 2000
		Esmoriz WWTP	Vasconcelos & Pereira, 2001
		Marco de Canaveses Reservoir	Saker et al., 2005; Pereira et al., 2008
		Tâmega River	Saker et al., 2005
		Vela Lake	Abrantes et al., 2009; de Figueiredo et al., 2006
		Serralves Lake	Xavier et al., 2007
		Alqueva Reservoir	Galvão et al., 2008; Galvão et al., 2008; Valério et al., 2008
		Odivelas Reservoir	
		Alvito Reservoir	
		Monte Novo Reservoir	Valério et al., 2008
Aphanizomenon flos-aquae	Latvia	Lielais Baltezers	Balode et al., 2006
		Mazais Baltezers	
	Belgium	Féronval	Willame et al., 2005
	Germany	Müggelsee	Dokulil et al., 2000
		Melangsee	Preußel et al., 2006
		Heiliger See	
	Belarus	Svisloch river	Mikheyeva et al., 2012
	Croatia	Kopački Rit park	Mihaljević & Stević, 2011
	Czechia	Svet	Blahova et al., 2009
		Ducibe	
	Serbia	Mrtva Tisa	Svirčev et al., 2013
		Borkov ac	
		Kudoš-Pavlov ci	
	Norway	Lake Edlandsvatn	Sivonen et al., 1992
	Turkey	Alaçatı Reservoir	Köker et al., 2022
	Portugal	Crestuma reservoir	Ferreira et al., 2001
		Mira Lake	Vasconcelos, 1999
		Douro River	
		Montargil Reservoir	Pereira et al., 2000
		Vela Lake	Abrantes et al., 2009; de Figueiredo et al., 2006
		Torrão Reservoir	Oliva Teles et al., 2008
		Alvito Reservoir	Galvão et al., 2008; Valério et al., 2008
		Funcho Reservoir	Galvão et al., 2008
		Monte Novo Reservoir	Valério et al., 2008

		Odivelas Reservoir	
		Enxoé Reservoir	
		Roxo Reservoir	
		Marco de Canavese Reservoir	Osswald et al., 2009; Pereira et al., 2008
		Aguieira Reservoir	Vasconcelos et al., 2011
Raphidiopsis raciborskii	Lithuania	Jiezno ež	Kokociński et al., 2017
	Austria	Alte Donau	Dokulil et al., 2000
		Mondsee lake (Salzkammergut)	
	France	Francs Pêcheurs	Briand et al., 2002; Coute et al., 1997
		Lacanau	Cellamare et al., 2010
		Soustons	
		River Seine a Ivry	Druart & Briand, 2002
		Malsaucy ponds, Étang Léchir and Lake Chanteraines	Cellamare et al., 2010
	Germany	Lake Lieps	Krienitz and Hegewald, 1996
		Melangsee	Fastner et al., 2003
		Langer See	
		Eichenteich	Botanic Garden and Botanical Museum of Berlin
		Falkenhagener See	
		Neuer See	
		Kleiner Schwielochsee	
		Schwielochsee	
		Bützsee	Stüken et al., 2006
		Ruppiner See	
		Molchowsee	
		Zermützelsee	
		Buckwitzer See	
		Vielitzsee	
		Werbellinsee	
		Braminsee	
		Großer Zernsee	
		Rahmer See	
		Fauler See	
		Petersdorfer See	
		Scharmützelsee	
		Großer Glubigsee	
		Springsee	
		Großer Kossenblatter See	
		Lebbiner See	
		Großer Storkower See	
		Schaplowsee	
		Großer Schauener See	
		Wolziger See	
		Kutzingsee	

		Zemmin-See	
		Pätzer Vordersee	
		Motzener See	
		Rangsdorfer See	
		Croisensee	
		Zeuthener See	
		Großer Zeschsee	
		Siethener See	
		Flakensee	
		Großer Krampe	
		Kietzersee	
		Oder-Spree	
		Spree	
		Byhleguhrer See	
		Gülper See	
		Wirchensee	
		Petznicksee	
		Großer Plessower See	Wiedner et al., 2007
		Zierker See	Mehnert et al., 2010
	Netherlands	De Poel (Amstelveense)	Dutch Foundation for Applied Water Research
		Kleine Poel (Amstelveense)	
		Sluipwyk (Plas sgravenkoop)	
		Binnenschelde (Bergen op Zoom)	
		Kortenhoefse Plassen (Kortenhoef)	
		Naarden	
		Schutsloterwijde	
		Bergschenhoek	
		Wijde Gat (Kortenhoef)	
		Uithoorn canal	
		Sint Jansklooster (agricultural canal)	
	Bulgaria	lake Vaya	Stefanova et. al, 2020
		Poray reservoir	
		lake Uzunguren	
		Srebarna Lake	Stoyneva, 2003
		Lake Burgas	
		Shabla (Durankulashko ezero Durankulak)	Stoyneva, 2016
	Croatia	Kopački Rit park	Mihaljević & Stević, 2011
		Sakadaš Lake	
	Czechia	Svet	Blahova et al., 2009
		Ducibe	
		Nové Mlýny	Kaštovský et al., 2010
		Babice u Uherského Hradiště	

		Meadow poll south of Lány	
		Zámecký rybník	
		Dubice u České Lípy	
		Malhostický rybník u Rtyně nad Bílinou	
		Novozámecký rybník	
		Dvorský rybník	
		Morava	
		Olomouc (Mlýnský potok)	
		Mlýnský rybník	
		Rybník Láska	
		Dobrá vůle	
		Koclířov	
		Rožmberk	
		Srálkovský rybník	
		Očko (Káraný)	
		VN Harcov	
		Jezero Ostrá	
		Koupaliště Sedmihorky	
		Březina	
		Rybník Rosnička	
		Stříbrný rybník	
		Koupaliště Trutnov	
		Rybník Dlouhý u Lanškrouna	
	Poland	Kursko	Kokociński & Soininen, 2012; Kokociński et al., 2009; Kokociński et al., 2013; Wilk-Woźniak & Najberek, 2013; Kobos et al., 2013; Budzyńska & Gołdyn, 2017
		Biskupieckie	
		Strykowskie	
		Kierskie Male	
		Żabiniec	
		Busko	
		Pniewskie	
		Chodzieskie	
		Kowalskie	
		Berzyńskie	
		Szydłowskie	
		Buszewskie	
		Niepruszewskie	
		Tomickie	
		Jelonek	
		Mogileńskie	
		Witobelskie	
		Rzepinko	
		Bnińskie	
		Bytyńskie	
		Lubosińskie	
		Pniewskie	

		Grylewskie	
		Świętokrzyskie	
		Boczowskie	
		Bnińskie	
		Biskupińskie	
		Zbąszyńskie	
		Kruchowskie	
		Rusałka	
		Pątnowskie	
		Jezioro Góreckie	
		Jezioro Łękno	
		Lake Malta	
		Jezioro Borusa	
	Russia	Lake Nero	Babanazarova et al., 2015; Meriggi et al., 2022
	Serbia	Aleksandrovac Lake	Svirčev et al., 2016; Predojević et al., 2015; Karadžić et al., 2013; Ćirić et al., 2015; Trbojevic, 2015; Tokodi et al., 2018
		Zasavica River	
		Ponjavica River	
		Kapetanski Rit	
		Palic	
		Ludaš Lake	
	Slovakia	Kopčany	Horecká & Komárek, 1979; Marsâlek et al., 2000; Marsâlek et al., 2000; Hindáková & Hindák, 2012; Hindák & Hindáková, 2013
		Janíčkov dvor	
		Gajary	
		Devínske	
		Castle-moat water in Holíč	
	Hungary	Lake Balaton	Padisák, 1997
		Fancsika I. víztároló	Horecká & Komárek, 1979; Padisák, 1997; Vasas et al., 2010; Vasas et al., 2010; Kidolgozása, 2004
		Lake Balaton	
		Danube	
		Dunakeszi	
		Levelek	
		Zala river	
		Dabas stream	
		Lake Szelid	
		Tisza river	
		Tomalom	
		Vadkerti-to	
		Zámolyi- víztározó	
		Kis-Balaton	
		Zamardi	
		Doboz	
		Endrőd- Középső- Holt-Körös	
		Tiszadobi Holt-Tisza	
		Klágya-Duna	
	Greece	Volvi	Gkelis & Zaoutsos, 2014

		Kerkini Reservoir	
		lake Doirani	
		lake Pamvotis	Gkelis et al. 2014
		Lake Kastoria	Kormas et al., 2010
		Lake Zazari	Vardaka et al., 2005
		Lake Petron	Christophoridis et al., 2018
		Lake Karla	Gkelis et al., 2017
		Kalamaki reservoir	
		river Struma	Padisák, 1997
	Italy	Lake Albano	Messineo et al., 2009
		Lake Trasimeno	Manti & Mattei, 2005
		Sartirana Lake	Manganelli, 2016
		Il Bivieri di Gela	Barone et al., 2010
		Lago di Castellaro	Manganelli, 2016
		Valle di Comacchio	Ghion et al., 2005
		Lake Cedrino	Manti & Mattei, 2005
	Turkey	Iznik lake	Köker et al., 2017
	Montenegro	Šasko Lake	Rakočević, 2018
	Spain	Vega del Jabalón	Cirés et al., 2014; Romo & Miracle, 1994; de Hoyos et al., 2004; Wörmer et al., 2011
		Vicario	
		Albufeira de Valencia	
		Embalse de Valuengo	
		Embalse de Brovales	
		Embalse de Cala	
		Embalse de Rosarito	
		Embalse de Alange	
		Embalse de Navalcán	
	Portugal	Odivelas Reservoir	Saker et al., 2003; Saker et al., 2004
		Montargil Reservoir	Saker et al., 2003
		Caia Reservoir	Saker et al., 2003; Saker et al., 2004
		Ardila River	Saker et al., 2003; Saker et al., 2004
		Vela Lake	Saker et al., 2003
		Patudos Reservoir	
		Mértola Reservoir	
		Maranhão Reservoir	Saker et al., 2004; Valério et al., 2005
		Bufo Reservoir	Saker et al., 2003
		Agolada Reservoir	
		Enxoé Reservoir	Valério et al., 2008