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Research Paper

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Management of Algal Blooms

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This research paper considers management options to prevent and control freshwater algal blooms.

Key Points

- Blue-green algal blooms are a global phenomenon characterised by a rapid accumulation of algae in aquatic environments.
- Algal blooms can have a variety of causes and wide-reaching harmful impacts on the environment, industry and society.
- Blue-green algae are gaining increasing attention in Northern Ireland and globally due to the increasing prevalence of algal blooms.
- Management strategies are being developed to address algal bloom prevention, including riparian buffers, removal of lake sediment, constructed wetlands, aeration, artificial mixing and removal of zebra mussels.
- There is also interest in methods to control algal blooms once they have formed. These methods are split into three categories, physical, chemical and biological control.
- Physical control methods considered include shading technology, barley straw, air flotation, clay flocculation, nanotechnologies, filtration, ultrasonication and ultraviolet.
- Chemical control methods considered include hydrogen peroxide, copper sulfate, peracetic acid and simazine.
- Biological control methods considered include algicidal bacteria, cyanophage and grazers.

Executive Summary

Algal blooms are a global phenomenon characterised by a rapid accumulation of algae in aquatic environments and have been gaining attention in Northern Ireland and around the world due to the increasing prevalence of algal blooms globally. Blue-green algae known as cyanobacteria are ancient photosynthetic organisms found in almost every habitat on Earth. Cyanobacteria are essential for the survival of life on Earth, however recently they have gained more attention for the consequences of blue-green algal blooms. These include environmental, human and animal health and industrial impacts. In the summer of 2023, and again more recently, algal blooms gained large-scale public attention due to large blooms in Lough Neagh and other lakes in Northern Ireland. Lough Neagh has received particular attention since it supplies around 40% of raw water in Northern Ireland. The increasingly poor ecological status of lakes in Northern Ireland alongside the prevalence of algal blooms has prompted calls to action from Members of the Legislative Assembly (MLAs) and the general public to the Northern Ireland (NI) Executive. This research paper considers management options to prevent and control freshwater algal blooms.

Algal bloom management options include methods to prevent the onset of algal blooms and control algal blooms once they have formed. Methods to prevent the onset of algal blooms include riparian buffers, removal of lake sediment, constructed wetlands, aeration, artificial mixing and removal of zebra mussels. These methods tend to focus on reducing the amount of nutrient pollution entering the water body (e.g. riparian buffers, removal of nutrient-rich lake sediment and constructed wetlands) or disrupting the physical conditions of the lake to make algal bloom formation unfavourable (e.g. aeration and artificial mixing).

Methods and technologies to control the proliferation of algal blooms once formed can be split into three categories (physical, chemical and biological) however, many technologies overlap. Physical control methods include shading technology, barley straw, air flotation, clay flocculation, nanotechnologies, filtration, ultrasonication and ultraviolet. Chemical control methods include hydrogen peroxide, copper sulfate, peracetic acid and simazine. The biological

control methods considered in this research paper are algicidal bacteria, cyanophage and grazers.

The research paper concludes by prompting considerations based on the research paper regarding the longevity of management options, their stage in the development process and strategies for Northern Ireland lakes.

Contents

1 Introduction

Algal blooms are a global phenomenon characterised by a rapid accumulation of algae in aquatic environments, often resulting in visible regions of algal growth on the water's surface. Algal blooms can occur in freshwater, marine and brackish environments and typically have multiple contributing factors that work together to promote algal growth. The rapid accumulation of algae during a bloom can have significant impacts on the environment, human and animal health, and industry. In Northern Ireland (NI), ongoing algal blooms in Lough Neagh, including during the summer of 2023 and a recent recurrence, have caused widespread concern and attention. This research paper considers management options to prevent and control freshwater algal blooms.

1.1 Research paper scope

Algal blooms have been researched extensively from the causes and impacts to potential prevention and control methods. This research paper considers management options to prevent and control freshwater algal blooms. This paper includes a selection of management options categorised by the primary objective of the method: prevention (section 2) or control of algal blooms (section 3).

It should be noted that this is a proactive research paper from the Research and Information Service (RaISe) at the Northern Ireland Assembly and the selection of methods discussed here is not absolute or exhaustive. The inclusion of a technology does not indicate preference over other technologies. Management options included in this research paper may not necessarily be suitable or authorised for use in Northern Ireland.

A key factor for algal bloom formation is excessive nutrients caused by runoff from agriculture, wastewater treatment and urban areas. It is acknowledged that managing nutrient flow from human activities is a long-term, effective and important consideration for the management of algal blooms in water bodies. However, this research paper considers the research surrounding other physical, chemical and biological management options which could prevent or control freshwater algal blooms.

1.2 Blue-green algae

Blue-green algae are gaining increasing attention in NI and around the world due to the increasing prevalence of algal blooms globally. Algal blooms occur when there is a rapid accumulation of algae in an aquatic environment and can form freshwater, marine and brackish water[1]. It is important to note that algae refers to a wide range of microorganisms including bacteria. However, blue-green algae specifically refers to a type of bacteria known as cyanobacteria.

Cyanobacteria are found in almost every habitat on Earth, from aquatic to terrestrial environments, as well as in extreme hydrothermal vents in the deep ocean[2]. They are ancient photosynthetic organisms and are vital to life on Earth[3]. In photosynthesis, light and carbon dioxide are taken up from the environment to generate energy and release oxygen and water into the environment, this is the principal process of primary production[4]. Marine algae, including cyanobacteria, which are responsible for 50% of all primary production globally[5]. Although plants and trees are well known for performing photosynthesis, the origin of photosynthesis on Earth is widely believed to have originated from an ancestor of cyanobacteria[6]. The relationship between cyanobacteria and other life on Earth relies on balance. Due to a changing

[1] Whitton, B.A., 'Diversity, Ecology, and Taxonomy of the Cyanobacteria' in *Photosynthetic Prokaryotes* (1992), p.1-51

[2] Arcadi, E. et al., 'Microbial communities inhabiting shallow hydrothermal vents as sentinels of acidification processes' *Frontiers in Microbiology* (2023) Vol. 14

[3] McFadden, G.I., 'Origin and Evolution of Plastids and Photosynthesis in Eukaryotes' *Cold Spring Harbor Perspectives in Biology* (2014) Vol. 6

[4] Sigman, D. M. & Hain, M. P. *The Biological Productivity of the Ocean* (2012), Accessed: 24 June 2024

[5] Field, C.B. et al., 'Primary production of the biosphere: integrating terrestrial and oceanic components' *Science* (1998) Vol.281, p.237-240

[6] As cited in footnote 3

climate, this balance is changing, a notable example is the increasing prevalence of blue-green algal blooms worldwide[7].

1.3 Causes

The causes of algal blooms are multifaceted with many contributing factors aligning to promote their formation. For further details, see RaISe research paper, An overview of algal bloom in Lough Neagh. These can include anthropogenic factors as well as climatic factors, including:

- Excessive nutrients, e.g. nitrogen and phosphorous
- Anthropogenic factors
- Increased water temperatures
- High sunlight
- Changes in rainfall patterns
- Increased thermal stratification

1.3.1 Excessive nutrients

The United States Environmental Protection Agency (US EPA) reports that excessive nutrients in the aquatic environment is a contributing factor to algal bloom formation[8]. Blue-green algae uptake many of their essential nutrients from the environment[9]. These are nutrients they cannot synthesise themselves and are critical for their growth and survival. In the natural environment, nutrients, such as nitrogen and phosphorous, are limited and algae growth is restricted. However, if there are excessive nutrients in the environment, algae growth is no longer restricted and blooms can form[10]. The nutrients primarily

[7] Hou, X. et al., 'Global mapping reveals increase in lacustrine algal blooms over the past decade' *Nature Geoscience* (2022) Vol.15, p.130-134

[8] United States Environmental Protection Agency (US EPA), *Nutrient Pollution: The Problem*, (23 April 2024), Accessed: 24 June 2024

[9] As cited in footnote 8

[10] As cited in footnote 8

associated with algal blooms are nitrogen and phosphorous[11]. These are associated with runoff from wastewater treatment, agriculture and industry[12].

1.3.2 Anthropogenic factors

Anthropogenic factors promoting algal growth are integrated with other causes of algal blooms, such as nutrient pollution. Anthropogenic factors are human actions that can lead to environmental change and in this case an increased likelihood of algal blooms. The College of Life Sciences at the University of New Hampshire states that these factors can include changes in land use, dam construction and deforestation[13]. Further, Teagasc[14] states that changes in land management and development frequently result in a degradation in water quality which is linked to algal blooms[15].

1.3.3 Increased water temperatures

The US EPA indicates that globally warmer water temperatures are a contributing factor in algal blooms becoming increasingly frequent and longer-lasting[16]. Warmer waters promote algal growth and extend the growing season of algae[17]. Increased water temperatures can also lead to increased stratification in a water body (see section 1.2.6)[18].

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[11] As cited in footnote 8

[12] National Ocean Service, *What is nutrient pollution?*, (18 January 2024), Accessed: 24 June 2024

[13] University of New Hampshire, *Causes of harmful algal blooms: Understanding the factors behind the phenomenon*, (22 November 2023), Accessed: 24 June 2024

[14] Teagasc is the Agriculture and Food Development Authority in the Republic of Ireland.

[15] Teagasc, *Land Management*, (n.d.), Accessed: 24 June 2024

[16] United States Environmental Protection Agency (US EPA), *Climate Change and Freshwater Harmful Algal Blooms*, (4 March 2024), Accessed: 24 June 2024

[17] As cited in footnote 16

[18] Wells, M.L. et al., 'Harmful algal blooms and climate change: Learning from the past and present to forecast the future' *Harmful Algae* (2015) Vol. 49

1.3.4 High sunlight

Cyanobacteria are photosynthetic so sunlight is essential to generate energy for their growth and survival[19]. It can be viewed as fuel or food for these organisms. Therefore, if it is sunny for an extended period, the incidence of algal blooms is likely to increase[20]. Sunlight as a contributing factor to blooms is most powerful when in combination with other factors such as warm water temperatures[21].

1.3.5 Changes in rainfall pattern

Changes in rainfall patterns contribute to the increasing prevalence of algal blooms globally[22]. The US EPA indicates that where periods of heavy rainfall increase, runoff from agriculture, industry and urban areas increases[23]. Furthermore, increased rainfall often results in more frequent sewage discharges into water bodies[24]. Increased runoff due to rainfall is likely to cause an increase in nutrients entering the water body, the effects of nutrient pollution are described above.

1.3.6 Increased thermal stratification

Warmer waters promote increased thermal stratification in water bodies which can increase the incidence of algal blooms[25]. Stratification is when separate and distinct temperature layers form in a water body[26]. When stratification occurs,

[19] Clark, R.L., et al., 'Light-Optimized Growth of Cyanobacterial Cultures: Growth Phases and Productivity of Biomass and Secreted Molecules in Light-Limited Batch Growth' *Metabolic Engineering* (2018) Vol.47

[20] As cited in footnote 13

[21] As cited in footnote 13

[22] As cited in footnote 17

[23] As cited in footnote 17

[24] Hughes, J. et al., 'Impacts and implications of climate change on wastewater systems: A New Zealand perspective' *Climate Risk Management* (2021) Vol.31

[25] Li, G., et al., 'Increasing ocean stratification over the past half-century' *Nature Climate Change* (2020) Vol.10

[26] As cited in footnote 18

the mixing between water of different temperatures and depths is reduced[27]. This reduction in mixing can lead to very warm surface waters, perfect for rapid algal growth[28].

1.4 Impacts

The impacts of algal blooms can be wide-reaching, affecting diverse areas of society and the environment. These include human and animal health, ecosystems and industries such as tourism and fishing.

1.4.1 Environment

The impact of algal blooms on ecosystems can be devastating[29]. Algal blooms in the surface waters can block sunlight penetrating deep into the water, this can seriously impact plant growth beneath the surface waters resulting in death and removal of species from ecosystems[30]. Further, an increased growth algal rate means an increased demand for resources such as oxygen in the water body[31]. This often leads to an intense reduction in oxygen in the environment. These oxygen-starved conditions are known as anoxic conditions and are frequently associated with the death of fish and other organisms reliant on oxygen from the water[32].

1.4.2 Human Health

[27] Visser, P., et al., 'Artificial mixing to control cyanobacterial blooms: a review' *Aquatic Ecology* (2015) Vol 50, p. 423-441

[28] As cited in footnote 18

[29] National Oceanic and Atmospheric Administration, *What is a harmful algal bloom?*, (26 April 2016), Accessed: 26 June 2024

[30] United States Environmental Protection Agency (US EPA), *The Effects: Dead Zones and Harmful Algal Blooms*, (3 January 2024), Accessed: 24 June 2024

[31] As cited in footnote 30

[32] Anderson, D.M., et al., 'Progress in understanding harmful algal blooms (HABs): Paradigm shifts and new technologies for research, monitoring and management' *Annual Review of Marine Science* (2012) Vol.4, p.143-176

Algal blooms can have harmful effects on human health frequently due to the release of cyanotoxins into the environment[33]. Cyanotoxins are harmful chemicals released by cyanobacteria. These toxins can be lethal to wildlife, livestock, and pets, and can cause illness in humans[34]. It is estimated that between 25 and 75% of cyanobacterial blooms are toxic[35]. Symptoms of cyanotoxin exposure can include abdominal pain, headache, sore throat, vomiting, diarrhoea and even pneumonia[36].

1.4.3 Animal Health

It is important to note that animals, much like humans, can be adversely affected by algal blooms[37]. Cyanotoxins can lead to a range of symptoms, including excessive drooling and foaming at the mouth, loss of appetite, stumbling, and abdominal tenderness[38]. It is highly recommended that pet and livestock owners take necessary precautions to ensure that their animals do not come into contact with algal blooms as they are at higher risk of death from exposure[39]. In fact, in 2021, there was a large wildlife mortality event in the USA caused by an algal bloom. This single event resulted in at least 2715 animals becoming ill with 92% of those animals dying[40].

1.4.4 Industry

Algal blooms can have a significant impact on industry particularly industries which are economically reliant on water bodies such as water providers, fishing,

[33] Otero, P. & Silva, M., 'Chapter 7 - The role of toxins: impact on human health and aquatic environments' in *The Pharmacological Potential of Cyanobacteria* (2022), p. 183

[34] Environment Agency, *Algal blooms: advice for the public and landowners*, (31 January 2017), Accessed: 24 June 2024

[35] Chen, H. et al., 'Cyanobacterial Toxins in Fresh Waters', in *Encyclopedia of Environmental Health.* (2011)

[36] United States Environmental Protection Agency (US EPA), *What Are the Effects of HABs*, (14 June 2024), Accessed: 24 June 2024

[37] American Veterinary Medical Associations, *Harmful algal blooms (HABs)*, (n.d.), Accessed: 24 June 2024

[38] As cited in footnote 37

[39] As cited in footnote 34

[40] Center for Disease Control (CDC), *Summary Report – One Health Harmful Algal Bloom System (OHHABS), United States, 2021*, (26 February 2024), Accessed: 24 June 2024

aquaculture and tourism[41]. These blooms frequently lead to a decline in water quality causing practical issues for water providers and communication challenges with the general public[42]. In extensive algal blooms, the water can become oxygen-starved causing large-scale fish death and presenting issues for fishing and aquaculture industries[43]. Tourism and recreational activities are frequently severely impacted by algal blooms leading to a reduction in visitors which can be detrimental to local economies[44].

1.5 Algal blooms in Northern Ireland

In the summer of 2023, extensive blue-green algal blooms occurred widely across Northern Ireland with those at Lough Neagh receiving close attention[45]. This led to questions over the safety of the water supply and lake and calls to action for the NI Executive to act on the increasingly poor ecological status of Lough Neagh[46]. For more information about Lough Neagh algal blooms, see RaISe briefing paper, an overview of algal bloom in Lough Neagh, and topical digest, algal blooms in Lough Neagh.

2 Prevention

The prevention of algal blooms is a pressing issue globally and has received large-scale public attention in Northern Ireland[47]. This section of the research paper considers methods to prevent the onset of algal blooms.

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41 Weir, M.J., et al., 'Economic impacts of harmful algal blooms on fishery-dependent communities' *Harmful Algae* (2022) Vol. 118

42 As cited in footnote 30

43 Trainer, V.L., et al., 'Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes' *Harmful Algae* (2020) Vol.91

44 JBC Technical Reports for European Commission, 'Algal blooms and its economic impact' (2016)

45 NI Water: Lough Neagh algae bloom expected to be 'more severe' this summer, Irish news, 31 January 2024

46 Minister to propose Northern Ireland's first environmental improvement plan, Independent, 13 February 2024, Accessed: 24 June 2024

47 As cited in footnote 45

2.1 Riparian buffers

Agricultural runoff, particularly nitrates and phosphorous, is associated with an increased incidence of algal blooms[48]. The use of riparian buffers to significantly reduce agricultural runoff entering water bodies has been successful in some regions[49].

Riparian buffers are the natural transitional zones between aquatic and terrestrial environments occupied with vegetation (figure 1)[50]. These zones play roles in stabilizing banks, filtering nutrients and reducing nutrient pollution in water bodies[51]. Riparian buffers are vegetated regions working as filters, catching sediment runoff and pollutants[52]. Excess phosphorous binds to soil. Therefore, the buffer retains sediment and phosphorus, preventing them from entering the water body[53]. Another way riparian buffers function is through the vegetation. As polluted water passes through the buffer, the plants and microbes absorb nutrients and other pollutants[54].

Some studies have recorded riparian buffers to remove up to 81% of nitrogen from water running through the buffer zone with wider riparian buffers removing larger amounts of nitrogen and phosphorus[55]. International studies show that the type of vegetation in the riparian buffer also contributes to its efficiency[56].

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[48] As cited in footnote 12

[49] Aguiar Jr, T.R., et al., 'Nutrient removal effectiveness by riparian buffer zones in rural temperate watersheds: The impact of no-till crops practices', *Agricultural Water Management* (2015) Vol.149, p.74-80

[50] US EPA, Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations (2005), p1

[51] As cited in footnote 50

[52] US Forest Service, *Riparian Forest Buffers*, (n.d), Accessed: 3 June 2024

[53] Lowrance, R., et al., 'Long-term sediment deposition in the riparian zone of a coastal plain watershed', *Journal of Soil and Water Conservation* (1986) Vol.41, p.266-271

[54] Mayer, P., et al., 'Long-term assessment of floodplain reconnection as a stream restoration approach for managing nitrogen in ground and surface waters', *Urban Ecosystems* (2022) Vol.25, p.879-907

[55] Philips, J., 'An evaluation of the factors determining the effectiveness of water quality buffer zones' *Journal of Hydrology* (1989) Vol.107, p133-145

[56] Hou, G., et al., 'A vegetation configuration pattern with a high-efficiency purification ability for TN, TP, AN, AP, and COD based on comprehensive assessment results' *Scientific Reports* (2019) Vol.9

Researchers in Brazil showed that woody vegetation zones are highly efficient at removing nitrogen and phosphorous, while grasses remove approximately 50% of these nutrients[57].

Overall, research shows that riparian buffer zones are successful at filtering nutrients and reducing nutrient pollution entering the water body[58]. In addition, many experiments have been performed in the natural environment[59]. However, riparian buffers require land on the edge of water bodies to be cultivated with low human disturbance to thrive[60].

Figure 1. Aerial image of stream with riparian buffer zone by [Yulian Alexeyev](#) on [Unsplash](#).

57 As cited in footnote 49

58 As cited in footnote 55

59 As cited in footnote 49

60 Hudson Valley Regional Council, Protecting and managing Hudson River streams: The Importance of stream buffer protection and management, (2015)

2.2 Removal of lake sediment

Excess nutrients in water bodies can lead to eutrophication, causing a rapid accumulation of algae[61]. Over decades of nutrient pollution, not only has the water become nutrient-rich, but the sediment is also affected[62]. Consequently, even if nutrient pollution from terrestrial environments is reduced, the nutrient-dense sediment can lead to the continuation of eutrophic conditions[63]. Therefore, the removal of lake sediment (otherwise known as dredging) is being explored as a possible prevention method against algal blooms.

Dredging involves removing sediment containing high levels of nitrogen and phosphorous[64]. This helps reduce the overall amounts of these nutrients in the water. Studies of lakes such as Lake Trummen[65], Lake Nanhu[66], and Lake Erie[67] have shown a decrease in nitrogen and phosphorous in both the water and sediment after dredging. However, the impact of dredging on phytoplankton[68] is not fully understood[69]. It has been observed that after dredging, there is a reduction in the diversity of phytoplankton, including cyanobacteria, and genetic changes may also occur[70]. This is believed to contribute to the overall reduction in algal blooms after dredging[71].

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[61] As cited in footnote 8

[62] Cronberg, G., 'Phytoplankton changes in Lake Trummen induced by restoration' *Folia Limnologica Scandinavica* (1982) Vol.18

[63] As cited in footnote 62

[64] Eos, *Lake Erie Sediments: All Dredged Up with Nowhere to Grow*, (31 August 2021), Accessed: 3 June 2024

[65] As cited in footnote 62

[66] Wan, W., et al., 'Dredging mitigates cyanobacterial bloom in eutrophic Lake Nanhu: Shifts in associations between the bacterioplankton community and sediment biogeochemistry' *Environmental Research* (2020) Vol.188

[67] As cited in footnote 64

[68] Phytoplankton are photosynthetic microorganisms occupying sunlit layers of freshwater and marine water bodies. Phytoplankton includes cyanobacteria/blue-green algae.

[69] Wan, W., et al., 'Dredging alleviates cyanobacterial blooms by weakening diversity maintenance of bacterioplankton community' *Water Research* (2021) Vol.202

[70] As cited in footnote 69

[71] As cited in footnote 69

Interestingly, Lake Erie, USA, has found an innovative use for the dredged sediment[72]. The sediment contains high levels of nitrogen and phosphorous. As a trial, in Ohio, USA, dredged lake sediment is mixed into crop soils as fertiliser[73].

Dredging has been successful at reducing nutrient levels and algal blooms in freshwater lakes globally and has been applied to diverse sizes of lakes with similar effects. A review of lake sediment dredging concludes dredging is an expensive process and the long-term implications are still uncertain[74]. However, there may be adverse effects to the ecosystem as a whole with vital aquatic plants being removed during the dredging process[75]. Maintenance dredging may also be required to maintain the nutrient levels if the nutrients entering the system are not reduced[76].

2.3 Constructed wetlands

Constructed wetlands (CWs) are used to reduce nutrient pollution in water bodies in over 50 countries worldwide[77]. Constructed wetlands utilise the natural biogeochemical and physical processes found in natural wetlands to remove nutrients from runoff and offer benefits to local ecosystems[78]. Historically, wetlands have been trialled to treat wastewater by removing polluting chemicals, such as phosphorous, nitrates and ammonia[79].

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72 As cited in footnote 64

73 As cited in footnote 64

74 Riza, M., et al., 'Control of eutrophication in aquatic ecosystems by sustainable dredging: Effectiveness, environmental impacts, and implications' *Case Studies in Chemical and Environmental Engineering* (2023) Vol.7

75 As cited in footnote 74

76 As cited in footnote 74

77 Wu, H., et al., 'Constructed wetlands for pollution control' *Nature reviews Earth and Environment* (2023) Vol. 4, p.218-234

78 As cited in footnote 77

79 Natural Resources Wales, *The wonder of wetlands: Nature's helping hand in reducing pollution*, (2 February 2023), Accessed: 5 June 2024

Constructed wetlands are a complex and diverse web of interactions resulting in the removal of polluting nutrients[80]. A key characteristic of wetlands is the relationship between plants, microbes and substrates[81]. When runoff enters wetlands, excess nutrients are absorbed by the soils, plants and microbes[82]. Microbes are often key players in these interactions converting nitrogen into inorganic and bioavailable forms of nitrogen which can be readily absorbed by plants[83]. There are many different types of constructed wetlands, however the most effective at reducing nutrient flow-through is a hybrid-constructed wetland which is a combination of vertical flow wetlands and horizontal flow wetlands[84]. The difference between these wetland designs is the direction of water travel through the wetland[85]. Hybrid-constructed wetland removal efficiencies have been recorded to be around 72% for ammonia, 63% total nitrogen and 72% total phosphorous[86]. A study compared constructed wetlands to other wastewater treatments and found that constructed wetlands tend to have low maintenance costs, can adapt to differences in water flow and provide ecosystem benefits[87].

In summary, constructed wetlands provide an approach to reducing nutrient pollution entering water bodies[88]. As a contributing factor in algal blooms, a reduction in nutrient pollution is likely to lead to a long-term reduction in the prevalence of algal blooms[89]. Constructed wetlands are effective at reducing

80 Arden, S. & Ma, M. 'Constructed Wetlands for Greywater Recycle and Reuse: A Review' *Science of the Total environment* (2020) Vol. 630, p.587-99

81 As cited in footnote 79

82 Takai, K., 'The Nitrogen Cycle: A Large, Fast, and Mystifying Cycle' *Microbes and Environments* (2019) Vol. 34, p.223-225

83 As cited in footnote 82

84 Davis, L., et al., *A Handbook of Constructed Wetlands*, (1995)

85 Parde, D. et al., 'A review of constructed wetland on type, treatment and technology of wastewater' *Environmental Technology & Innovation* (2021) Vol. 21

86 As cited in footnote 77

87 As cited in footnote 85

88 As cited in footnote 79

89 As cited in footnote 8

nutrient pollution from runoff. However, they require designated land with low disturbance[90].

2.4 Aeration

Still or stagnant water, warm temperatures, and high sunlight are favourable conditions for algal bloom formation. Aeration is a technique which may be able to combat these factors[91]. Aeration is the process of adding air into a water body usually via an aeration device[92].

There are several ways that aeration can prevent the formation of algal blooms and mitigate the negative consequences. Aeration can discourage algal bloom formation through surface agitation[93]. Algal blooms are more common in water with low movement, such as stagnant water so increased surface water agitation reduces the frequency of bloom formation[94]. This also increases circulation in the water body similar to artificial mixing methods[95] (section 2.5). Additionally, aeration helps regulate gases in the water by adding oxygen, which can prevent the death of fish and plants during an algal bloom[96].

Aeration aids in balancing nutrients and gases in the water and initiates water movement increasing the mixing of water layers and destratification[97]. These can contribute to reduced formation of algal blooms over time and also minimise the effect of algal blooms on the ecosystems when they occur. However, scientific journal articles on aeration are limited in number and focus primarily on the artificial mixing characteristic of aeration[98].

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[90] As cited in footnote 84

[91] Kasco Marine, *How Aeration Improves Algae Issues*, (10 February 2016), Accessed: 5 June 2024

[92] As cited in footnote 91

[93] As cited in footnote 91

[94] As cited in footnote 91

[95] NEIWPCC, Harmful Algal Bloom control Methods Synopses (2015)

[96] As cited in footnote 91

[97] Destratification is the disruption of stratified waters (see section 1.2.6)

[98] As cited in footnote 27

2.5 Artificial mixing

Artificial mixing has been used to prevent algal bloom growth for many years. It aims to reduce algal blooms by disrupting thermal stratification and creating physical conditions which deter algal growth[99]. Artificial mixing works by counteracting the natural buoyancy of cyanobacteria which is caused by gas vesicles[100] and other buoyancy mechanisms[101].

Artificial mixing alters the structure of a lake, resulting in changes in the biomass and composition of phytoplankton[102]. This process involves imposing strong mixing which traps cyanobacteria in turbulent flow[103]. The mixing must be deep enough to restrict sunlight reaching the cyanobacteria, thereby limiting their growth[104]. Deep mixing in lakes also reduces the overall water temperature further disrupting optimal conditions for cyanobacterial growth[105]. This effect is reduced in shallower lakes and highly buoyant taxa, like cyanobacteria, require a depth of at least 15 metres for effective artificial mixing[106]. Research indicates that reducing the cyanobacterial buoyancy can allow other algae, such as diatoms, to compete more effectively for nutrients[107]. Interestingly, this can cause a shift in the composition of phytoplankton from a higher proportion of cyanobacteria to green algae and diatoms[108].

Artificial mixing reduces stratification, bringing the average temperature of the water lower[109]. However, despite an overall decrease in temperature, there is

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99 As cited in footnote 27

100 Gas vesicles are hollow structures inside a cell. They are not permanent structures and can be created for many reasons including cellular transport and buoyancy.

101 Walsby, A.E., 'Gas Vesicles' *Microbiological Reviews* (1994) Vol. 58, p.94-144

102 As cited in footnote 27

103 As cited in footnote 27

104 As cited in footnote 27

105 Cooke, G.D., et al., 'Restoration and management of lakes and reservoirs' *Regulated Rivers: Research and Management* (1994) Vol. 9

106 As cited in footnote 27, p. 435

107 As cited in footnote 27, p. 434

108 As cited in footnote 27, p. 436

109 As cited in footnote 27, p. 437

an increase in temperature at the deeper depths[110]. This higher temperature may result in increased mineralisation and a higher phosphorous release from the sediment[111]. However, this presents a greater issue in deeper, thermally stratified water bodies[112]. Similarly to aeration, artificial mixing increases the oxygen content of the water and can protect organisms living in the water body during an algal bloom[113].

In summary, artificial mixing reduces overall water temperature, increased oxygen content and disruption to the surface waters, all of which are methods to prevent algal bloom formation and protect the fish and plants in the water body[114]. Artificial mixing programmes are generally more successful when the water body is not experiencing sufficient vertical mixing[115]. Mixing strategies are generally more limited when the amount and distribution of mixing devices do not cover the entirety of the lake and if the lake is too shallow[116].

2.6 Removal of zebra mussels

Zebra mussels originate in the Caspian and Black Sea basins and are an invasive species in Northern Ireland[117]. Their efficient transport through water bodies has resulted in the widespread prevalence of the mussels throughout Ireland[118]. Their transport is frequently due to human activities such as shipping

[110] As cited in footnote 27, p. 431

[111] As cited in footnote 27, p. 431

[112] As cited in footnote 27, p. 431

[113] As cited in footnote 27, p. 431

[114] As cited in footnote 27

[115] As cited in footnote 27

[116] As cited in footnote 27

[117] Karatayev, A.Y. & Burlakova, L.E., 'What we know and don't know about the invasive zebra (Dreissena polymorpha) and quagga (Dreissena rostriformis bugensis) mussels' *Hydrobiologia* (2022), p.21

[118] McLean, S.P., et al., 'Establishment of the zebra mussel Dreissena polymorpha (Pallas, 1771) In Lough Neagh, Northern Ireland', Biology and Environment: Proceedings of the Royal Irish Academy(2010) Vol. 110B, p.1

and boating. Specifically, zebra mussels often attach to the hulls of boats[119]. Zebra mussels are filter feeders, meaning they feed on phytoplankton and zooplankton, reducing their numbers in water[120]. This often results in a clearing effect, the water becomes clearer and sunlight can penetrate deeper. The zebra mussel population causes substantial adverse effects including disruption of nutrient cycling which can result in negative effects for fish and plankton[121].

Zebra mussels have been associated with an increased incidence of algal blooms[122]. This is because, during selective filtering, zebra mussels alter the ratios of nitrogen to phosphorous in the water[123]. This causes rapid accumulation of cyanobacteria, specifically *Microcystis*[124]. The relationship between zebra mussels, phosphorous and cyanobacteria is complex with different concentrations of phosphorous resulting in different rates of accumulation of *Microcystis*[125].

As an invasive species with a high reproductive rate, there has been interest in understanding methods to remove the mussels from water bodies globally. Methods for removal include hand-removal[126], hydro-blasting[127], oxygen

[119] Morton, B.S., 'The anatomy of Dreissena polymorpha and the evolution and success of the heteromyarian form in the Dreissenoidea'. In: T F Nalepa and D W Schloesser (eds.) Zebra Mussels: Biology, Impacts and Control (1993), p.190

[120] Ten Winkel, E.H. & Davids, C. 'Food selection by Dreissena polymorpha Palla' *Freshwater Biology* (1982), p.553-558

[121] Maguire, C.M. & Sykes, L.M., 'Zebra mussel management strategy for Northern Ireland 2004-2010', Queens University Belfast (2004), p9

[122] Bykova, O. et al., 'Do zebra mussels (Dreissena polymorpha) alter lake water chemistry in a way that favours Microcystis growth?'. *Science of the Total Environment* (2006) Vol. 371, p369

[123] As cited in footnote 122

[124] As cited in footnote 122

[125] As cited in footnote 122

[126] J Wimbush et al., 'Eradication of colonizing populations of zebra mussels (Dreissena polymorpha) by early detection and SCUBA removal: Lake George, NY' *Aquatic Conservation: Marine and Freshwater Ecosystems* (2009) Vol.19, p.711

[127] Culver, C. et al., 'Quagga and zebra mussel eradication and control tactics' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1* (2013), p.10

deprivation[128], potassium chloride[129], copper-based treatments[130], pH[131], biopesticides[132], and pressure pulses[133] and bio-bullets[134]. These treatments are most effective for new and localised infestations. Further information addressing Zebra mussel distribution, biology, removal and legislation can be found in the RaISe briefing paper: 'Zebra Mussels in Northern Ireland'.

3 Control

Due to climate change, the prevalence of algal blooms is increasing worldwide. As a result, finding ways to control algal blooms is a pressing question for communities globally. There are numerous methods for controlling algal blooms, and innovative technologies are being routinely developed. This section will discuss various prominent methods of algal bloom control, including mechanical, chemical, and biological solutions.

4 Physical control

4.1 Shading technology

Light is essential for cyanobacterial survival and encourages algal growth through photosynthesis. Therefore, methods have been proposed to reduce

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128 Wittmann, M. et al., 'The Control of an Invasive Bivalve, Corbicula fluminea, Using Gas Impermeable Benthic Barriers in a Large Natural Lake', *Environmental Management* (2012) Vol. 49, p.1

129 Fisher, S.W. et al., 'Molluscicidal activity of potassium to the zebra mussel, Dreissena polymorphia: toxicity and mode of action', *Aquatic Toxicology* (1991) Vol. 20, p1

130 Hammond, D. & Ferris, G., 'Low doses of EarthTec QZ ionic copper used in effort to eradicate quagga mussels from an entire Pennsylvania lake' (2019) *Management of Biological Invasions*, Vol.10

131 Claudi, R. et al., 'Impact of pH on survival and settlement of dreissenid mussels' *Aquatic Invasions* (2012) Vol.7, p.28

132 ProFarm, *Marrone Bio – Zequanox*

133 Schaefer, R., et al., 'Control of zebra mussels using sparker pressure pulses'. *Journal of the American Water Works Association* (2010) Vol. 102, p.1

134 Aldridge, D.C. et al., 'Microencapsulated BioBullets for the Control of Biofouling Zebra Mussels', *Environmental Science and Technology* (2006) Vol. 40, p.1

algal blooms by introducing shading technology such as vegetation and enclosures[135].

Research indicates that algal growth increases with higher light intensity and warmer surface temperatures[136]. Shading technology can reduce light intensity and surface water temperature, therefore preventing rapid algal growth[137]. Where algal growth is restricted in shaded areas, there tends to be higher nutrient levels because algae are not absorbing the nutrients at the same rate[138].

Shading methods can be combined with other techniques, such as riparian buffers, to decrease algal blooms[139]. Riparian shading involves using woody vegetation in the areas between water bodies and potential sources of nutrient pollution, like farmland, wastewater treatment facilities, and urban areas[140]. However, shading technology is often limited by size or location[141]. While riparian shading effectively reduces algal blooms on the edges of water bodies, other more portable shading technologies can be used in open areas of the water bodies[142].

4.2 Barley straw

Barley straw controls algal blooms via multiple mechanisms and has primarily been applied to lakes and ponds for algal management[143]. It has been suggested that barley straw releases phenolic compounds which can reduce

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135 Cao, C., et al., 'Eutrophication and algal blooms in channel type reservoirs: A novel enclosure experiment by changing light intensity' *Journal of Environmental Sciences* (2011) Vol. 23, p.1660-1670

136 As cited in footnote 8

137 As cited in footnote 135

138 As cited in footnote 135

139 Burrell, T., 'Riparian shading mitigates stream eutrophication in agricultural catchments' *Freshwater Science* (2014) Vol. 33, p.73-84

140 As cited in footnote 139

141 As cited in footnote 139

142 As cited in footnote 135

143 Anderson, D.M. et al., 'Harmful Algal Blooms (HABs) and desalination: a guide to impacts, monitoring and management' (2017), p.209

the growth of some algae (dinoflagellates)[144], however, barley straw also releases hydrogen peroxide as it decomposes[145]. Hydrogen peroxide is a well-established compound used to control algal growth including cyanobacteria (see section 5)[146]. Mechanical shearing can increase the speed of decomposition, but this method is most effective in closed systems such as lakes[147].

4.3 Air flotation

Dispersed air flotation is a popular method in wastewater treatment to separate solid particles from liquid suspension[148]. It has been explored as an effective method to recover algae from water bodies, primarily for use as biofuels[149].

Flotation methods are well-established in algae recovery[150]. Bloom-infested water enters a chamber and compressed air is injected[151]. The air bubbles float through the mixture to the surface attaching to the algal cells on the way up and pulling them to the surface[152]. The algae are then removed from the top via a skimming device[153].

Air flotation is an energy-intensive process and often requires the construction of a processing unit near the water body[154]. Studies show that air flotation is a

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144 Terlizzi, D. E. et al., 'Inhibition of dinoflagellate growth by extracts of barley straw (Hordeum vulgare)'. *Journal of Applied Phycology* (2002) Vol. 14, p.275–280.

145 Iredale, R. S., et al., 'A series of experiments aimed at clarifying the mode of action of barley straw in cyanobacterial growth control'. *Water Research* (2012) Vol. 46, p.6095–6103

146 As cited in footnote 145

147 As cited in footnote 143

148 Wastewater Digest, *What is dissolved air flotation (DAF)?*, (24 April 2024), Accessed: 26 June 2024

149 Alhattab, M. and Brooks, M.S., 'Dispersed air flotation and foam fractionation for the recovery of microalgae in the production of biodiesel' *Speration Scienc and Technology* (2017) Vol.52, p.2002-2016

150 As cited in footnote 149

151 Uduman, N., et al., 'Dewatering of microalgal cultures: a major bottleneck to algae-based fuels.' *Journal of Renewable and Sustainable Energy* (2010) Vol.2

152 As cited in footnote 151

153 As cited in footnote 148

154 As cited in footnote 148

rapid and highly effective method of separating algal cells and water[155]. In some circumstances, air flotation has been paired with foam fractionation, a method to collect the algae from the surface of the water[156]. This includes adding foaming particles to the compressed air that causes the algal cells to be trapped in foam for removal[157]. Most of the research regarding air flotation methods has been conducted with industry in mind, either algal removal in wastewater treatment or in algal recovery for energy[158].

4.4 Clay flocculation

Clay flocculation to control algal blooms has been used worldwide in marine and freshwater environments. Clay is a common flocculent used, however researchers are exploring using modified clay for flocculation. This clay has additional components for more effective destruction of algal blooms[159].

Flocculation is the process of a flocculent, such as clay, and water being sprayed over the algal bloom surface[160]. The flocculent solution kills the algal cells by causing them to aggregate and sink[161]. Clay flocculation has been used on 'fairly large-scale' algal blooms with an '80-95% removal efficiency of biomass from the surface waters'[162]. In Western Australia, a clay flocculent has been modified to bind to phosphorous[163]. As a result phosphorous in the water sinks alongside the algal cells to the lake bed[164]. This technique has the potential to destroy the algal bloom and also introduce phosphorous limitation.

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155 Edzwald, J.K. 'Dissolved air flotation and me' *Water Research* (2010) Vol. 44, p.2077–2106.

156 Burghoff, B., 'Foam fractionation applications' *Journal of Biotechnology* (2012) Vol. 161, p.126–137

157 As cited in footnote 156

158 Wang, L.K., et al., *Flotation Technology* (2010)

159 National Centers for Coastal Ocean Science, *Clay Treatments to Control Red Tide Unlikely to Harm Blue Crabs*, (8 January 2024), Accessed: 4 June 2024

160 As cited in footnote 159

161 Sengco, M. & Anderson, D.M. 'Controlling harmful algal blooms through clay flocculation' *Journal of Eukaryotic Microbiology* (2004) Vol. 52, p.169-72

162 As cited in footnote 161

163 Modified clay helping reduce algal blooms by binding to phosphorus which causes phenomenon, ABC News, 15 February 2024, Accessed: 4 June 2024

164 As cited in footnote 163

A possible negative consequence of clay flocculation is increased ammonium regeneration. Ammonium is a nitrogen-based compound and can promote algal growth[165].

Research is ongoing regarding the best flocculants. ‘Ball’ clay has proved successful at removing marine algal blooms[166]. Poly-aluminium chloride-clay has also proved successful at water treatment plants[167]. Other successful flocculants such as chitosan and clay slurry[168].

The impact of clay flocculants on the environment varies greatly. An increase in sinking particles causes environmental changes to the lake bed, a habitat for molluscs and crustaceans[169]. Clams and blue crabs in Florida[170] and the Gulf of Mexico[171] are not significantly impacted by the application of clay flocculants according to research. However, at specific concentrations when dissolved in acetic acid, chitosan flocculant has been shown to cause increased mortality in rainbow trout[172]. In 2003, researchers showed that yellow loess (a yellow silt) caused ‘significant negative impact’ on filer-feeding invertebrates[173].

4.5 Other nanotechnologies

165 Paerl, H.W., et al., ‘Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change’ *Science of the Total Environment* (2011) Vol. 409, p.1739-45

166 As cited in footnote 143, p.210

167 As cited in footnote 143, p.210

168 As cited in footnote 143, p.210

169 Seo, K., et al., ‘Effect of yellow clay on respiration and phytoplankton uptake of bivalves’ *Fisheries Science* (2008) Vol.74, 120-127

170 As cited in footnote 159

171 Archambault, M., et al., ‘Effects of suspended and sedimented clays on juvenile hard clams, Mercenaria mercenaria, within the context of harmful algal bloom mitigation’ *Marine Biology* (2004) Vol. 144, p.553-565

172 Bullock, G., et al., ‘Toxicity of acidified chitosan for cultured rainbow trout (*Oncorhynchus mykiss*)’ *Aquaculture* (2000) Vol.185, p.273-280

173 Shumway, S., et al., ‘Effect of yellow loess on clearance rate in seven species of benthic, filter-feeding invertebrates’ *Aquaculture Research* (2003) Vol.34, p.1391-1402

Nanotechnology is a rapidly developing field in algal bloom management including photocatalysis, flocculation, oxidation and adsorption[174]. Nanotechnology refers to molecules and technologies sized between 1 and 100 nanometres[175]. In section 4.4 (above), a nanotechnology, modified clay flocculation, is considered. In this section, other nanotechnologies are considered as algal bloom management options.

Photocatalysis has been proposed as a method to control algal blooms using titanium dioxide (TiO_2) semiconductor electrodes[176]. Under light, these electrodes undergo a chemical change which means they can react with other compounds to form radicals[177] and reactive oxygen species[178] which cause algal death[179].

Adsorption is another promising nanotechnology method which could be used to control nutrient levels in water bodies, specifically phosphorous[180]. Adsorption is the phenomenon of gas or liquid particles binding to the surface layer of a solid. Nanomaterials are often good adsorbents due to their large surface area per unit mass[181]. Nanoadsorbents possessing phosphorus binding sites may be used to remove phosphorous from water with zinc oxide (ZnO) of particular interest[182].

174 Song, J., et al., 'Nanoparticles, an Emerging Control Method for Harmful Algal Blooms: Current Technologies, Challenges, and Perspectives' *Nanomaterials* (2023) Vol.13

175 Malik, S., et al., 'Nanotechnology: A Revolution in Modern Industry' *Molecules* (2023) Vol. 28

176 Kim, S. & Lee, D., 'Preparation of TiO2-coated hollow glass beads and their application to the control of algal growth in eutrophic water' *Microchemical Journal* (2005) Vol. 80, p.227-232

177 Radicals are atoms, compounds or molecules with at least one unpaired electron on the outermost shell of an atom (also known as a valence electron).

178 Reactive oxygen species are highly reactive chemicals containing at least one oxygen atom and at least one unpaired electron.

179 Wang, X. et al., 'A highly efficient TiOX (X = N and P) photocatalyst for inactivation of Microcystis aeruginosa under visible light irradiation' *Separation and Purification Technology* (2019) Vol. 222, p.99-108

180 As cited in footnote 174

181 Vunain, E. et al., 'Dendrimers, mesoporous silicas and chitosan-based nanosorbents for the removal of heavy metal ions: A review' *International Journal of Biological Macromolecules* (2016) Vol. 86, p. 570-586

182 Li, X. et al., 'Enhanced phosphate removal from aqueous solution using resourceable nano-CaO2/BC composite: Behaviors and mechanisms' *Science of the Total Environment* (2020)

According to a recent literature review, nanoparticles are a promising technology for algal bloom management with molecules such as TiO_2 and ZnO exhibiting anti-algae properties[183]. Existing nanotechnologies often have a high algicidal rate which is usually within the first 24 hours[184]. Nanotechnology also presents options for nutrient removal from water bodies through adsorption. However, further research is needed to ascertain the specific toxicity and ecosystem impacts of using these technologies in the natural environment[185].

4.6 Filtration

Filtration is a well-established wastewater treatment strategy popular worldwide[186]. There are two main methods of filtration: sand filtration and membrane filtration[187]. Sand filtration is a simple and inexpensive method of removing algal cells from water. Pressure is used to pull water through different coarseness of sand until the algal cells are trapped within the sand (slow sand filtration)[188]. The sand from the filtration units can be used to fertilize soil once the lifespan of the filters is complete[189]. Another filtration method is membrane filtration, which involves a selective permeation membrane that filters water based on a pressure or concentration difference, trapping the microalgae in the membrane[190].

Sand filtration systems offer a simplistic design and construction[191]. However, membrane filtration systems can deal with greater amounts of algal cells[192].

183 As cited in footnote 174

184 As cited in footnote 174

185 As cited in footnote 174

186 Esen, I.I., et al., 'Algae removal by sand filtration and reuse of filter material' *Waste Management* (1991) Vol. 11, p.59-65

187 Zeng, G., et al., 'Comparison of the Advantages and Disadvantages of Algae Removal Technology and Its Development Status' *Water* (2023) Vol.15

188 As cited in footnote 186

189 As cited in footnote 186

190 As cited in footnote 187

191 As cited in footnote 186

192 As cited in footnote 187

'Fouling' is a consequence of both filtration methods and is the process of algal cells and other suspended matter caking over the membrane or clogging the sand[193]. This increases resistance in filtration and loss of permeability, requiring the membrane or sand to be replaced[194]. Filtration methods can be static or mobile with researchers designing a floating filtration technique using geotextile filters to combat algal blooms in shallow lakes[195].

4.7 Ultrasonication

Cyanobacteria are photosynthetic and require light to generate energy. Therefore cyanobacteria remain buoyant and float in the surface waters. Ultrasonic waves can affect buoyancy regulation. This prevents algae from gaining significant buoyancy and therefore not gaining enough sunlight to bloom[196].

Ultrasound disrupts the growth of algae via the generation of cavitation bubbles[197]. These bubbles burst causing localised regions of extreme temperature (up to 5000 °C)[198]. The extreme temperature results in a disruption in the buoyancy of cyanobacteria causing them to sink[199]. Cyanobacterial sensitivity to ultrasound radiation varies between species[200]. Cyanobacteria with greater surface area are more susceptible to ultrasound treatment[201]. The

193 As cited in footnote 186

194 As cited in footnote 186

195 Phys.org, *Researchers fight shallow lake algae blooms with floating filtration technique*, (18 April 2023), Accessed: 25 June 2024

196 Park, J., et al., 'Recent advances in ultrasonic treatment: Challenges nd field applications for controlling harmful algal blooms (HABs)' *Ultrasonics Sonochemistry* (2017) Vol. 38, p.326-334

197 Suslick, K., 'Sonochemistry' *Science* (1990)

198 As cited in footnote 197

199 As cited in footnote 196

200 Purcell, D., et al., 'The influence of ultrasound frequency and power, on the algal species Microcystis aeruginosa, Aphanizomenon flos-aquae, Scenedesmus subspicatus and Melosira sp.' *Environmental technology* (2013) p.2477-2490

201 As cited in footnote 200

impact of ultrasound on ecosystems is not fully understood. However, some studies indicate no increase in fish mortality or behaviour change[202].

Ultrasound radiation is a compact and simple-to-use method to control algal blooms[203]. Whether ultrasound can be used on large scales is not fully understood[204]. Changes in factors like rainfall, light intensity, temp, and water can make the technology less reliable[205].

4.8 Ultraviolet (UV)

Ultraviolet (UV) irradiation has been used in disinfection for over 100 years and is a well-established method to stop microbial propagation[206]. Recently UV-C, a type of UV irradiation, is being explored as a method to control algal blooms[207]. High UV irradiation kills cyanobacteria through the inhibition of photosynthesis[208].

The infrastructure required for UV-C radiation treatment is minimal with simple equipment[209]. This equipment can be attached to mobile devices to expand the application to larger water bodies[210]. Compared to other algal bloom management options, UV-C is chemical-free which means there is a lower risk of disinfection by-products which could cause adverse effects on the ecosystem[211]. Previous studies have mostly been laboratory-based using the

202 Griessler Bulc, T., et al., 'The efficiency of a closed-loop chemical-free water treatment system for cyprinid fish farms' *Ecological Engineering* (2011) Vol.34, p.873-882

203 As cited in footnote 196

204 As cited in footnote 196

205 As cited in footnote 196

206 Downing, A.M.W. and Blunt, T.P., 'III. Researches on the effect of light upon bacteria and other organisms' *Proceedings of the Royal Society of London* (1878) Vol.26, p.488–500.

207 Li, S. et al., 'UV-C irradiation for harmful algal blooms control: A literature review on effectiveness, mechanisms, influencing factors and facilities' *Science of the Total Environment* (2020) Vol. 723, p.137986

208 As cited in footnote 207

209 As cited in footnote 207

210 As cited in footnote 207

211 As cited in footnote 207

cyanobacteria *Microcystis aeruginosa*, therefore 'larger field tests' and 'deeper research on [the] mechanisms' causing algal death as a result of UV irradiation[212].

5 Chemical control

Chemical control methods involve the removal of algal blooms by the addition of chemicals to the water body. Historically popular chemical control methods include hydrogen peroxide and copper sulphate. It is important to note that the chemical control options included in this research paper may not be suitable or authorised for use in Northern Ireland and approval may be required for use.

5.1 Hydrogen peroxide

Hydrogen peroxide is well-established as an agent for destroying bacterial cultures in laboratory settings[213].

Hydrogen peroxide is a compound with strong oxidising capabilities, making it an effective disinfectant[214]. In 2020, the efficacy of hydrogen peroxide as an agent to clear algal blooms was assessed in four diverse lakes in the USA[215]. Within this study, the effect of the agent on target cyanobacteria and non-target microorganisms was addressed. Hydrogen peroxide was administered at four micrograms per litre of water reducing cyanobacterial levels from 85% of the total phytoplankton community to 29%[216]. Other algae were not negatively impacted by hydrogen peroxide and increased their proportion of the phytoplankton community[217]. In pond trials, fish and prawns were not affected

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212 As cited in footnote 207

213 Drabkova, M. et al., 'Combined exposure to hydrogen peroxide and light-slecetive effects on cyanobacteria, green algae and diatoms' *Environmental Science and Technology* (2006) Vol. 41, p.309-314

214 As cited in footnote 213

215 Lusty, M.W. and Gobler, C.J., 'The Efficacy of Hydrogen Peroxide in Mitigating Cyanobacterial Blooms and Altering Microbial Communities across Four Lakes in NY, USA' *Toxins* (2020) Vol.12, p.428

216 As cited in footnote 215

217 As cited in footnote 215

by adding hydrogen peroxide to the water[218]. Overall, 'larger scale and whole ecosystem experiments' are required to fully understand the impact of hydrogen peroxide on bloom mitigation in the natural environment[219].

5.2 Copper sulfate

Copper sulfate was a commonly used chemical control method in the twentieth century and is an effective method for removing algal blooms from water bodies[220]. Copper sulfate inhibits nitrogen fixation[221]. Nitrogen fixation is the process of converting atmospheric nitrogen to usable nitrogen in the cell. The inhibition of this process limits nitrogen availability in the cell resulting in reduced cyanobacterial growth[222]. Copper sulfate is routinely added to water supplies alongside chloride ions to reduce microalgal populations[223]. However, despite its efficiency at controlling cyanobacterial populations, the usefulness of copper sulfate in the natural environment is limited[224]. This is because copper sulfate is non-specific and has been shown to cause damage to marine animals and plants[225].

5.3 Peracetic acid

Peracetic acid, also known as peroxyacetic acid or PAA is a widespread antimicrobial agent and disinfectant[226]. Peracetic acid is an oxidiser and can be

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[218] Ng, P.H. et al., 'Hydrogen peroxide as a mitigation against *Microcystis* sp. Bloom' *Aquaculture* (2023) Vol.577

[219] As cited in footnote 215, p.428

[220] McKnight, D.M, et al., 'CuSO4 treatment of nuisance algal blooms in drinking water reservoirs' *Environmental Management* (1983) Vol. 7, p.311-320

[221] Elder, J.F. and Horne, A.J., 'Copper cycles and CuSO4 algicidal capacity in two California lakes' *Environmental Management* (1978) Vol. 2, p.17–30.

[222] Sarma, R. & Prakash, P., 'Chapter 14 - Physiological aspects of cyanobacterial nitrogen fixation and its applications in modern sciences' in *Advances in Cyanobacterial Biology* (2020), p.205-217

[223] Zamyadi, A., et al., 'Toxic cyanobacterial breakthrough and accumulation in a drinking water plant: a monitoring and treatment challenge' *Water Research* (2012) Vol. 4, p. 1511-1523

[224] As cited in footnote 143, p.211

[225] As cited in footnote 143, p.211

[226] United States Department of Agriculture Food Safety and Inspection Service (USDA FSIS), Health Hazard Information Sheet Peroxyacetic Acid (PAA), (n.d)

derived from hydrogen peroxide, acetic acid and sulfuric acid[227]. A field evaluation of seven algicidal products includes peracetic-acid based products (Peraclean and VigorOx SP-15)[228]. These products were shown to significantly reduce cyanobacterial communities with minimal impact on other algae[229]. The study noted the cost of peracetic-acid based products was ‘moderate to high’ compared to the other chemical control methods evaluated[230].

5.4 Simazine

Simazine is a very effective herbicide with previous widespread usage[231]. A study found simazine among the most effective chemical control methods[232]. Simazine is a non-specific herbicide that inhibits photosynthetic pathways and restricts the growth of algae, plants and other photosynthetic organisms[233]. The non-specificity of herbicidal action means non-target organisms are also impacted[234]. In 2004, most European Union member states banned simazine use as an herbicide[235]. The ECHA categorises simazine as ‘very toxic for aquatic life’ and ‘very toxic to aquatic life with long lasting effects’[236]. Recently calls for action have been introduced in the USA to limit the use of simazine and

[227] United States Department of Agriculture Agricultural Marketing Service (USDA AMS), Peracetic Acid, (2000)

[228] Buley, R.P. et al., ‘Field evaluation of seven products to control cyanobacterial blooms in aquaculture’ *Environmental Science and Pollution Research* (2021) Vol. 28, p.29971–29983

[229] As cited in footnote 228

[230] As cited in footnote 228

[231] Breckenridge, C.B., et al., ‘PBPK-Based Probabilistic Risk Assessment for Total Chlorotriazines in Drinking Water.’ *Toxicological Sciences* (2016) Vol. 150, p.269-282

[232] Anantapantula, S. & Wilson, A., ‘Most treatments to control freshwater algal blooms are not effective: Meta-analysis of field experiments’ *Water Research* (2023) Vol. 243. P.120342

[233] Qian, H., et al., ‘PGR5 and NDH pathways in photosynthetic cyclic electron transfer respond differently to sublethal treatment with photosystem-interfering herbicides’ *Journal of Agricultural Food Chemistry* (2014) Vol.62

[234] Department, Government of Western Australia Department of Agriculture and Food, *Toxic algal blooms*, 14 April 2020, Accessed: 25 June 2024

[235] 2004/247/EC: Commission Decision of 10 March 2004 concerning the non-inclusion of simazine in Annex I to Council Directive 91/414/EEC and the withdrawal of authorisations for plant protection products containing this active substance

[236] European Chemicals Agency, *Simazine Substance Infocard*, (n.d.), Accessed: 25 June 2024

similar herbicides[237]. This context may make it non-viable for use in Northern Ireland.

6 Biological control

Biological control methods involve the removal of algal blooms through the introduction of biological organisms. This section includes biological control methods, including algicidal bacteria, algicidal viruses (cyanophage), and grazers.

6.1 Algicidal bacteria

Bacterial interactions are extensive complex and diverse encompassing mutually beneficial symbiotic relationships to parasitic interactions. Algicidal bacteria refer to bacteria involved in antagonistic interactions with algae[238]. Algicidal action can occur via many modes including both indirect and direct action[239]. Notable algicidal bacteria includes *Streptomyces globisporus*[240],

The bacterial species *S. globisporus* is antagonistic towards the harmful algal bloom-forming cyanobacteria *Microcystis aeruginosa*[241]. Its mechanism of action is through a direct attack, where long filamentous 'arms' of *S. globisporus* wrap around the cyanobacteria[242]. This direct cell-to-cell attack is specific to *M. aeruginosa* and *S. globisporus* does not seem to have 'major impacts' on other green algae[243].

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[237] United States Environmental Protection Agency, *EPA Releases Final Biological Evaluations for Glyphosate, Atrazine, and Simazine,* (12 November 2021), Accessed: 25 June 2024

[238] Coyne, K. et al., 'Algicidal Bacteria: A review of Current Knowledge and Applications to Control Harmful algal Blooms' *Frontiers in Microbiology* (2022) Vol. 13, p.11

[239] As cited in footnote 238

[240] Zeng, Y. et al., 'A Streptomyces globisporus strain kills Microcystis aeruginosa via cell-to-cell contact' *Science of the Total Environment* (2021) Vol. 769, p.144489

[241] As cited in footnote 240

[242] As cited in footnote 240

[243] As cited in footnote 240

Previous research has indicated that algicidal bacteria are an effective method to manage algal growth[244]. Previously, most studies assessing the impact of algicidal bacteria have been conducted in laboratory settings in a one-on-one with one species of algicidal bacteria and one species of cyanobacteria[245]. Other limitations noted in a review of algicidal bacteria include laboratory culture experiments including higher cell densities than are likely to exist in nature[246]. A review in 2022, considered the 'convincing evidence' for control of algal bloom in nature by algicidal bacteria to increase the amount of 'naturally occurring algicidal bacteria during the late stages of blooms'[247]. The effectiveness and environmental impact of adding algicidal bacteria into the natural environment are not fully understood[248].

6.2 Cyanophage

The natural environment consists of a delicate balance of diverse organisms including bacteria and viruses[249]. Bacteriophage are viruses that infect bacteria and have recently gained prominence due to their potential to treat diseases through phage therapy[250]. Cyanophage are viruses infecting cyanobacteria. The potential for cyanophage to be used to manage algal blooms is being explored.

Cyanophage technologies work by enhancing the natural cycle of viral-bacterial interactions[251]. These cyanophage-cyanobacteria interactions can occur via the lytic cycle[252]. The lytic cycle is initiated when a virus infects the bacteria[253]. The

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244 As cited in footnote 238

245 As cited in footnote 238

246 As cited in footnote 238

247 As cited in footnote 238

248 As cited in footnote 238

249 Bhatt, P. et al., 'Cyanophage technology in removal of cyanobacteria mediated harmful algal blooms: A novel and eco-friendly method' *Chemosphere* Vol. 315, p.1

250 American Society for Microbiology, *Phage Therapy: Past, Present and Future*, (31 August 2022), Accessed: 24 June 2024

251 Grasso, C.R. et al., 'A Review of Cyanophage–Host Relationships: Highlighting Cyanophages as a Potential Cyanobacteria Control Strategy' *Toxins* (2022) Vol. 14., p.2

252 As cited in footnote 251

253 Weinbaur, M.G., 'Ecology of prokaryotic viruses' *FEMS Microbiology Reviews* (2006) Vol.28

virus then uses the host's DNA replication machinery to replicate their DNA and once many new viruses have formed, they burst out of the cell[254]. Bursting out of the cell breaks the cell wall and results in cell death[255].

A 2022 review of cyanophage-host relationships reported that cyanophage are specific to their cyanobacterial hosts and the addition of the viruses may not impact other microorganisms in the water body[256]. Other research has indicated that viruses have limited stability outside of the host and are susceptible to death by UV irradiation[257]. Therefore, the abundance of uninfected cyanophage in the water body is likely to be low when there is low cyanobacterial abundance[258]. So far, researchers have isolated cyanophage infecting a variety of cyanobacterial hosts from the natural environment and the mechanisms of action are being researched[259]. The 2022 review indicated that more research regarding cyanophage-cyanobacterial interactions and algal blooms in the natural environment is required[260].

6.3 Grazers

Grazers are biological organisms that feed on phytoplankton, for example, zooplankton or protozoa[261]. Most grazers have feeding preferences therefore

[254] As cited in footnote 253

[255] As cited in footnote 253

[256] As cited in footnote 251

[257] Cheng, K. et al., 'Solar radiation-driven decay of cyanophage infectivity, and photoreactivation of the cyanophage by host cyanobacteria' *Aquatic Microbial Ecology* (2007) Vol. 48, p. 13-18

[258] As cited in footnote 257

[259] As cited in footnote 249, p.1

[260] As cited in footnote 249, p.9

[261] Protozoa are single-celled eukaryotic organisms some of whom can consume cyanobacteria.

their consumption is specific[262]. Interestingly, research in the 1990s[263] indicated the 'fate of most phytoplankton in the sea is to be consumed by grazers'[264].

Important considerations of this method reported in a 2008 review include that the grazer must be well-understood and chosen based on the cyanobacteria causing the algal bloom[265]. This is critical since many grazers are specific and if multiple cyanobacteria are causing the bloom, the grazer may not consume all species[266]. Grazers have been recorded to consume non-toxic species which result in the proliferation of a separate toxic species due to lack of competition[267]. Another consideration is that microalgae may have defence strategies against grazers which could limit their efficacy[268]. Furthermore, it has been suggested that eutrophic conditions increase the production of grazing deterrents resulting in increased phytoplankton populations[269]. Whilst grazers are considered to have a significant impact on algal populations, these interactions are ecologically complex and could result in unforeseen complications for the ecosystem[270]. The 2008 review suggests more research is required to understand the mechanisms at play and this control method would benefit from combination with a reduction in nutrient levels in the water body[271].

[262] Buskey, E., 'How does eutrophication affect the role of grazers in harmful algal bloom dynamics?' *Harmful Algae* (2008) Vol. 8, p. 152-157

[263] Banse, K., 1992. Grazing, temporal changes of phytoplankton concentrations, and the microbial loop in the open sea. In: Falkowski, P.G., Woodhead, A.D. (Eds.), Primary Production and Biogeochemical Cycles in the Sea. Plenum, New York, pp. 409–440.

[264] As cited in footnote 262

[265] As cited in footnote 262

[266] As cited in footnote 262

[267] Tillman, U., 'Interactions between Planktonic Microalgae and Protozoan Grazers' *Journal of Eukaryotic Microbiology* (2005) Vol. 51, p. 156-168

[268] As cited in footnote 262

[269] Kemp, W. M., et al., 'Nutrient enrichment, habitat variability and trophic transfer efficiency in simple models of pelagic ecosystems' *Marine Ecology Progress Series 223* (2001), p.73–87.

[270] As cited in footnote 143

[271] As cited in footnote 143

7 Considerations

This is research paper considers research associated with the management of algal blooms and prompts potential considerations including:

- Lough Neagh is the largest lake in the UK. Is one algal bloom management approach adequate, or will a multifaceted strategy be necessary?
- Given the poor ecological status of Northern Ireland lakes, incidences of algal blooms are likely to occur in the immediate future despite prevention measures. Is there a need for a management strategy encompassing both prevention and control? If so, what management technologies are complementary?
- What are the long-term implications of persistent algal blooms in Northern Ireland lakes? And how can management strategies be coordinated for long-term management in Northern Ireland?
- Many algal bloom management strategies are in their infancy/require additional development to be appropriate for Northern Ireland lakes, how can this be achieved? What role will the public sector take in this process?