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Innovative approaches for sustainable lake restoration

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ABSTRACT

Nature restoration requires optimisation to ensure approaches are effective, address broad societal challenges and are economically viable. This structured literature review addresses the knowledge gap in holistic evaluations of emerging lake protection and restoration approaches, particularly those using nature-based and circular methodologies. In addition to benefiting biodiversity, these approaches aim to deliver co-benefits to society, such as resilience to climate change or sustainable economic development. The in-lake circular solutions reduce internal nutrient loading while enabling nutrient and carbon recovery, thus having potential for reducing lacustrine greenhouse gas emissions. The importance of prioritising the capture of pollutants at source or before they reach the lake is, however, undeniable. Nature-based solutions across catchments target water and nutrient retention on land by creating sponge landscapes and provide co-benefits consistent with multiple EU and global policy goals, including the EU Water Resilience Strategy, EU Nature Restoration Regulation and the UN Sustainable Development Goals. Our review highlights the necessity for developing a tailored combination of measures that can address multiple pressures. Developing a restoration programme for an individual lake should initially involve a thorough lake-specific diagnosis of the problems and their causes. This systemic diagnosis guides the development of an integrated catchment–lake strategy, combining multiple measures to yield the most durable restoration outcomes. Further evidence of the costs and benefits of innovative nature-based and circular solutions is needed to support their wider adoption and achieve successful lake restoration at wider scales.

1. Introduction

Eutrophication remains a major ecological challenge in freshwater ecosystems worldwide (Poikane et al., 2024). It is primarily driven by excess inputs of inorganic nitrogen (N) and phosphorus (P) from agricultural runoff, wastewater discharges, and other anthropogenic sources (Smith and Schindler, 2009; Chislock et al., 2013; Grizzetti et al., 2021). Eutrophication-driven degradation of lakes threatens the biodiversity of freshwater-dependent species, weakens the value of cultural and provisional aquatic ecosystem services and impacts the social and economic benefits provided by lakes (Chislock et al., 2013; Reynaud and Lanzanova, 2017; Birk et al., 2020; Spence et al., 2023). One of the widespread impacts of eutrophication is harmful algal blooms (HABs). HABs increase in magnitude and frequency with nutrient pollution and appear to

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be intensifying with global warming and summer droughts (Richardson et al., 2018). Additionally, eutrophication may substantially increase greenhouse gas (GHG) emissions from lakes by shifting them from carbon sinks into sources of carbon dioxide (CO_2) and methane (CH_4) driven by increased cycling of autochthonous carbon (Beaulieu et al., 2019; Morales-Williams et al., 2021). Collectively, these adverse impacts of eutrophication underscore the need for protecting and restoring lakes from deterioration.

Through the implementation of key European Union (EU) policies, such as the Water Framework Directive (WFD; 2000/60/EC), Nature Restoration Regulation (NRR), Urban Wastewater Treatment Directive (UWWTD), and the Nitrates Directive (ND), thousands of measures for water protection and aquatic ecosystem restoration have been implemented across Europe. However, due to excess nutrients originating from both catchment and in-lake sources, nearly half of European lakes still fail to reach good ecological status under the WFD (EEA, 2024) and most protected freshwater habitats and species remain in unfavourable conservation status (EEA, 2020). One of the identified reasons for limited success in improving lake status is that protective measures are implemented at insufficient scale to tackle diffuse sources of pollution (Wiering et al., 2020). Another reason is the inefficiency of restoration measures at tackling legacy nutrients in lake bed-sediments, resulting in long time lags before the effects of these measures become apparent (Carvalho et al., 2019; Horppila, 2019; Poikane et al., 2024). Therefore, there is a need for more effective mitigation and lake restoration measures to deliver successful water and habitat quality improvements, enhance biodiversity and secure the ecosystem services that lakes provide to society and the economy.

Recently, the lake restoration community has called for more sustainable solutions to lake restoration, including nature-based solutions (NbS) and circular approaches that may enable gradual lake recovery without drastic interventions (WWQA, 2023; Tammeorg et al., 2024a; Tammeorg et al., 2025b). NbS, by definition, protect, sustainably manage and restore natural or modified ecosystems, whilst at the same time, address societal challenges effectively and adaptively, and provide human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Circular blue economy solutions (CBS), here defined as the inclusion of efficient recovery of resources by integrating circular economy principles into the blue economy, also have the potential to deliver societal co-benefits. Additionally, some measures are neither NbS nor CBS, but more specifically Biodiversity-focused Solutions (BfS) that foster biodiversity enhancement, utilising established restoration measures innovatively. Numerous reviews (Zamparas and Zacharias, 2014; Triest et al., 2016; Kibuye et al., 2021; Abell et al., 2022) and meta-analyses (e.g., Jeppesen et al., 2005; Jeppesen et al., 2007; Spears et al., 2016) demonstrate the efficacy of current lake restoration solutions in reducing the symptoms of eutrophication. However, these are focused primarily on single measures whilst there are currently no comprehensive and systematic evaluations across NbS, BfS, and, in particular, CBS which limits scope in measure selection and the design of lake restoration programmes, globally.

To support the adoption of novel restoration strategies in current lake basin management, aggregated information on the availability, feasibility, efficacy and profitability of innovative solutions is needed. In this review, we aim to discover and document the range and potential of emerging restoration innovations available to protect and restore lakes. Innovative solutions, herewith defined as new approaches (inventions) or measures developing the applicability, performance and sustainability of existing solutions, were mapped by reviewing existing peer-reviewed literature. Information was searched on the implementation, applicability, costs, and impacts of preventative external (or 'catchment focused') solutions for improved water protection, and internal (or 'in-lake focused') measures for enhanced lake restoration with special emphasis on NbS, BfS and CBS. To evaluate the additional value of these innovative solutions to current lake basin management, their efficacy was evaluated in relation to co-benefits associated with several EU policy goals (e.g., Biodiversity Net Gain, Pollution Reduction, WFD, Green Deal, Zero Pollution) following an evaluation framework developed by Carvalho et al. (2024). Transformation of lake basin management requires enhanced knowledge on both good and bad practices as well as capacity building. Hence, we also point out innovations with no proven efficiency that should be avoided.

2. Methods

To review existing peer-reviewed literature, the search engines Web of Science (https://apps.webofknowledge.com), Bielefeld Academic Search Engine (BASE, https://www.base-search.net/), Scopus (https://www.scopus.com), Aquatic Sciences and Fisheries Abstracts (ASFA https://www.fao.org/fishery/en/openasfa) and Google Scholar (https://scholar.google.com) were used with a defined scope. In each of these five search tools, we used a search string based on a set of terms related to lake restoration and protection combined with innovations, nature-based or circular solutions using the Boolean operators "OR" and "AND". Additionally, the symbol "*" was used as a suffix for terms likely to have multiple endings (e.g., the term restor* will capture restoration, restoring, restore). The following string was used to explore each of the five search engines: "lake restor*" OR "lake manage*" OR "lake protect*" AND "innovati*" OR "nature?base*" OR "circular*". The last access date for the searches was 12 December 2024.

The systematic literature search returned 1579 entries after removing duplicates. Manual screening took place in two stages. Relevance of each publication was first evaluated based on abstracts and titles with the following criterion: does it include a technical/NbS/CBS/BfS solution for lake restoration or water protection? (Yes/No/Unclear). The title and abstract screen yielded 527 appropriate entries for full-text screening. The same criterion omitting the option "unclear" was applied for full-text screening accompanied by two new criteria: 1) does it include concrete implementation of a technical/NbS/CBS/BfS solution for lake restoration or water protection? (Yes/No) and 2) does it include empirical data to monitor impacts of the solution? (Yes/No). Subsequently, conceptual studies without concrete implementation of measures together with studies solely focusing on modelling were excluded. Additionally, review papers were excluded from data extraction and were used as background studies instead. Cohen's Kappa (Cohen, 1960; Côté et al., 2013) was used to compare the consistency in inclusion/exclusion assessment in full-text screening between two individuals who both screened the same batch of 26 papers (representing 5% of all the entries in the full-text screening phase). Both individuals came up with the exact same conclusion on the inclusion/exclusion of these publications, and we concluded that our findings were unlikely to have been biased by differences between the individuals conducting the assessment. The full-text screening resulted in 208 appropriate literature entries for data extraction.

During the data extraction, information on the implementation, applicability and constraints, costs, and impacts of water protection and restoration methods were compiled from all the studies included. Where applicable, i.e. enough information for evaluation was provided, impacts and additional value of measures described were assessed in relation to several policy relevant indicators (e.g., lake ecological or chemical status, biodiversity net gain, greenhouse gas emission reduction, flood and drought resilience, human health and wellbeing) following the framework by Carvalho et al. (2024). Additionally, the technology readiness level (TRL) of innovations from scale TRL 1 (basic principles observed) to TRL 9 (actual system proven in operational environment) as defined in the Horizon 2020 framework program were assessed based on the information provided in the publications. The strength of evidence was considered when assessing the TRLs. Consequently, approaches supported by only a few years of limited monitoring data were assigned lower TRLs than those with demonstrated proof of concept at operational scales and validated through extensive, long-term datasets.

To visualize the distribution and development timeline of innovative lake restoration solutions, “ggplot 2”, “rnaturalearth”, and “tidyverse” in R v4.4.2 (https://www.r-project.org/) were used.

3. Spatial coverage of the reviewed innovations

No restrictions on the geographical location or the time frame for the studies were set in the literature search. Subsequently, all continents except Antarctica were represented in the reviewed research. Most of the reviewed studies were based in Europe, Asia, and North America. Specifically, when all the case studies on laboratory, mesocosm, catchment and in-lake scales were considered, case studies from the USA, China, Poland, Finland and the Netherlands were the most represented (Fig. 1). In general, the number of publications was highest in countries with higher Gross Domestic Product (GDP) (e.g., USA, Europe), indicating higher resources for scientific research. Additionally, studies based in countries with high policy focus for water resources were most represented (e.g., China, Australia, Europe).

Focusing on lake-scale experiments only, 128 different lakes were identified, and innovations were most frequently applied to lakes in Poland, USA, China and Denmark (Fig. 2). From these studies, Chinese, Danish, and Polish research mainly had focus on in-lake measures, such as algal harvesting, aeration, biomanipulation, P inactivation, macrophyte re-establishment and sediment removal (e.g., Lauridsen et al., 2003; Chen et al., 2017; Dunalska et al., 2018; Chao et al., 2022; Haasler et al., 2023; Chmiel et al., 2024; Haasler et al., 2024), whereas external measures such as catchment water management, stormwater basins and floating treatment wetlands (FTWs) (e.g., Liebl, 2010; Hartshorn et al., 2016; Kuster et al., 2022; Adhikari et al., 2023; Na Nagara et al., 2024) were the main focus (nearly 70%) of USA studies.

4. Temporal coverage of the reviewed innovations

The number of published studies on different types of innovations in our dataset has increased markedly during the last decades (Fig. 3). The oldest solutions that we labelled as NbS, BfS or CBS date back to the late 1990s, when studies on the protection and re-establishment of macrophytes as a means to reduce bank erosion and to support lake recovery first appeared in the reviewed literature (Coops et al., 1996; Søndergaard et al., 1996), and when the re-use potential of aluminum hydroxide precipitates originating from urban stormwater management was first discussed (Livingston, 1999).

During the 2000s, published studies on technical innovations, that we could not consider as NbS, BfS or CBS categories, focused on P inactivation and aeration (Dixit et al., 2007; Churchill et al., 2009; Moore and Christensen, 2009; Moore et al., 2009; Moore et al., 2012), whereas NbS and BfS were focused on biomanipulation (Ventelä and Lathrop, 2005; Perrin et al., 2006; Jeppesen et al., 2007), macrophyte harvesting, protection and re-establishment (Lauridsen et al., 2003; Ventelä and Lathrop, 2005; Lövstedt and Larson, 2010), constructed wetlands (CWs) and wetland re-establishment (Macquarie and Etra, 2001; Gunes and Tuncsiper, 2009). Also, sediment reuse as an innovative CBS approach for improved erosion control and lake shoreline protection first appeared in scientific literature in the early 2000s (Comoss et al., 2002).

Since the 2010s, the number of innovations and measures that can be labelled as NbS, BfS and CBS have substantially increased in lake restoration research (Fig. 3). Regarding NbS, this is expected given when the concept was first defined in the literature (Cohen-Shacham et al., 2016) and because it was included as an alternative search term (see Methods). In addition to biomanipulation and macrophyte management (Kirkkala, 2014; Van Zuidam and Peeters, 2015; Qin et al., 2019), floating treatment wetlands (FTWs), artificial reefs, phytoremediation and green infrastructure such as stormwater basins started to receive increased attention as potential NbS and BfS in the 2010s (Liebl, 2010; Santos et al., 2011; Zhang, 2012; Honour et al., 2013; Yamamoto et al., 2014; Henny and Kurniawan, 2019; Henny and Kurniawan, 2019b). Studies on sediment removal and P recovery from the water column as potential CBS were increasingly published (de Vicente et al., 2010; de Vicente et al., 2011; Funes et al., 2016; Álvarez-Manzaneda and De Vicente, 2017; Funes et al., 2017; Del Arco et al., 2018; Funes et al., 2018; Álvarez-Manzaneda et al., 2019; Alvarez-Manzaneda et al., 2019; Sittoni et al., 2019), as well as on the re-use potential of algal and fish biomass (Chen et al., 2017; Ruokonen et al., 2019). Also, studies on algaecides, P inactivation and sediment capping representing technical innovations to control internal loading and alleviate the symptoms of eutrophication were published (e.g., van Oosterhout and Lürling, 2011; Özkundakci et al., 2011; Pan et al., 2012a; Lürling and van Oosterhout, 2013; Meis et al., 2013; Calomeni et al., 2015; Geer et al., 2016; Jersak et al., 2016; Spears et al., 2016; Waajen et al., 2016; Waajen et al., 2017; Bishop et al., 2018; Gibbs and Hickey, 2018; Sinha et al., 2018; Pan et al., 2019).

During the 2020s, number of published literature on measures designed to deliver on both NbS and BfS outcomes such as two-stage channels (TSCs) (Västilä et al., 2021; Huttunen et al., 2024; Västilä and Jilbert, 2025) and continuous cover forestry (CCF) for improved pollution control while supporting catchment biodiversity has increased (Mason et al., 2021; Hertog et al., 2022; Palviainen et al., 2022; Härkönen et al., 2023; Miettinen et al., 2025; Sarkkola et al., 2025). Additionally, soil amendments as potential catchment focused CBS started to increasingly occur in scientific studies (Rasa et al., 2021; Norberg and Aronsson, 2022; Uusi-Kämppä et al., 2022; Ekholm et al., 2024; Ollikainen et al., 2024), and hypolimnetic withdrawal and treatment systems (HWTS) as potential in-lake focused CBS (Silvonen et al.,

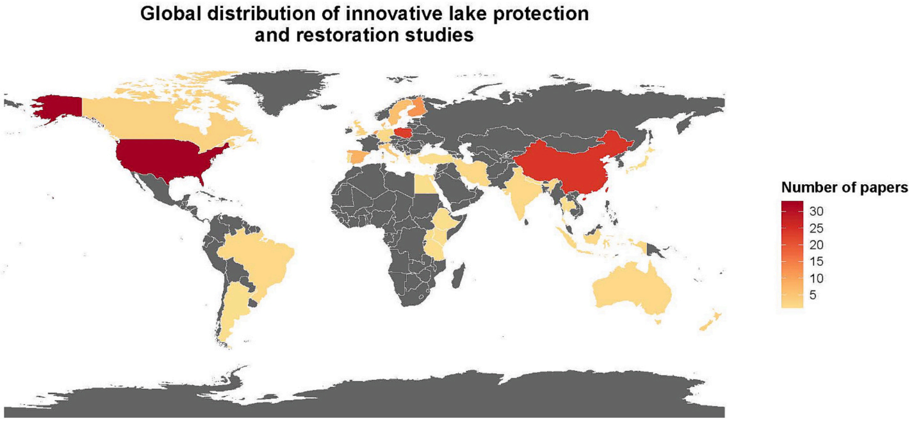

Fig. 1. Global distribution of reviewed innovative lake protection and restoration studies at laboratory, mesocosm, catchment and lake scales. Grey colour indicates countries with no reviewed studies.

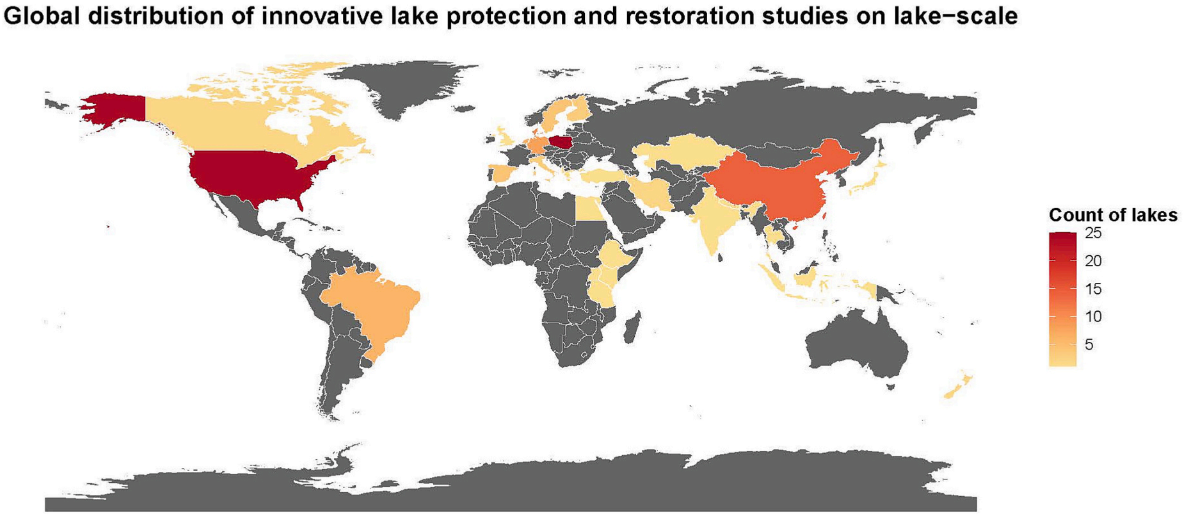

Fig. 2. Global distribution of reviewed innovative lake protection and restoration studies at whole-lake scale. Grey colour indicates countries with no reviewed studies.

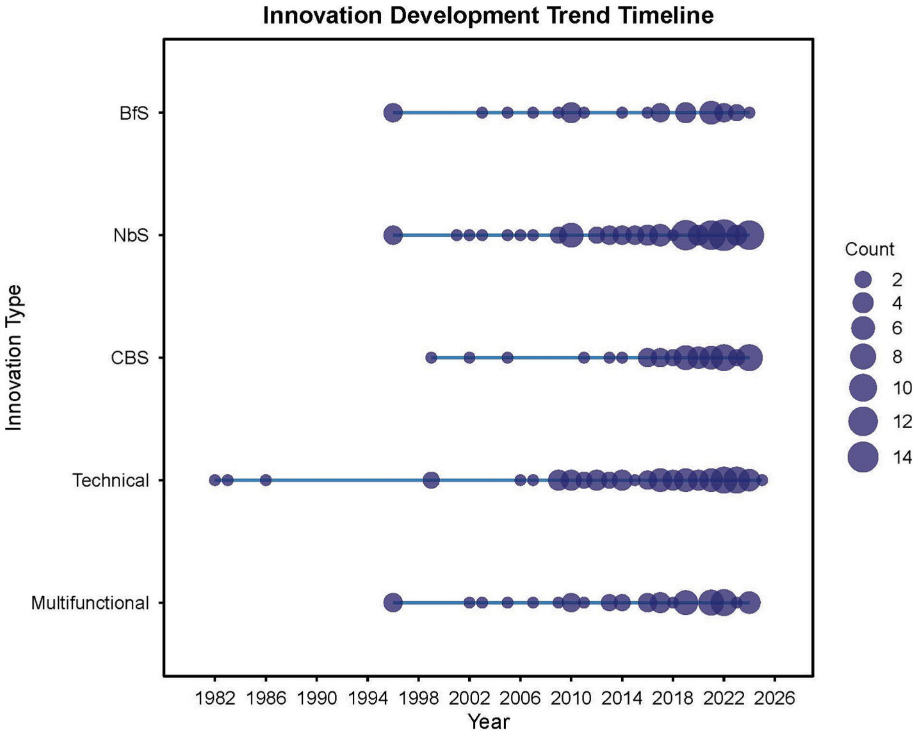

Fig. 3. Timeline of innovative lake protection or restoration solutions in reviewed literature. The solution categories are nature-based solutions (NbS), circular blue-economy solutions (CBS), biodiversity-focused solutions (BfS) and technical solutions that do not directly fall within the other categories. Additionally, the multi-functional category refers to solutions that combine elements of BfS, CBS, NbS and technical innovations.

2021; Silvonen et al., 2022; Silvonen et al., 2023; Tammeorg et al., 2024a).

5. In-lake focused innovations for advanced lake recovery

The reviewed 208 publications represented a total of 26 different clusters of emerging technologies and approaches (Tables 1-2). From the reviewed publications, 125 (60%) dealt with in-lake measures for managing internal loading and reducing the symptoms of eutrophication. External solutions for improved water protection, pressure reduction and management actions on catchment scales were considered in 70 (34%) of the reviewed studies. The remaining 13 publications (6%) considered combined solutions on catchment and in-lake scales.

Most of the in-lake innovations reviewed were novel applications of well-established methods such as, for instance, different approaches of aeration (e.g., Podsiadłowski et al., 2018; Osuch et al., 2020; Shi et al., 2021; Łopata et al., 2023; Chmiel et al., 2024), P inactivation (e.g, van Oosterhout and Lürling, 2011; Dithmer et al., 2016b; Waajen et al., 2016; Zamparas and Kyriakopoulos, 2021; Grochowska et al., 2023; Kang et al., 2023) and sediment removal (e.g., Marlin, 1999; Braga et al., 2024; Haasler et al., 2024; Huo et al., 2024; Tammeorg et al., 2024a), many of which with estimated TRLs of 6-9 and technologies demonstrated at operational scales.

Several in-lake methods could be labelled as multifunctional

Table 1

Objectives, applicability and constraints, range of costs, benefits and disadvantages of the reviewed in-lake restoration innovations. The solution categories here defined are nature-based solutions (NbS), circular blue-economy solutions (CBS), biodiversity-focused solutions (BfS) and technical solutions that do not directly fall within the other categories. All the costs expressed in the original publications are here converted to € and the value of 2025. The technology readiness level (TRL) of innovations from scale TRL 1 (basic principles observed) to TRL 9 (actual system proven in operational environment) as defined in Horizon 2020 framework program were assessed by authors based on the information provided in the reviewed publications.

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
Aeration | Oxygenation (Technical, BfS; 6-9)	Prevention of oxygen depletion | Reduction of internal P loading	Deep, thermally stratifying lakes | Commercial oxygen reactors and bubble-bloom diffusers widely available | Results only during intervention, requires continuous maintenance | Inadequate as a sustainable solution, unless renewable energy supply can be utilised	Installation, €1,200–20,000 per ha, operation €480–5,000 per ha annually	Potentially reduced internal P loading | Potentially increased nitrification-denitrification processes in the water-sediment interface and improved N removal | Potentially reduced proliferation of HABs | Improved oxygen conditions to support fish populations, benthic invertebrates and zooplankton	Negligible impacts on water column nutrient concentrations | Increased hypolimnetic temperature and turbulence | Disbenefits for organic matter mineralisation, zooplankton and cold-stenothermic fish | Potential benefits for turbulence-tolerant cyanobacteria, mixed results | High energy demand	(Dixit et al., 2007; Brzozowska and Gawrońska, 2009; Liboriussen et al., 2009; Holmroos et al., 2016; Grochowska et al., 2017; Podsiadłowski et al., 2018; Dondajewska et al., 2019a; Osuch et al., 2020; Ruuhijärvi et al., 2020; Shi et al., 2021; Łopata et al., 2023; Mehdizadeh et al., 2023; Salonen et al., 2023; Sellergren et al., 2023; Chmiel et al., 2024)
Algaecides (Technical; 8-9)	Killing cyanobacteria, eradicating algal blooms	Surface waters with HABs | Requires suitable chemicals with many of them copper-based or hydrogen, calcium and sodium carbonate peroxides | Proper dosage always to be determined in laboratory | Short-term and rapid intervention | Requires regular repetition. Some products are prohibited (legal constraints)	Not provided	Relatively rapid decay of cyanobacteria with no residue in case of peroxides | With optimal dosage, some chemicals (e.g., H_2O_2) rather selective against cyanobacteria	Not tackling excess nutrients | Possible negative impacts for non-target planktonic organisms especially with copper-based products or generic herbicides | Potential cyanobacterial cell damage, release of toxins into the water and accumulation of chemicals into the sediment with copper-based products | Rapid breakdown of H_2O_2 affecting its efficiency	(Jančula and Maršálek, 2011; Matthijs et al., 2012; Calomeni et al., 2015; Geer et al., 2016; Matthijs et al., 2016; Bishop et al., 2018; Sinha et al., 2018; Lürling et al., 2020a; Sukenik and Kaplan, 2021; Kang et al., 2022a; Kang et al., 2022b; Weenink et al., 2022; Piel et al., 2024; Yun et al., 2024)
Algal harvesting (CBS; 7-8)	Reduction of cyanobacterial biomass	Industrial wastewater or drinking water treatment with closed systems and optimised harvesting efficiency | Eutrophic lakes, reservoirs or retention ponds | Requires suitable harvesting devices and technologies | Potentially high energy demand | Scalability potential to whole-lake scale remains uncertain	Not provided	Reduced algal biomass, toxins and other contaminants | Potentially improved water quality for recreational activities | Potential for reducing internal loading | Potential for using harvested algae as source of food, feed, biofuels, pharmaceuticals or alternative substrate in biotechnological processes | Potential for simultaneous elimination of other harmful compounds (e.g. PCBs)	Possible negative impacts for non-target planktonic organisms | Possible food or feed applications require toxin removal	(Molina Grima et al., 2003; Vijayakumar and Menakha, 2015; Chen et al., 2017; Pandhal et al., 2018; Singh and Patidar, 2018; Ali et al., 2020; Macário et al., 2021; Napiórkowska-Krzebietke and Łuczyński, 2022; Prabha et al., 2022; Macário et al., 2023)
Artificial reefs (NbS, BfS, CBS; 3-9)	Mimic natural habitats and restore habitat complexity | Provide shelter, feeding, and breeding sites for fish, invertebrates and waterfowl	Lakes where natural substrate and/or aquatic vegetation have been lost due to human impact | Lakes with high water level fluctuation | Requires suitable construction material, potential for using recycled materials | Long-term impacts understudied	Not provided	Improve fish and local invertebrate richness and abundance | May reduce local phytoplankton biomass and cyanobacterial abundance | Support breeding waterfowl	Negligible impacts on water quality	(Bolding et al., 2004; Ostendorp, 2008; Nummi et al., 2013; Yamamoto and Freitas, 2014; Zhu et al., 2021)
Biomanipulation (NbS, CBS, BfS; 9)	Removal of excess P | Reduction of internal loading |	From small to large, shallow to deep lakes with dense fish	Up to €1,000 per ha annually	Reduction of cyanobacterial blooms | Reduction of nutrients	Overfishing of the target species possible | Harm to non-target fish and	(Hansson et al., 1998; Søndergaard et al., 2000; Benndorf et al.,

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Table 1 (*continued*)

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
	Support for the healthy functioning of the food web	populations | Intense removal of planktivorous and benthivorous fish required | Annual repetition often needed for maintenance		with fish biomass | Reduced sediment resuspension and internal P loading | Support for indigenous fish populations | Benefits for waterfowl due to reduced food competition | Circular economic co-benefits if the removed fish can be used as food, feed or biogas production	potentially waterfowl from bycatch	2002; Mehner et al., 2002; Ventelä and Lathrop, 2005; Perrin et al., 2006; Søndergaard et al., 2007; Jeppesen et al., 2012; Anttila et al., 2013; Triest et al., 2016; Urrutia-Cordero et al., 2016; Qin et al., 2019; Fox et al., 2020; Ruuhijärvi et al., 2020; Salonen et al., 2020; Sarvala et al., 2020; Sellergren et al., 2023; Tammeorg et al., 2024a)
Effective micro-organism technology EM (Technical; 0-1)	Suppress cyanobacterial production via competitive exclusion	Not applicable to lakes | No proven efficiency	Not provided	NA	No proven efficiency on phytoplankton control | Elevated nutrient concentrations	(Higa, 1998; van Vliet et al., 2006; Lürling et al., 2010; Dondajewska et al., 2019b; Lürling and Mucci, 2020; Tomczyk et al., 2024; Zakarya et al., 2025)
Hypolimnetic withdrawal and treatment systems HWTS (Technical, CBS; 3-8)	Removal of excess P from lakes during stratification | Reduction of internal P loading	Deep, thermally stratifying lakes | Withdrawal rate to be adjusted to not compromise stratification | Requires periodic replacement of sorption beds and regular maintenance of the filtration system | Requires constant energy supply during operation | Only short-term, small-scale studies available, applicability not evaluated on a whole lake-scale	€10,000–20,000 per ha initial costs for the construction | Operational costs not provided	May reduce lake water P concentration in longer-term | Prevents negative downstream water quality impacts associated with conventional HW | Potential for P reuse if extracted from the precipitate | Potential for energy recovery	High energy demand | Consumes more time and resources than the conventional HW | No impacts on N removal unless combined with constructed wetlands and/or reactive media for N | Risk of epilimnetic P increment due to HWTS effluent	(Dunalska et al., 2007; van der Hoek, 2011; Bormans et al., 2016; Nürnberg, 2020; Łożyńska et al., 2021; Silvonen et al., 2021; Silvonen et al., 2022; Silvonen et al., 2023; Härkönen et al., 2024; Tammeorg et al., 2024a)
Littoral and shoreline protection, island habitat creation (NbS, BfS, CBS; 7-9)	Restoration of degraded littoral areas and land-water transition zones | Creation of littoral habitats and land-water transition zones	From small to large lakes where natural littoral areas and land-water transition zones have been lost due to human impact | Requires suitable construction material, potential for using recycled materials	Up to €780,000 per constructed island ha (Marker Wadden)	Support for lacustrine food webs | Increased abundance of macroinvertebrates | Support for spawning fish | Support for breeding waterfowl | Support for erosion control | Potentially improved nutrient cycling between land and water	Temporal degradation of water quality, macroinvertebrates and macrophytes within the construction site	(Comoss et al., 2002; Brauns et al., 2007; Panagopoulos and Dimitriou, 2020; Ijff et al., 2021; Jin, 2021; Ruswick et al., 2021; van Leeuwen et al., 2021; Meerhoff and de los Ángeles González-Sagrario, 2022; Stouten et al., 2022; van Leeuwen et al., 2023)
Macrophyte harvesting (NbS, BfS, CBS; 9)	Control nuisance macrophyte growth | Removal of invasive macrophyte species | Restore lost recreational amenities	Lakes with dense macrophyte stands | Requires repetition	Up to €250 per ha annually	Controlling invasive species | Improved recreational amenities | Improved reproduction success of waterfowl via increased share of open water areas | Potential for using harvested biomass for energy production, feed, insulation, construction	Removal of submerged species may lead to algal blooms and negatively affect planktonic and benthic communities | Negligible impact on water nutrient concentration | Potential initial increase in CO_2 emissions due to loss of photosynthesis	(Muñoz Escobar et al., 2011; Xu et al., 2014; Bajwa et al., 2015; Colbers et al., 2017; Sarvala et al., 2020; Harpenslager et al., 2022; Thiemer et al., 2023; Nega et al., 2024; Olden, 2024; Shi et al., 2024; Tammeorg et al., 2024a; Zoppi et al., 2024)
Macrophyte protection and	Restoration of degraded macrophyte stands	Lakes with suppressed macrophyte stands |	Not provided	Improved water clarity | Restored habitat complexity | Increased	The survival rate of transplanted macrophytes varies | Waterfowl can	(Coops et al., 1996; Søndergaard et al., 1996; Lauridsen

(continued on next page)

Table 1 (*continued*)

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
re-establishment (BfS, NbS; 3-5)		Transplantation process laborious		refugia for zooplankton | Increased habitats and refugia for macroinvertebrates and young fish | Reduced erosion risk | Reduced resuspension	significantly suppress macrophyte regrowth	et al., 2003; Lövstedt and Larson, 2010; Marion and Orth, 2010; Van Zuidam and Peeters, 2015; Wang et al., 2021; Magri et al., 2023; Castelnuovo et al., 2024; Han et al., 2024)
Phosphorus inactivation (Technical, BfS, CBS; 3-9)	Reduce water P concentration | Reduce sediment P release | Inhibit cyanobacterial production	Requires usage of different coagulants | Several well-studied and scientifically validated coagulants commercially available | Sequential application of different coagulants may improve efficiency while reducing environmental harm | Proper dosage always to be determined site-specifically in laboratory | Result longevity varies, may require repetition | Environmental permit country-specifically required	€60–24,000 per ha applied | Depend on the doses and chemicals used	Rapid reduction of water column P concentration | Potential emergency measure for inhibiting HABs | Reduced bioavailability of sediment P | Potentially increased La-P pools in LMB treated sediments | Potentially increased abundance of submerged macrophytes | Potential for using drinking water treatment residue as coagulant	Potential decline of water column pH with some of the coagulants | Potentially increased turbidity during application | Potential temporal collapse of zooplankton | Potential fish kills | Potential harm for mussel reproduction and larval development | Potential negative impacts on zoobenthos | Potential harm for charophytes | Potential increase of nitrous oxide (N_2O) emissions via altered N cycling	(Moore and Christensen, 2009; Egemose et al., 2010; van Oosterhout and Lürling, 2011; Lürling and Faassen, 2012; Immers et al., 2013; Lürling and van Oosterhout, 2013; Meis et al., 2013; Nogaro et al., 2013; Moos et al., 2014; Zamparas and Zacharias, 2014; Dithmer et al., 2016a; Huser et al., 2016; Spears et al., 2016; Waajen et al., 2016; Wang et al., 2016; Dunalska et al., 2018; Funes et al., 2018; Lürling et al., 2020a; Rybak et al., 2020; Sarvala et al., 2020; van Oosterhout et al., 2020; Zamparas et al., 2020; Kuster et al., 2021; Lin et al., 2021; Yin et al., 2021; Zamparas and Kyriakopoulos, 2021; Drewek et al., 2022; Kang et al., 2022b; Kuster et al., 2022; Liu et al., 2022; Zhan et al., 2022; Grochowska et al., 2023; Kang et al., 2023; Sarvala and Helminen, 2023; Sellergren et al., 2023; Berthelsen et al., 2024; Zhang et al., 2024)
Phosphorus adsorbents (Technical, CBS; 3-5)	Reduce water P concentration | Recover P from water column	Requires usage of suitable adsorbents such as magnetic nano- or micron-sized particles (MPs) with Fe; calcium carbonate-based products; or La-modified adsorbents | Scalability potential to whole-lake scale remains questionable	Not provided	Successful P removal from aqueous solutions in laboratory conditions | Potential for P reuse if extracted from the absorbent	Potential negative impacts on zooplankton | Potentially increased turbidity during application | Adsorbent preparation may require excessive amounts of water and energy in addition to chemicals	(de Vicente et al., 2010; de Vicente et al., 2011; Merino-Martos, 2014; Funes et al., 2016; Álvarez-Manzaneda and De Vicente, 2017; Funes et al., 2017; Del Arco et al., 2018; Funes et al., 2018; Álvarez-Manzaneda et al., 2019; Alvarez-Manzaneda et al., 2019; Burska et al., 2019; Xia et al., 2020; Zamparas et al., 2020; Del Arco et al., 2021; Pryputniewicz-Flis et al., 2021; Xu et al., 2022; Chen et al.,

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Table 1 (*continued*)

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
						2025; Tan et al., 2025)
Sediment capping (Technical; 6-8)	To minimize release of nutrients or contaminants from the sediment by inserting an artificial barrier	Small lakes or selected shallow lake areas | Requires usage of suitable capping material (e.g. sand, silt, clay, calcite, activated carbon, biochar, zeolite, organoclay) | Potential for adding oxygen to sediment-water interface when introducing oxygen nanobubble (NB) carriers | Repetition potentially required | Environmental permit country-specifically required	Not provided	Up to >90% P release reduction both in laboratory and lake-scale studies | Some of the capping materials (e.g., ceraicite, dolomite, zeolite) also control N release with >90% potential reduction | Potential reduction of CH_4 and N_2O emissions when introducing oxygen NB carriers	Temporal negative impacts on benthic macroinvertebrates | Mixed results on potential ecotoxicological impacts | Contaminants remain in place posing a risk of contaminant loss, re-exposure, or disturbance after capping | Most studies short-term, spanning <1 yr monitoring	(Özkundakci et al., 2011; Pan et al., 2012a; Jersak et al., 2016; Vlassopoulos et al., 2017; Gibbs and Hickey, 2018; Zhang et al., 2020; Waters et al., 2022; Ali et al., 2023; Lundmark et al., 2023; Sunaryani et al., 2023; Lürling et al., 2024)
Sediment removal (NbS, CBS; 7-9)	Decrease internal P loading | Increase the lake depth for recreational purposes	Shallow lakes with high internal loading | Require dewatering and proper disposal of sediment | Geotubes provide possibilities for handling and dewatering of sediment on site | Environmental permit country-specifically required	€9–50 per m^3 sediment removed	Long-term water quality benefits if the amount and depth of sediment removed is sufficient | Support for the recolonization of submerged macrophytes if turbidity is reduced due to the intervention | Potentially increased recreational amenities | Provides circular economic co-benefits if sediment can be reused in fertilization or construction | Potential for using dredged sediment to create habitats and support biodiversity	Increased turbidity, nutrient and heavy metal concentrations during implementation | Risk of harmful substance resuspension during implementation | Negative temporal impacts on macroinvertebrates | Negative temporal impacts on fish spawning habitats | Laborious handling of sediment | Improper handling and disposal may result in intervention failure	(Pierce, 1970; Peterson, 1982; Marlin, 1999; Cooke et al., 2005; Björk et al., 2010; Harmsen et al., 2012; Phillips et al., 2015; Bormans et al., 2016; Phillips et al., 2016; Sittoni et al., 2019; Lürling et al., 2020b; Abell et al., 2022; Kang et al., 2023; Zhang et al., 2023; Cao et al., 2024; Haasler et al., 2024; Lürling et al., 2024; Simoni et al., 2024; Fořt et al., 2025; Härkönen et al., 2025; Wan et al., 2025)
Ultrasonication (Technical; 0-1)	Suppress cyanobacterial production via cell disruption	Not applicable to lakes | No proven efficiency	Not provided	NA for lake-scale. Reduced cyanobacterial abundance and biomass under small-scale laboratory conditions	No proven efficiency in cyanobacterial control on lake-scale | Negative impacts on non-target planktonic organisms | No impact on nutrient concentration	(Jong Lee et al., 2000; Tang et al., 2004; Joyce et al., 2010; Wu et al., 2011; González-Fernández et al., 2012; Rajasekhar et al., 2012; Wu et al., 2012; Purcell et al., 2013a; Purcell et al., 2013b; Lürling and Tolman, 2014; Wang et al., 2014; Lessmann and Nixdorf, 2015; Lürling et al., 2016b; Park et al., 2017; Lürling and Mucci, 2020; Kibuye et al., 2021; Vaughan et al., 2023; Tischer et al., 2025; Van Wichelen et al., 2025)

measures combining elements from NbS, CBS or BfS. For instance, biomanipulation as a NbS (Triest et al., 2016) can also be considered BfS when implemented to primarily support waterfowl biodiversity in lakes (Fox et al., 2020) or even a CBS if fish biomass is removed and sold for economic gain (Tammeorg et al., 2024a). Many technical P inactivation solutions are focused on reducing the availability of nutrients, and, therefore, have the potential for providing longer-term ecosystem-level benefits via e.g. re-establishment of natural flora (van Oosterhout et al., 2022). In this way, they could also be considered as a BfS in cases where their potential negative consequences on biodiversity (e.g. toxicity) can be overcome by proper coagulant selection, optimized timing and dosage. To reduce the negative impact of in-lake P inactivation measures on biodiversity, more environmentally friendly materials and application procedures have been developed and commercialized, such as novel modifications of conventional lanthanum (La)-modified bentonites (LMBs) with estimated TRL of 7 (Wang et al., 2024; Zhang et al., 2024).

Table 2

Objectives, applicability and constraints, range of costs, benefits and disadvantages of the reviewed external lake protection innovations. The solution categories here defined are nature-based solutions (NbS), circular blue-economy solutions (CBS), biodiversity-focused solutions (BfS) and technical solutions that do not directly fall within the other categories. All the costs expressed in the original publications are here converted to € and the value of 2025. The technology readiness level (TRL) of innovations from scale TRL 1 (basic principles observed) to TRL 9 (actual system proven in operational environment) as defined in Horizon 2020 framework program were assessed by authors based on the information provided in the reviewed publications.

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
Advances in wastewater treatment (NbS, CBS; 1-9)	Reduce external loading	Combination of physical, biological and chemical processes for pollutant removal from sewage | Treatment techniques dependent on the specific features of wastewaters | NbS such as selenium-enriched microalgae and constructed wetlands applicable to complement industrial treatment technologies and to treat combined sewer overflows | Potential for nutrient recovery with source separation systems but their implementation in urban areas would require an entire system change of the wastewater treatment sector	Not provided. Highly case- and pollutant-specific	Reduced P and N loading to surface waters | Potential for reusing the treated wastewaters and the recovered nutrients	High energy and space demand | Generated sludge needs special utilization (e.g. composting or burning) if treated with grey infrastructure | Reuse of source separated human urine in fertilisation poses a risk of field acidification	(Sonune and Ghate, 2004; Wielemaker et al., 2018; Malila et al., 2019; Botturi et al., 2020; Gukelberger et al., 2020; Rizzo et al., 2020; Lage et al., 2021; Li et al., 2021; Lehtoranta, 2022; Lehtoranta et al., 2022; Osmani et al., 2023; Dubey et al., 2024)
Catchment water management (NbS; 9)	Control discharge from the catchment | Reduce external loading	Catchments with high proportion of agricultural and forested areas | Combination of technical and nature-based solutions for flood management and water retention | Means for catchment water management include e.g., controlled drainage, no tillage, conservation of wetlands, establishment of water retention ponds, continuous cover forestry, targeted fertilization, winter cover crops and perennials | Measures applicable and adaptable to different scales and geographical locations | Controlled drainage requires careful technical design to be effective | Supportive policies and incentives crucial for implementation	Not provided	Improved flood and drought resilience | Reduced erosion risk | Decreased suspended sediment, TP and POC loads | Improved crop yields | Benefits for drinking water treatment with | May reduce the need for ditch network maintenance | Continuous cover forestry may reduce GHG emissions from drained peatland forests	Potential losses of field area with costs to landowners not fully compensated | Lower net revenue to forest owners with continuous cover forestry compared to conventional rotation management | Potentially higher spreading risk of tree stand root pathogens than in conventional rotation management | Potentially higher risk of damage to tree compared to conventional rotation management caused by more frequent harvesting with heavy off-road forest machinery	(Weatherbe and Sherbin, 1994; Withers and Jarvis, 1998; Sharpley et al., 2000; Oledn, 2001; Withers and Lord, 2002; McGahan et al., 2004; Zhou et al., 2005; Lamsodis et al., 2006; Dawson and Smith, 2007; Zhang et al., 2011; Schütz et al., 2012; Ramos et al., 2013; Macintosh et al., 2018; Nieminen et al., 2018; Vinten et al., 2019; Reilly et al., 2020; Mason et al., 2021; Nikraftar et al., 2021; Salla et al., 2021; Spicer et al., 2021; Staccione et al., 2021; Hertog et al., 2022; Palviainen et al., 2022; Härkönen et al., 2023; Robotham et al., 2023; Janatrostami, 2024; Kalman and Bene, 2024; Glass and Burgess, 2025; Miettinen et al., 2025; Sarkkola et al., 2025)
Constructed wetlands (NbS; 9)	Remove nutrients, heavy metals, and pollutants from runoff	Urban, agricultural and forested environments | Can be established in several design, e.g., as free water surface wetlands with sedimentation basins and macrophyte zones; horizontal sub-surface flow fields with a porous medium under the surface; vertical flow wetlands comprising of a flat bed of gravel and sand planted with macrophytes | Contribute to urban green-blue infrastructure | Usage of	Not provided	Cost-effective solution compared to traditional wastewater treatment plants | Reduced nutrient, heavy metal, organic compound and SS loads | Potential removal of pesticides | Potential removal of organic micropollutants and microplastics | Improved flood and drought risk resilience | Potential local biodiversity co-benefits for macroinvertebrates, fish, waterfowl and reptiles	Effectiveness reduced during cold season | Potential losses of land area	(Gunes and Tuncsiper, 2009; Vohla et al., 2011; Xie et al., 2012; Nowak et al., 2013; Vymazal, 2014; Wu et al., 2014; Morvannou et al., 2015; Vymazal and Březinová, 2015; Liquete et al., 2016; Dotro et al., 2017; Skrzypiec and Gajewska, 2017; Thangavel, 2017; Kasak et al., 2018; Vymazal and Dvořáková Březinová, 2018; Koskiaho and Puustinen, 2019; Stefanakis, 2019; Ji et al., 2020; Nguyen et al., 2020; Nivala et al., 2020;

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Table 2 (*continued*)

Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
		reactive media may improve purification efficiency | Applicable from warm to temperate and boreal zones | Requires sufficiently large areas with optimal spatial targeting				Rizzo et al., 2020; Ijff et al., 2021; Nguyen et al., 2021; Tao and Xiong, 2021; Djodjic et al., 2022; Kill et al., 2022; Kupiec et al., 2022; Mostafa et al., 2022; Sánchez-Almodóvar et al., 2022; van den Berg et al., 2022; Vymazal, 2022; Irvine et al., 2023; Rizzo et al., 2023; Schwammberger et al., 2023; Vassalle et al., 2023; Koukoura et al., 2024; Rochera et al., 2024; Sarti et al., 2024)
Inlet phosphorus inactivation (Technical; 7-9)	Remove P from runoff	Agricultural and urban catchments | Requires usage of different coagulants | Scientifically validated coagulants commercially available | Proper dosage always to be determined site-specifically in laboratory | Requires repetition | Environmental permit country-specifically required	Up to €1,600 per treated ha annually	Potentially reduced external loading via improved P retention in ditches and water protection structures | Potential subsidiary benefits from adsorption of P in the receiving lake water column | Potentially lower negative impacts to lake biota compared to whole-lake treatments	Success sensitive to dose and mixing | Requires repetition, application to be coincided with times of high external P loading | Flocs and solids may need to be collected in a settling basin prior to discharge of the treated water to the lake	(Livingston, 1999; Churchill et al., 2009; Mueller et al., 2015; Smith et al., 2016; Mueller et al., 2019; Kuster et al., 2022)
Floating Treatment Wetlands (FTWs), Floating Beds and vegetated rafts (NbS, BfS; 4-9)	Remove nutrients, heavy metals, and pollutants from runoff	Urban stormwater basins, urban and agricultural constructed wetlands | Contribute to urban green-blue infrastructure | Adaptable to deep to shallow conditions | Limited long-term monitoring | Also suggested for small lakes but the scalability potential remains questionable | Anchoring and wave exposure are challenges | Some setups only tested on laboratory scales	Not provided	Potentially improved nutrient and heavy metal removal via phytoremediation | Improved local macroinvertebrate, fish and waterfowl diversity | Flood buffering | Aesthetic and recreational value | Potential for GHG reduction | Urban amenity enhancement	Plant nutrient uptake performance varies by season | Small-scale units with limited effectiveness, impact on water quality can be negligible	(Weragoda et al., 2010; Wang and Sample, 2011; Headley and Tanner, 2012; Pan et al., 2012b; Borne et al., 2015; Chang, 2016; Hartshorn et al., 2016; Tao et al., 2017; Vlassopoulos et al., 2017; Henny and Kurniawan, 2019; Henny et al., 2019; Colares et al., 2020; Ozan and Yilmazer, 2020; He et al., 2022; Rodrigues et al., 2022; Lundmark et al., 2023; Nuruzzaman et al., 2023; Schwammberger et al., 2023; Vo et al., 2023; Batista et al., 2025)
Permeable reactive barriers (NbS, CBS; 3-7)	Nutrient and pollutant removal from groundwater or surface runoff	Underground technological solutions installed *in situ* to pre-treat contaminated groundwater | Includes a wall filling with reactive material perpendicular to the potential trajectory of the contaminated water | Industrial catchments | Potential for treating agricultural runoff but scalability potential remains questionable	Not provided	Possibilities for reusing natural plant waste materials as a filling material for reactive barriers	Complicated management and replacement of reactive media	(Blowes et al., 1997; Phillips, 2009; Bednarek et al., 2010; Gillham et al., 2010; Izydorczyk et al., 2013; Bus et al., 2019; Frątczak et al., 2019; Song et al., 2021)
Restoration of peatlands and wetlands (NbS; 9)	Improve water retention | Restore degraded habitats	Requires rewetting drained peatlands, or re-establishment of former wetlands | Can also be conducted by ditch diversion to partially dried peatlands | Potential for reintroducing NbS ecosystem engineers such as beavers	Up to M€3.6 per ha	Reduced nutrient export in longer term | Improved carbon sequestration and climate protection potential | Improved flood and drought risk management | Increased biodiversity	Risk of increased initial export of nutrients and organic carbon | Limited knowledge on water quality impacts of ditch diversion	(Macquarie and Etra, 2001; Comoss et al., 2002; Lamsodis et al., 2006; Hoffmann and Baattrup-Pedersen, 2007; Bonn et al., 2016; Koskinen et al., 2017; Law et al., 2017; Juutinen et al., 2020; Zou et al., 2022; Alamenciak et al., 2023; Härkönen et al., 2023; Pendea et al., 2023; Granqvist, 2024)

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Solution (Category; TRL)	Objective	Applicability and constraints	Range of costs	Benefits	Disadvantages	References
Sediment interceptors and sediment traps (Technical, NbS, CBS; 5-9)	Reduce sediment and pollutant loads from runoff	Urban and agricultural catchments with high sediment transport | Installed at inflows and function by trapping suspended solids through gravity-based separation, settling mechanisms or by geotextile silt fences | Applicable to small and large lake inflows | Require frequent maintenance and removal of accumulated material | Effectiveness can vary with flow regime	Not provided	Moderate efficiency in reducing suspended solid and nutrient loads | Low areal footprint and scalable design	May require frequent maintenance | Effectiveness can vary with flow regime	(MacPherson, 2006; Chang et al., 2010; He et al., 2014; Kumar et al., 2019; Kupiec et al., 2022; Smith and Muirhead, 2024)
Soil amendments (CBS; 7-9)	Reduce P leaching from agricultural soils	Agricultural fields | Requires usage of suitable reactive media, e.g. structure lime, limestone, pulp mill sludge, autoclaved aerated concrete, zeolite, biochar | Gypsum suitable to marine catchments only, not to lake catchments	Not provided apart from gypsum, for which €257 per ha	Reductions of up to ~25-60% in phosphate and total phosphorus, and suspended sediment loads at field tests | Reduced erosion risk from the treated field area | Improved soil structure | Potential benefits to crop yields | No field losses to farmers | Many reactive media originate from recycled sources	High CO_2 emissions for structure lime from pristine materials | Catchment-scale reductions require treating large share of fields | Performance of reactive media may decrease over years | Gypsum not suitable on lake catchments as it contains sulphate	(Svanbäck et al., 2014; Bus et al., 2019; Ollikainen et al., 2019; Ollikainen et al., 2020; Rasa et al., 2021; Norberg and Aronsson, 2022; Uusi-Kämppä et al., 2022; Ekholm et al., 2024; Ollikainen et al., 2024)
Stormwater basins (9)	Reduce nutrient, suspended solids and heavy metal loads from urban runoff	Urban and peri-urban catchments with high impervious surface cover and runoff volume | Suitable for pre-treatment of stormwater before entering lakes or rivers | Scalable and adaptable to different land-use intensities | Contribute to urban green-blue infrastructure | Requires sediment removal and regular maintenance	Not provided	Effective removal of TSS and heavy metals | Can potentially enhance local biodiversity and public amenity if vegetated	Sensitive to rainfall intensity | Performance may vary with season | Mixed results on nutrient removal efficiency | Performance may decline without proper design and sufficient maintenance	(Liebl, 2010; Honour et al., 2013; Adhikari et al., 2023)
Two-stage channels, floodplains and vegetated drainage ditches (NbS, BfS; 7-9)	Ensure agricultural drainage with lesser ecological impacts than conventional ditching	Agricultural ditches, streams and small rivers | Requires establishing a floodplain on one or both sides of an existing agricultural ditch, stream or small river | Damming of low-flow channel may improve purification efficiency | Also applicable to forested and urban channels | Possibilities to combine with woody riparian buffers | Only few studies spanning over 2-3 years | Efficiency dependent on floodplain inundation frequency, width of low-flow channel, channel history and sediment properties | Insufficient support from agricultural policies hinders the applicability	Construction €13–40 per 1 m channel length	Enhances denitrification | Potential reduction of suspended sediment and P loading | Locally increased richness of stream invertebrates, diatoms and plants | Locally increased richness of riparian beetles and plants | Potential benefits for fish diversity with self-cleansing low-flow channels | Potential increase in flood resilience | Less frequent and disruptive maintenance compared to conventional channels	May increase suspended sediment loads if main channel is self-cleansing | Mixed results on P retention efficiency | Excess deposition of suspended sediment to low-flow channel harmful to local biodiversity | Losses of field area to farmers | Costs for landowners not fully compensated through European Union agri-environmental subsidy scheme (CAP-AES)	(Roley et al., 2012; Davis et al., 2015; Mahl et al., 2015; Gumiero and Boz, 2017; Nsenga Kumwimba et al., 2018; Vymazal and Dvořáková Březinová, 2018; DeZiel et al., 2019; Kindervater and Steinman, 2019; Trentman et al., 2020; Västilä et al., 2021; Damphousse et al., 2024; Hallberg et al., 2024a; Hallberg et al., 2024b; Huttunen et al., 2024; Västilä and Jilbert, 2025)

Also, applications of different coagulants in the oxidised littoral areas and anoxic profundal zones (Grochowska et al., 2023) and sequential "Floc & Lock" procedures for water column P inactivation, phytoplankton removal and sediment capping (van Oosterhout and Lürling, 2011; van Oosterhout et al., 2022) with estimated TRL of 8-9 have resulted in 80-90% reduction of water column P concentration over the long-term (i.e., decade post intervention), while at the same time reducing the potential harm for biota with targeted dosing of coagulants.

Recycled industrial side-stream materials such as drinking water treatment residue (DWTR) (Kuster et al., 2023), and spent lime have also been investigated to reduce costs and the need for raw materials in P inactivation (Wang et al., 2016; Kuster et al., 2021). These side-stream materials have potential for controlling both external (Kuster et al., 2022) and internal P loading, increase P inactivation and algal flocculation (Wang et al., 2016; Kuster et al., 2021; Kuster et al., 2023; Xia et al., 2023). However, the efficacy of Fe-rich DWTR may be affected by low redox conditions (Zhan et al., 2022), and DWTR requires pretreatment due to potential risk for heavy metal leaching (Kuster et al., 2021). Consequently, the TRL of side-stream materials is still low (3) and feasibility in natural environments requires further investigation.

Innovative CBS applications have also been developed for closed-circuit hypolimnetic withdrawal and treatments systems (HWTS; Silvonen et al., 2021; Silvonen et al., 2022; Silvonen et al., 2023; Tammeorg et al., 2024a), commercial fish removal and reuse of biomass in food, feed or biogas production (Tammeorg et al., 2024a), macrophyte removal and reuse as building and insulation materials, feed, or in renewable energy production (Muñoz Escobar et al., 2011; Bajwa et al., 2015; Colbers et al., 2017; Tammeorg et al., 2024a; Zoppi et al., 2024), and sediment removal and reuse in different purposes such as creating islands (Jin, 2021; van Leeuwen et al., 2021; Stouten et al., 2022), for use as a fertiliser (Braga et al., 2024; Haasler et al., 2024; Huo et al., 2024) and as a building material (Fořt et al., 2025). In these applications, the excess nutrients and biomass from lakes are reframed as recoverable and alternative resources and materials (Table 1).

Additionally, several different adsorbents for P recovery from the water column have been the focus of experimental research with a TRL of 3–5 (de Vicente et al., 2010; Funes et al., 2018). However, the upscaling potential of these P adsorbing agents remains questionable due to high material, water and energy demands in production and limited evidence on the performance on whole-lake scale (Table 1). HWTS as another potential solution for more permanent P removal from lakes (Silvonen et al., 2021; Silvonen et al., 2022; Silvonen et al., 2023; Tammeorg et al., 2024a) also lacks longer-term, whole-lake studies evaluating its restoration performance at larger scales. While sediment removal, P inactivation and continued biomanipulation have proven to produce long-term water quality benefits if external loading has simultaneously been managed within tolerable boundaries (e.g., Huser et al., 2016; Spears et al., 2016; Triest et al., 2016; Lürling et al., 2020b; Salonen et al., 2020; Härkönen et al., 2025; Wan et al., 2025), the long-term evidence is often scarce for many in-lake measures due to restricted duration of post-intervention monitoring (Cianci-Gaskill et al., 2024; Tammeorg et al., 2025b).

Some measures and products (e.g., barley straw, ultrasonication, and effective micro-organisms (EM)) have also been proposed for use but lack evidence on their effectiveness (Lürling et al., 2016b). Further, with some measures (e.g. ultrasound), no benefits for eutrophication control have been proven while harmful consequences to non-target organisms may be likely (Lürling et al., 2016b; Lürling and Mucci, 2020). Despite this, when supported by effective sales techniques and misinformation such measures can become widely used. This creates the misconception that if measures are used widely then they must be effective. We stress that measures with harmful implications for non-target organisms and no proven benefits for eutrophication control should be avoided.

Biological NbS and BfS, such as protection and restoration of shoreline habitats, installation of artificial reefs and creation of new littoral zones and artificial islands in heavily modified systems, can stimulate multiple trophic levels in aquatic food webs (Santos et al., 2011; Nummi et al., 2013; Yamamoto and Freitas, 2014; Ijff et al., 2021; Zhu et al., 2021; Stouten et al., 2022; van Leeuwen et al., 2023). These approaches also have potential links to circular economies if the habitat construction material can be obtained from recycled sources, such as recovered sediments (Phillips et al., 2016; Jin, 2021; van Leeuwen et al., 2021; Stouten et al., 2022; van Leeuwen et al., 2023), biomass-derived fillers from power generation byproducts (Zhu et al., 2021) or natural wood (Yamamoto and Freitas, 2014). Indeed, innovative solutions have the potential to deliver multiple benefits in the context of different EU policy relevant indicators in addition to contributing to the implementation of WFD (Fig. 4, Table 1). We identified a variety of co-benefits of the proposed in-lake measures from the literature, such as improving lake ecological status and addressing zero-pollution goals.

According to the reviewed publications, several in-lake measures such as biomanipulation, sediment removal and P inactivation have potential to improve lake ecological status and address zero pollution goals via reducing internal P loading, reducing water P concentration and suppressing cyanobacterial growth (e.g., Søndergaard et al., 2007; Huser et al., 2016; Spears et al., 2016; Triest et al., 2016; Urrutia-Cordero et al., 2016; Lürling et al., 2020b; Tammeorg et al., 2024a; Tammeorg et al., 2024b; Xiang et al., 2024; Härkönen et al., 2025; Wan et al., 2025) (Table 1). At the same time, these measures can benefit biodiversity net gain via promoting submerged macrophyte re-establishment and rebalancing fish communities together with supporting the natural functioning of aquatic food webs (Spears et al., 2016; Waajen et al., 2016; Fox et al., 2020; van Oosterhout et al., 2022; Berthelsen et al., 2024; Härkönen et al., 2025), and potentially support health and well-being if water quality can be improved to support recreational activities, such as swimming and water sports (Gołdyn et al., 2014; Łożyńska et al., 2021; Liu et al., 2022). Additionally, circular approaches in biomanipulation and sediment removal can support circular economies and promote sustainable food systems by providing resources for food and feed production and alternative fertilisers (Kiani et al., 2021; Kiani et al., 2023; Haasler et al., 2024; Tammeorg et al., 2024a; Tammeorg et al., 2025b). Algal removal, in turn, may benefit both health and well-being (Chen et al., 2017) and provide alternative resources for biotechnologies (Pandhal et al., 2018; Koreiviene et al., 2019; Macário et al., 2021). Harvesting biomass (algae, macrophytes and fish) also indirectly removes nutrients (total phosphorus (TP) and total nitrogen (TN)) and, therefore, reduces internal pathways of nutrient recycling, without disturbing the bottom sediments of lakes or requiring addition of expensive coagulants. This circular approach to using nature to capture and recover nutrients has the potential, therefore, to be cost-effective and less damaging to the lake environment. However, sustainability criteria for commercial biomanipulation are lacking and should be developed to ensure environmentally safe implementation (Tammeorg et al., 2024a). Additionally, the scalability potential of algal and macrophyte harvesting is still poorly developed with renewable energy harvesting technologies requiring further development, although some success for large-scale harvesting has been demonstrated at Lake Taihu, China, with biogas production as the main product (Miao et al., 2014). The possible negative side-effects of algal and macrophyte harvesting on non-target organisms (such as zooplankton) and toxin release remains understudied.

The co-benefits that were less frequently identified in the reviewed literature included sustainable energy and sustainable transportation (Fig. 4, Table 1). For instance, HWTS has potential for energy recovery if the withdrawn hypolimnetic water can be used in cooling (van der Hoek, 2011), and removed algal, fish and macrophyte biomass can be used for renewable energy production (Muñoz Escobar et al., 2011; Tammeorg et al., 2024a; Zoppi et al., 2024). Mooring management, in turn, can benefit sustainable transport and support biota if the negative impacts of anchoring to submerged macrophytes, sediment and macroinvertebrates can be reduced using hook-buoys (Ostendorp et al., 2009).

Interestingly, none of the reviewed original research included in this dataset suggested reduced GHG emissions from lakes resulting from restoration. Increased lacustrine emissions are driven by eutrophication, deoxygenation and increased primary production (DelSontro et al., 2018; Beaulieu et al., 2019; Pickard et al., 2021; Zheng et al., 2022; Søndergaard et al., 2023). Recently, a review by Ali et al. (2023) suggested that sediment capping using oxygen nanobubbles (NB) potentially reduces CH_4 and N_2O emissions by restoring aerobic conditions in deep sediments. It has also been shown that ecological restoration of a

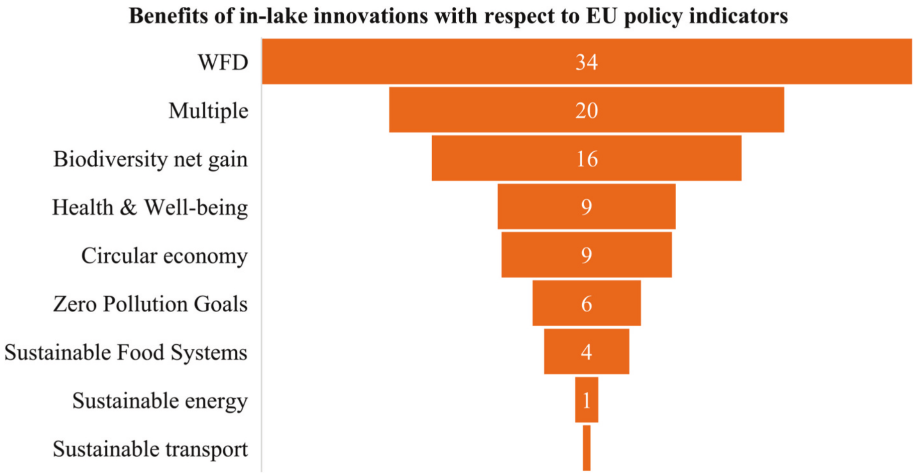

Fig. 4. Benefits provided by reviewed innovative in-lake measures. The benefits are expressed as proportions (%) of all the impacts that could be assessed based on data presented in reviewed publications.

lake with external pollution control, algal removal and submerged macrophyte recolonisation have resulted in reduced CO_2 and N_2O fluxes (He et al., 2025). Macrophyte removal, in turn, can promote short-term increases in CO_2 emissions due to reduced photosynthesis, whereas the net effect on CH_4 emissions depends on, e.g., the type of removed macrophytes, and the extent of their removal (Harpenslager et al., 2022). More information on the impacts of different in-lake restoration measures in counteracting lacustrine GHG emissions is needed.

Similarly, none of the reviewed publications had data to support evaluation of potential co-benefits to green growth or inclusivity, although the implementation of lake restoration in general could promote jobs in environmental monitoring and management, and improvement of lake ecological status could support ensuring safe water quality to all and benefit communities dependent on lake resources.

6. External, catchment focused innovations for improved lake protection

Based on our analysis of the external innovations for lake protection, integrated actions, such as controlled drainage, no tillage, cover crops, improved irrigation efficiency, continuous cover forestry and natural flood management at both the plot and catchment scales are increasingly being adopted to mitigate the harmful water-quality impacts of drainage in agriculture and forestry (Zhang et al., 2011; Nikraftar et al., 2021; Salla et al., 2021; Miettinen et al., 2025; Sarkkola et al., 2025). At the same time, water-management practices increasing the catchment water retention capacity combined with other cropping and forest management strategies preventing nutrient losses remain the most effective approaches for pollution control (Zhang et al., 2011; Nikraftar et al., 2021; Robotham et al., 2023; Miettinen et al., 2025). Land-use driven nutrient loading and reduced habitat heterogeneity negatively affect taxonomic and functional diversity of freshwater species on local and regional levels (Xie et al., 2024; Mykrä et al., 2025). With reduced disturbance of terrestrial and fluvial environments, more naturalised land-use and water-management practices can provide co-benefits to biodiversity (Västilä et al., 2021; Sarkkola et al., 2025; Västilä and Jilbert, 2025) together with multiple economic co-benefits to society (Nikraftar et al., 2021; Robotham et al., 2023; Glass and Burgess, 2025; Miettinen et al., 2025) (Fig. 5, Table 2). Of all the benefits assessed in the reviewed publications concerning external solutions, most addressed zero-pollution and WFD goals, with multiple co-benefits also being common (Fig. 5, Table 2).

The controlled drainage and utilisation of different water retention structures can substantially benefit zero-pollution and WFD goals by decreasing suspended sediment (SS), TP and particulate organic carbon (POC) loads to surface waters (Zhang et al., 2011; Robotham et al., 2023). Additionally, these management actions improve flood and drought resilience (Lamsodis et al., 2006; Salla et al., 2021; Robotham

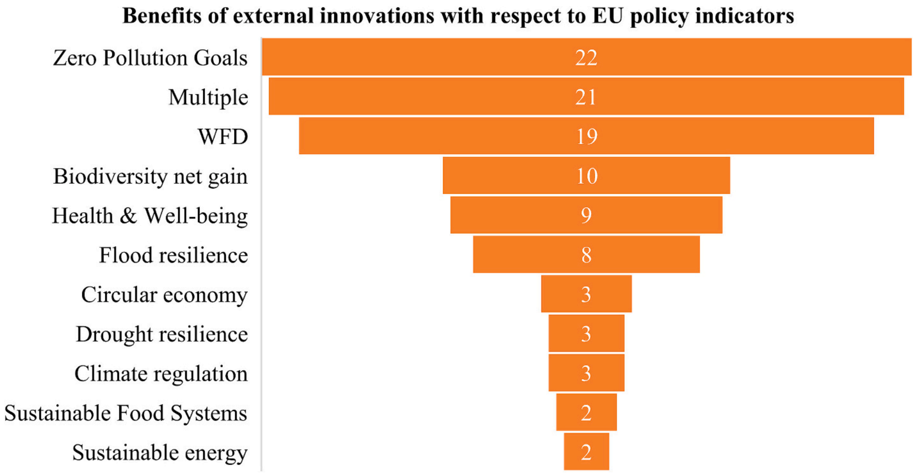

Fig. 5. Benefits provided by reviewed catchment-scale measures for improved lake protection. The benefits are expressed as proportions (%) of all the impacts that could be assessed based on data presented in reviewed publications.

et al., 2023; Janatrostami, 2024), increase water levels in lakes suffering from prolonged droughts (Nikraftar et al., 2021), and sustain crop yields (Zhang et al., 2011) (Table 2). Peatland restoration and wetland re-establishment, in turn, increase the water retention capacity in catchment areas as sponge landscapes, thus delivering resilience to floods and droughts (Macquarie and Etra, 2001). These strategies may also benefit zero-pollution goals in the longer-term through decreased external nutrient loading (Koskinen et al., 2017; Juutinen et al., 2020), enhance biodiversity, and have the potential to reduce GHG emissions thus supporting climate regulation (Macquarie and Etra, 2001; Hoffmann and Baattrup-Pedersen, 2007; Bonn et al., 2016). However, short-term negative implications for zero-pollution goals can also arise, as nutrient and organic carbon loads to surface waters often initially increase after implementation (e.g., Koskinen et al., 2017).

Recent advances in water protection also include innovative CBS adsorbents and reactive media for improved pollution control, such as soil amendments on agricultural fields for improved erosion control (Svanbäck et al., 2014; Rasa et al., 2021; Norberg and Aronsson, 2022; Uusi-Kämppä et al., 2022; Ekholm et al., 2024; Ollikainen et al., 2024), inflow P inactivation (Mueller et al., 2015; Smith et al., 2016; Mueller et al., 2019; Kuster et al., 2022), permeable reactive barriers (PRB) that intercept runoff (Bus et al., 2019), and sediment interceptors deployable in drainage channels to trap SS and nutrients (Chang et al., 2010; He et al., 2014; Kupiec et al., 2022). Soil amendments have the potential to significantly reduce soil erodibility and associated nutrient leaching, while improving the soil condition and potentially increasing crop yields (Svanbäck et al., 2014; Norberg and Aronsson, 2022; Uusi-Kämppä et al., 2022; Ekholm et al., 2024; Ollikainen et al., 2024). At the same time, they may also appeal to farmers because they do not reduce arable land or income (Ollikainen et al., 2019; Ollikainen et al., 2020). However, the performance of soil amendments declines over time (Rasa et al., 2021; Ekholm et al., 2024), and there is still a lack of long-term studies evaluating the longevity of the treatment performance. PRBs, on the other hand, are sub-terranean technological solutions originally aimed at pre-treating contaminated groundwater (Blowes et al., 1997; Borden et al., 1997) but they may also act as biogeochemical barriers on riparian buffers to enhance N and P retention in urban and agricultural runoff (Bednarek et al., 2010; Izydorczyk et al., 2013; Bus et al., 2019; Frątczak et al., 2019). Different adsorbents, including some CBS, such as sawdust, corn cobs, culm, and limestone, with the addition of denitrifying microorganisms, have been tested with a 70-85% reduction of N (Bednarek et al., 2010; Izydorczyk et al., 2013; Frątczak et al., 2019). The P reduction, in turn, has varied substantially from 13-90% with the highest efficiency recorded in short-term laboratory studies (Bednarek et al., 2010; Izydorczyk et al., 2013; Bus et al., 2019; Frątczak et al., 2019). The PRBs designed for diffuse pollution control require further studies concerning the longevity of performance (Izydorczyk et al., 2013; Bus et al., 2019; Frątczak et al., 2019) and the need for maintenance and replacement of reactive material in designing PRBs in general remains crucial (Phillips, 2009).

Sediment interceptors, in turn, are systems typically installed at lake inflows or water protection structures and function by trapping SS and associated P through gravity-based separation or settling mechanisms (Chang et al., 2010; He et al., 2014; Kupiec et al., 2022), geotextile silt fences, silt traps and decanting earth buds, detainment bunds, modified drainage ditches or farm ponds (Smith and Muirhead, 2024), and porous filters (Kumar et al., 2019). Studies on these engineering solutions have evaluated the performance under field conditions with an estimated TRL of 5-9 and demonstrated moderate effectiveness in reducing suspended solids and particulate nutrients (Chang et al., 2010; He et al., 2014; Kupiec et al., 2022; Smith and Muirhead, 2024). However, their effectiveness depends on the interceptor's volume in relation to the size of the catchment area, discharge and sediment size distribution, and they require regular maintenance (He et al., 2014; Smith and Muirhead, 2024).

Well-established NbS, such as constructed wetlands (CWs) and stormwater basins, are applicable to a wide range of purposes, from wastewater treatment to controlling diffuse pollution from urban, agricultural and forested landscapes (Gunes and Tuncsiper, 2009; Vohla et al., 2011; Xie et al., 2012; Wu et al., 2014; Vymazal and Dvořáková Březinová, 2018; Nguyen et al., 2020; van den Berg et al., 2022; Härkönen et al., 2023; Irvine et al., 2023; Vassalle et al., 2023; Vo et al., 2023) (Table 2). CWs and stormwater basins support zero-pollution goals via reducing P, N, SS, organic compound, and heavy metal loading to surface waters and can potentially also retain pesticides, micropollutants and microplastics (Honour et al., 2013; Nowak et al., 2013; Vymazal, 2014; Vymazal and Březinová, 2015; Kasak et al., 2018; Kill et al., 2022; Vymazal, 2022; Adhikari et al., 2023; Irvine et al., 2023; Koukoura et al., 2024; Sarti et al., 2024). They also promote biodiversity net gain via providing habitats for macroinvertebrates, fish and waterfowl (Kupiec et al., 2022; Mostafa et al., 2022), support flood and drought risk mitigation via increasing the water storage capacity within the catchment areas (Tao and Xiong, 2021; Sánchez-Almodóvar et al., 2022), and potentially benefit sustainable energy and climate regulation by serving as passive treatment with minimal energy inputs (Gunes and Tuncsiper, 2009; Nguyen et al., 2020; Nguyen et al., 2021). In wastewater treatment, different applications of CWs may also provide circular economy and sustainable food systems benefits, if, for instance, selenium-enriched microalgae from wastewater treatment ponds can be reused and refined as feed (Li et al., 2021), or the treated wastewater can be reused for irrigation (Gunes and Tuncsiper, 2009; Nguyen et al., 2020; Dubey et al., 2024) or in aquaculture (Gukelberger et al., 2020). In addition, CWs could benefit small communities with decentralized wastewater treatment facilities.

Nevertheless, the ability of CWs in retaining dissolved substances is often limited, especially during the cold-water season, and decreases with CW age (Kasak et al., 2018; Koskiaho and Puustinen, 2019; Vymazal, 2022). In general, CWs are more efficient in removing N pollution than in retaining P as is exemplified from an evaluation of the performance of 23 Danish CWs yielding a mean (±SD) TN removal of 41% (±25%) N ha^{-1} $year^{-1}$ while the TP removal was -5% (±37%) P ha^{-1} $year^{-1}$ (Audet et al., 2020). Vegetation is key for efficient phosphorus removal in CWs as it stabilises sediment and reduces resuspension, increases CWs resilience to flow extremes, and enables phytoremediation (Zamora et al., 2019; Kill et al., 2022). Optimal design of CWs should thus consider biological, chemical, geomorphic, hydraulic, and nutrient loading factors. Large-sized, multi-celled CWs are preferred, as they minimise short-circuiting and water stagnation, dampen nutrient pulses, and maximise contact between water, sediment, and vegetation across cells to optimise sedimentation and nutrient uptake. In addition, the design should include sediment and vegetation management (Webb et al., 2025). In some cases, structures mimicking the functions of natural habitats, such as floating treatment wetlands (FTWs) or floating beds have been accompanied with CWs to facilitate nutrient uptake and promote microbial pollutant degradation (Weragoda et al., 2010; Borne et al., 2015; Hartshorn et al., 2016; Tao et al., 2017; Ozan and Yilmazer, 2020; He et al., 2022; Batista et al., 2025). FTWs have demonstrated reductions in P, N, Chl *a*, and heavy metals while also providing habitat for birds and aquatic invertebrates (Colares et al., 2020), albeit longer-term performance data under variable seasonal conditions are still limited for these innovations. Additionally, the size, coverage and position of floating modules for optimal performance still require further investigation.

Finally, two-stage channels (TSCs), vegetated drainage channels and floodplains as NbS and BfS to improve water quality and support aquatic and riparian biodiversity have been developed as part of promoting urban green-blue infrastructure and naturalising agricultural landscapes (Roley et al., 2012; Davis et al., 2015; Mahl et al., 2015; DeZiel et al., 2019; Kindervater and Steinman, 2019; Trentman et al., 2020; Västilä et al., 2021; Huttunen et al., 2024; Västilä and Jilbert, 2025). However, information on the performance of TSCs in reducing P and N loads on field-scale is mixed (Mahl et al., 2015; Speir et al., 2020; Hallberg et al., 2024a; Hallberg et al., 2024b; Han et al., 2025; Västilä and Jilbert, 2025) and there is a lack of studies evaluating their treatment performance in the longer-term. Nevertheless, TSCs seem to support the local richness of in-stream invertebrates, diatoms and macrophytes, as well as riparian beetles and plants (Västilä et al., 2021; Huttunen et al., 2024), and may require less frequent and disruptive maintenance than conventional dredging.

While the different edge-of-field and end-of-pipe approaches have the potential to complement broader, pollution preventative catchment-scale water protection strategies, these measures have limited ability to trap nutrients and substances especially in dissolved forms.

7. System analysis guided selection of integrated measures is the most viable approach

The stimulus for any lake restoration programme is always identification of a problem that is limiting the desired state or use of a lake. In all cases, understanding the cause of the problem, rather than the symptoms, is decisive in addressing the problem sustainably (Lürling et al., 2016a; Lürling et al., 2024; Tammeorg et al., 2024a; Tammeorg et al., 2025b). This diagnosis of the cause of the problem, termed *lake system analysis*, is the initial step in developing a plan for lake protection and restoration. For water quality problems, determining the magnitude of external and internal loads, together with a lake's boundary conditions and sensitivity to change, is important to identify which measures are best to pursue and which lakes have the highest chance for restoration success (Politi et al., 2024).

Often, a strategy combining multiple measures in both the catchment and in-lake has proven to provide the best results with the greatest durability (e.g., Özkundakci et al., 2010; Salonen et al., 2020; Lürling et al., 2024). Especially in shallow lakes, the impacts of single restoration efforts can be hampered with non-linear response trajectories mediated by, for example, interactions with biota (Gulati and van Donk, 2002; Scheffer, 2004; Jeppesen et al., 2012; Sarvala et al., 2020; Abell et al., 2022). Consequently, in most cases, a combination of in-lake measures may deliver the best chance of long-term success if they address both the nutrient load and water turbidity (e.g., Lürling et al., 2023; Lürling et al., 2024).

As P and N loading often have different source pathways, combinations of measures may improve possibilities for managing both nutrients, that is increasingly viewed as being important for reducing both the abundance and toxicity of HABs (González Sagrario et al., 2005; Paerl et al., 2016; Hellweger et al., 2022). While several studies have shown limited success of, for instance, aeration/oxygenation in controlling P release (Gächter and Wehrli, 1998; Gächter and Müller, 2003; Horppila et al., 2017; Tammeorg et al., 2017), this method, and also sediment capping, are among very few in-lake innovations that have the potential for improved N control in lakes (Table 1) (Holmroos et al., 2016; Sunaryani et al., 2023). With sediment removal, N control may be limited compared to that of P (Wan et al., 2025) and chemical P inactivation may alter N cycling with negative consequences for nitrous oxide (N_2O) emissions (Nogaro et al., 2013). Harvesting of lake biomasses, in turn, may have potential for simultaneous removal and recovery of both P and N (Tammeorg et al., 2024a) but the impacts remain poorly quantified.

The importance of applying integrated restoration strategies that combine external and internal solutions is underscored with several cases displaying negligible impact of extensive in-lake restoration measures in the presence of persistent external loading (e.g., Søndergaard et al., 2007; Waajen et al., 2019; Lürling et al., 2023; Zhang et al., 2023; Tammeorg et al., 2024b). Notably, only a minority of reviewed studies (6%) examined a combination of catchment and in-lake measures. This may reflect a publication bias towards studies of individual measures, rather than evaluations of long-term restoration programs that integrate multiple measures over time. Nutrient load reduction measures should in general consider control across all pathways from source to transport and destination with controlling practices utilised at sufficient scales (Osmond et al., 2019).

The substantial costs of restoring lakes are often outweighed by the significant economic benefits to society (Spence et al., 2023). Preferably, a system analysis should include a cost-benefit analysis to evaluate best applicable measures. Introduction of cost-effective measures for freshwater pollution control is vital especially in low- and middle-income countries where financial resources are limited (Abbasov and De Blois, 2021). However, our review revealed that most of the scientific studies do not provide any information on costs (Tables 1-2), and even fewer evaluate them in relation to monetarised estimates of the ecological, economic and social benefits. Insufficient pre- and post-intervention monitoring, lack of reporting cost data and assessment of costs relative to environmental benefits make it difficult to assess cost-effectiveness, longevity, and scalability of many of the reviewed interventions. More comprehensive monitoring of the costs and benefits of restoration programs are needed to demonstrate restoration success (Carvalho et al., 2024). The costs for different interventions are strongly geographical-context and case-sensitive, so their assessment should be a key component in system analysis in order to determine suitable restoration measures that can be sustained for longer term success (Sellergren et al., 2023; Tammeorg et al., 2024a; Tammeorg et al., 2025b).

8. Mainstreaming technical innovations requires supportive societal structures

While many lakes are affected by multiple pressures, nutrient pressures are among the most pervasive and affect a majority of lakes (Birk et al., 2020; Poikane et al., 2024). This highlights the need to more comprehensively address diffuse and legacy nutrient pollution sources (Wiering et al., 2020; Sanchez Trancon and Leflaive, 2024). However, the implementation of source-oriented measures relies largely on individual countries which can be problematic for transboundary lakes. Specific water legislation, such as the European WFD, often lacks integration with other policy areas, tools or sanctions to enforce effective measures to reduce diffuse nutrient pollution (Boezeman et al., 2020; Wiering et al., 2023). Indeed, prerequisites for multifunctional, NbS-type catchment management approaches to become more mainstream in lake protection and restoration, include uptake of such regulative instruments, economic incentives and financing schemes that support the transition. For instance, the EU's current agri-environmental subsidy scheme (CAP-AES) insufficiently compensates land losses to farmers following the implementation of TSCs in streams (Västilä et al., 2021). Similarly, the conventional rotation forest management (RFM) may provide higher private net revenue compared to CCF (Miettinen et al., 2025), which is inadequately compensated in current forestry policies. Nevertheless, hybrid strategies combining catchment water management and capital-intensive end-of-pipe approaches tackling pollutants at several scales are identified as profitable solutions also in the water treatment sector (Glass and Burgess, 2025).

The need for creating circular economies around lake restoration and protection has been highlighted by Tammeorg et al. (2024a); Tammeorg et al., (2025b). Several in-lake measures such as sediment and biomass removal have potential for providing alternative resources and material for food, feed, energy production and construction, and enabling the reuse of legacy nutrients in the catchment (Haasler et al., 2024; Tammeorg et al., 2025a). However, possible harmful substances in e.g., lake sediment need to be addressed to allow for their wider reuse (Fořt et al., 2025), and the field-application of lake sediments or biomass as alternative fertilisers varies by country-specific legislation and regulation on fertilizers (Renella, 2021). Additionally, despite the great potential in fostering circular economies, some measures such as source-separation systems in wastewater treatment are perhaps not realistic to upscaling to large urban areas as they would require an entire change of the wastewater treatment infrastructure (Lehtoranta et al., 2022). However, collection systems for either black water or urine diversion can be applicable in smaller scale settlements such as peri-urban contexts (Wielemaker et al., 2018; Malila et al., 2019; Lehtoranta et al., 2022).

As concluded by Tammeorg et al. (2025b), it is also necessary to ensure comprehensive, long-term post-intervention monitoring activities in restoration programmes and funding schemes to allow for reliable evaluation of the environmental benefits in the longer-term and societal and economic impacts of the restoration programme (Carvalho et al., 2024).

9. Conclusions

Our review has critically addressed several knowledge gaps regarding innovative lake restoration measures, with the novelty of considering not only the performance, but also the practical feasibility, co-benefits and costs, to ensure lake restoration effectively supports multiple policy goals, and is sustainable and economically viable. Based on our review, in-lake innovations often refine existing, well-established methods, for example, improving their sustainability, biodiversity outcomes, and circular-economy co-benefits. Engineering solutions (e.g., sediment removal, P inactivation, HWTS) have advanced in environmental friendliness, P recovery, and potential for P reuse, thus supporting the sustainability transition. Nature-based, biological in-lake measures are often multifunctional and provide co-benefits for biodiversity support, circular resource use, and ecological restoration (e.g., biomanipulation, macrophyte restoration, habitat creation). However, the scalability potential and long-term effectiveness remain uncertain for some of the emerging technologies with limited long-term monitoring of their effectiveness (HWTS) and only restricted proof of concept at operational scales (P adsorbents). Some measures are also marketed without proof of concept on operational scales (ultrasonication, EM). We stress the need for controlled experiments on emerging technologies to produce evidence that confirms cause-effect and avoids the risk of broadcasting placebo effects across restoration networks, which leads to poor decision making and loss of public trust.

Sustainable lake restoration requires sustainable land use that protects lakes from further deterioration. Catchment water management, improved agricultural and forestry practices and other nature-based approaches across catchments (e.g., controlled drainage, no tillage, continuous cover crops, continuous cover forestry) are the most effective ways to prevent diffuse pollution from entering the water cycle whilst also delivering co-benefits, such as biodiversity net gain, flood and drought resilience, and GHG reductions. They can, therefore, support delivery of multiple sustainability policies (WFD, NRR, European Green Deal, IPCC, UN SDGs 6, 9, 13, 14). While NbS and CBS water protection structures, such as constructed wetlands, floating treatment wetlands, and sediment/nutrient interceptors may help reduce pollution, they still have limited capacity, especially for uptake of dissolved pollutants from the water cycle. Consequently, prevention of pollution at source is essential and should accompany any end-of-pipe solutions.

Despite advances in lake restoration methods, no quick fixes or 'one-size-fits-all' solutions exist, calling for holistic, systemic strategies managing external loading within tolerable boundaries and considering catchment and in-lake processes to address multiple pressures. However, only a minority of reviewed studies evaluated combined catchment and in-lake approaches, despite such combinations offering the highest and most durable restoration success for sustainable lake restoration. In all cases where a water quality issue in a lake has been identified, a search for the underlying causation is required to address the problem adequately. A system analysis and consequent guided selection of multiple measures provide the highest chance for restoration success.

This review highlights the necessity for adopting a tailored combination of measures to address multiple pressures and deliver co-benefits for climate resilience or new circular economies. Many of these restoration measures can also be applied to prevent lake degradation in areas that are still less impacted by anthropogenic activities. In addition to more evidence on the effectiveness and scalability of these measures, wider implementation requires coherent policies, community-driven and inclusive water governance, political willingness to address pollutants at source and financial investments in restoration programs that are underpinned by the long-term social and economic benefits that lake restoration provides.

CRediT authorship contribution statement

Laura H. Härkönen: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miquel Lürling:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Li Kang:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Kirstine Thiemer:** Writing – review & editing, Validation, Methodology, Investigation. **Kaisa Västilä:** Writing – review & editing, Validation, Methodology, Investigation. **Renata Augustyniak-Tunowska:** Writing – review & editing, Validation, Methodology, Investigation. **Jolanta Grochowska:** Writing – review & editing, Validation, Methodology, Investigation. **Marko Järvinen:** Writing – review & editing, Validation, Methodology, Investigation. **Michał Łopata:** Writing – review & editing, Validation, Methodology, Investigation. **Fabio Masi:** Writing – review & editing, Validation, Methodology, Investigation. **Anacleto Rizzo:** Writing – review & editing, Validation, Methodology, Investigation. **Chiara Sarti:** Writing – review & editing, Validation, Methodology, Investigation. **Martin Søndergaard:** Writing – review & editing, Validation, Methodology, Investigation. **Renata Tandyrak:** Writing – review & editing, Validation, Methodology, Investigation. **Kristiina M. Vuorio:** Writing – review & editing, Validation, Methodology, Investigation. **Lilith Kramer:** Writing – review & editing, Validation. **Bryan M. Spears:** Writing – review & editing, Validation, Funding acquisition. **Maeve McGovern:** Writing – review & editing, Validation. **Eerika Albrecht:** Writing – review & editing, Validation. **Laurence Carvalho:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI-assisted technologies were used in the writing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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Glossary

Biodiversity-focused Solutions (BfS): Solutions focused primarily on active biodiversity restoration, such as habitat creation.

Circular Blue-economy Solutions (CBS): Actions that include recovery of resources (nutrients, biomass) in the restoration process stimulating a blue economy around restoring freshwaters.

Nature-based Solutions (NbS): Actions to protect, conserve, restore, sustainably use and manage natural or modified ecosystems, which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits.

Nature Restoration Regulation (NRR): European legislation that sets legally binding requirements to restore degraded habitats, effective from 2024.

Technology Readiness Levels (TRL): A method for defining the maturity of a product or solution and its relation to the market. TRL is assessed on a scale from 1 to 9, ranging from foundational research (TRL 1) to a fully demonstrated and commercialised solution (TRL 9).

Water Framework Directive (WFD): European Directive focused on protecting water bodies, avoiding deterioration, and ensuring restoration when necessary. Effective from 2000.