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Phytoremediation in aquaculture in Poland as an element supporting the improvement of surface water quality

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Abstract: Low and poor-quality water resources in Poland require rational and responsible use of them also in aquaculture. In recent years, there has been an increase in fish consumption, but also a change in consumer preferences. The development of innovative aquaculture methods leads to a reduction in water consumption, even by 20%, as is the case with recirculation aquaculture systems with salmonid fish production. In turn, sewage sludge generated in the purification process should be directed to the third stage of their purification, i.e. a hydrophyte lagoon. High requirements for the discharge of post-production water into aquatic ecosystems call for even more restrictive water management at every stage of fish production. The use of phytoremediation based on knowledge about the adaptation of aquatic and wetland plants to development in artificial aquatic ecosystems is an important element supporting the improvement of surface water quality. Thanks to the processes of rhizofiltration, phytoextraction and phytodegradation, hydrophytes effectively participate in reducing the concentration of nutrients and additionally metal ions. In turn, in fish farms focused on intensive carp production, part of the water drained from ponds in autumn can be subjected to phytoremediation in channels with an ecotone zone, thus improving the quality of these ecosystems. The key here is the selection of plants for the proposed solutions using phytoremediation and guaranteeing the effectiveness of this technology.

Keywords: constructed wetlands, consumption of farmed fish, ecotone zone, fishing farms, phytoremediation, ponds, recirculating aquaculture systems, water quality

INTRODUCTION

Poland is characterised by poor water resources compared to EU countries. According to data from the Central Statistical Office (Pol.: Główny Urząd Statystyczny – GUS) (GUS, 2023), 72% of water consumption for the needs of the national economy and population in Poland in 2022 was for industry, 9% for fishing (filling and replenishing fish ponds), and 19% was related to the operation of the water supply network. Unfortunately, only 4% of water consumption for production purposes was to replenish closed water circuits. About 6.5% of the total amount of sewage produced was discharged without treatment (0.14 km^3). The result of the use of freshwater resources in the national economy, despite the introduction of additional systems for the treatment of municipal and industrial sewage and the reduction of fertiliser use in agriculture, is a slow but progressive process of water pollution, including their eutrophication. This is confirmed by data from the Chief Inspectorate for Environmental Protection (Pol.: Główny Inspektorat Ochrony Środowiska), which monitors the quality of surface waters (rivers, lakes, transitional and coastal waters) based on the assessment of water bodies (WBs). Thus, in 2016–2021, only 22 WBs (0.5%) of river waters had good condition, and 4,563 WBs (99.5%) were characterised by poor condition. In relation to lake waters, the quality was slightly better: 12 water bodies – good condition (1%), and 1,032 – poor condition (99%). In turn, the quality of transitional and coastal waters assessed in 2021 indicated poor condition in both the Vistula and Odra River basins. Data on groundwater quality monitoring from 2022 are definitely better. The largest number of measurement points for free and confined waters corresponded to quality class II (36% for groundwater and 47% for deep water, respectively). Despite these unfavourable assessments of water quality in Poland, consumers' concerns about metal contamination of farmed fish meat were not confirmed in carp studies (Tkachenko *et al.*, 2021).

Growing nutritional needs and awareness of the importance of good quality food products, including fish, for health, force the intensification of their production and increase the efficiency of the use of available water resources. One of the most frequently used solutions in building aquaculture resistant to climate change is the introduction of closed water circulation systems (Wróbel *et al.*, 2023). The effect of such a technological change is a reduction in water consumption, even by 20%, as is the case with recirculating aquaculture systems (RAS) with salmonid production in Poland. The use of this technology in combination with wastewater treatment as a result of phytoremediation will additionally have a positive impact on the perception of aquaculture as an environmentally responsible food production sector. In water management in fish ponds, it is also important to take into account knowledge about the properties of macrophytes and their phytoremediation role due to the chemical properties of surface water used to fill and replenish ponds (Francová *et al.*, 2019).

It was assumed that the increase in the consumption of farmed fish would influence the development of intensive aquaculture systems that take into account the quality of surface waters, and the development of aquaculture resistant to climate change will be based on a closed-loop economy and the use of phytoremediation technology for water treatment and purification of post-production waters.

The aim of this study, based on a literature review, was to:

a) determine the size and structure of consumption of leading species of farmed fish in Poland and the importance of water quality in fish production;
b) discuss the possible impact of increased intensification of fish production systems on the quality of post-production waters discharged into surface waters;
c) systematise knowledge on vegetation management in fish ponds and the importance of phytoremediation mechanisms in the protection and preservation of aquatic ecosystems;
d) characterise the composition of aquaculture wastewater and discuss the transformation of nitrogen and phosphorus compounds and organic matter in various types of constructed wetlands;
e) characterise the phytoremediation capacity of *Phragmites australis*;
f) present the possibilities and limitations of using this technology in aquaculture, and indicate future prospects for its development based on current scientific research presented in scientific and industry journals and scientific papers.

The research will result in:

– ensuring consumers that increasingly used intensive aquaculture systems ensure good quality fish meat, and that innovative fish production technologies, together with sustainable management of post-production waters, can have a beneficial effect on the quality of surface waters;
– indicating more effective solutions for the use of phytoremediation in resource-efficient and climate change-resistant aquaculture.

MATERIALS AND METHODS

The results of scientific research in the form of peer-reviewed articles published in scientific and industry journals and scientific papers constitute material for analyses of the literature on the volume and structure of consumption of the main farmed fish in Poland, sources of water intake and the use of phytoremediation in aquaculture in the context of improving the quality of surface waters.

In order to collect source materials, the Google Scholar search engine and the Agricultural & Environmental Science Collection database of the ProQuest platform were used. The literature review was based on the following keywords: 1) phytoremediation, 2) aquaculture, 3) fresh water, 4) *Oncorhynchus mykiss*, 5) *Cyprinus carpio*, which were combined to detail and systematise the knowledge. Due to the limitations of this form of publication, articles describing the results of studies taking into account the use of algae in wastewater treatment in aquaculture were excluded from the analysis.

RESULTS AND DISCUSSION

CHANGES IN THE CONSUMPTION OF FARMED FISH AND IMPORTANCE OF WATER QUALITY IN FISH PRODUCTION

In recent years, Poland has been observing a slow but continuous increase in fish consumption (Fig. 1). Consumers are increasingly interested in salmonids (Fig. 2) available on the market throughout the year, in contrast to carp, which is mainly in demand during the New Year period. Carp meat is soft and has a strong earthy smell, which influences the change in consumer preferences (Wang *et al.*, 2024). Also, the increase in knowledge about fish welfare and nutritional values of other species of farmed fish as well as the acceptance of higher prices of these food products are the reasons for the increased demand for other fish species, including trout. In 2022, fish consumption per person in

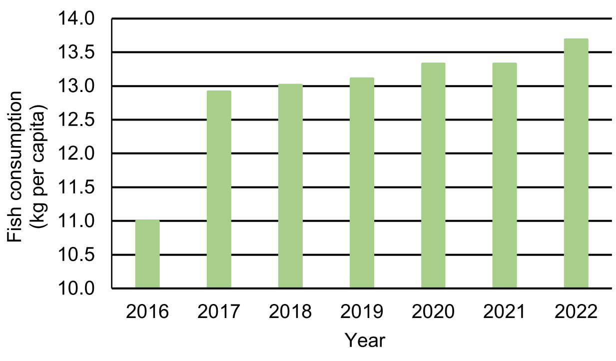

Fig. 1. Fish consumption in Poland (kg per capita) in 2016–2022; source: own elaboration based on data by GUS (2023), EIO (2023)

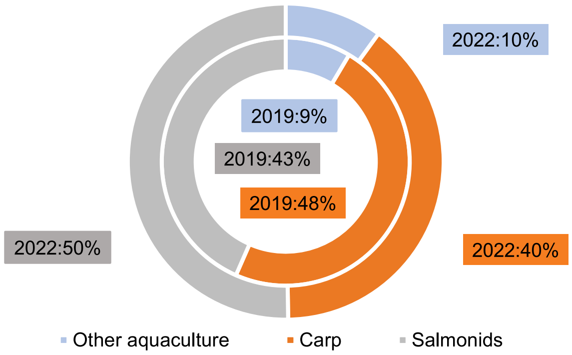

Fig. 2. Polish structure of aquaculture in 2019 and 2022; source: own elaboration based on data by GUS (2023), EIO (2023)

Poland was estimated at 13.69 kg, which is about 57% of the EU average (EIO, 2023). In this respect, the promotion of fish consumption and fish products is the basis for the development of this food production sector.

Eurofish International Organisation (EIO, 2023) data on fish production intensity (Fig. 2) indicate that in 2022 extensive fish farming (i.e. pond farming of carp in polyculture with other species) accounted for about 46% of the total aquaculture production intended for consumption, while intensive aquaculture (i.e. farming in tanks and raceways, recirculating aquaculture systems (RAS), runs and pens for salmonids, sturgeons, *Clarias gariepinus*, fish roe for consumption) reached the level of 54%.

The observed changes in fish production systems were reflected in the amount of water taken to fill and replenish fish ponds (Fig. 3). Over the last twelve years (2010–2022), water withdrawal was characterised by great diversity. In 2022, compared to 2010, there was an almost 23% decrease in water consumption in this aquaculture sector (Fig. 3). There are various reasons for this state of affairs. One of them is the decrease in the profitability of carp ponds.

Therefore, in the coming years, in accordance with the provisions of the aquaculture development strategy in Poland, further growth in the intensive form of fish production should be expected, which will result in reduced water consumption.

The control of water collected and used in food production is comprehensive, and its quality should be very good due to microbiological and physicochemical parameters. For the production of carp in mono and polyculture, water is most often collected from surface waters, and in the case of salmonid fish,

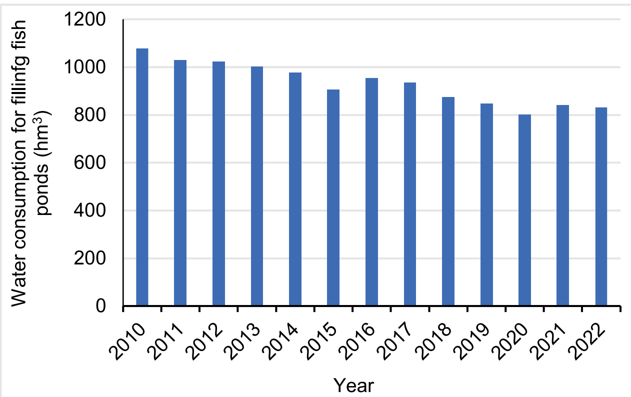

Fig. 3. Water consumption for filling fish ponds (hm^3) in 2010–2022; source: own elaboration based on data by GUS (2023)

including trout, from deep waters. In both cases, it is necessary to purify it to the level of requirements set in the conducted breeding and rearing of these fish (Tab. 1).

Table 1. Physico-chemical conditions in the production environment of: salmonids (*Oncorhynchus mykiss*) in the recirculating aquaculture systems and *Cyprinus carpio* in semi-intensive ponds

Parameter	*Oncorhynchus mykiss* (recirculating aquaculture systems)	*Cyprinus carpio* (semi-intensive ponds)
O_2 (mg·dm^{-3})	>80% saturation	>30% saturation
pH	6.5–8.2	6.0–8.5
DO (mg·dm^{-3})	no data	2.75–8.63
BOD_5 (mg·dm^{-3})	up to 4	3.54–28.14
COD_{Mn} (mg·dm^{-3})	up to 15	6.18–12.53
Hardness (°dH)	15	no data
Iron (mg·dm^{-3})	up to 0.5	no data
Ammonia (mg·dm^{-3})	up to 0.2	0.19–9.81
Free CO_2 (mg·dm^{-3})	up to 5	no data
SS (mg·dm^{-3})	<80	24.17–99.33
TP (mg·dm^{-3})	no data	0.46–4.72
TN (mg·dm^{-3})	no data	2.68–16.03
TOC (mg·dm^{-3})	no data	12.13–30.22
T_w (°C)	14–18	18–24

Explanations: *DO* = dissolved oxygen, BOD_5 = biochemical oxygen demand, COD_{Mn} = chemical oxygen demand, *TP* = total phosphorus, *SS* = suspended solids, *TN* = total nitrogen, *TOC* = total organic carbon, T_w = water temperature.
Source: own elaboration based on Goryczko (2008), Szarek, Skibniewska and Guziur (2008), and Všetičková *et al.* (2012).

The treatment of waters intended for carp breeding and cultivation should be taken into account due to the eutrophication of surface waters and the occurrence of high concentrations of heavy metals in waters from industrial areas (GUS, 2023). Many researchers emphasise (Gałczyńska *et al.*, 2019; Mandal and Bera, 2024) that waters rich in, among others, nitrogen and phosphorus compounds affect the development and growth of carp pond vegetation in different ways. As a result of this threat, the management of plant biomass at various stages of carp production in the conditions of polyculture (accompanying species: *Cirrhinus cirrhosus*, *Hypophthalmichthys molitrix*, *Tinca tinca* and predatory species: *Esox lucius*, *Sander lucioperca* or *Silurus glanis*) requires knowledge about the adaptation of plants to inhabit eutrophic reservoirs. Regardless of the physicochemical properties of water, plants must tolerate their damage and/or uprooting during fish feeding (Francová *et al.*, 2019). The phytoremediation properties of this group of organisms contribute significantly to the removal of metals from water and bottom sediments. Applying the principles of the Code of good practice for fish breeding and cultivation in carp ponds (Cieśla *et al.*, 2023), such fish production is similar to the practices used in organic farms (Adámek, Mössmer and Hauber, 2019). Due to the fact that the breeder regulates the development of aquatic vegetation on the premises, biomass is removed from the pond, which also participates in improving the quality of wastewater discharged into flowing or standing waters. This fact is confirmed by many studies, which is why it is recognised that carp breeding and rearing in ponds has a beneficial effect on aquatic ecosystems by, among others, balancing biogenic compounds, participating in their capture and storage (Barszczewski and Kaca, 2012; Všetičková *et al.*, 2012). Proper management of plant biomass makes fish farming safe for the consumer. In many countries, surface waters are heavily polluted with heavy metals, and consumers' concerns about their high concentration in fish meat are justified (Tolkou, Toubanaki and Kyzas, 2023, Hu *et al.*, 2024), in contrast to Poland (Tkachenko *et al.*, 2021).

Deep waters used in the production of salmonids must be treated without fail because they are characterised by an increased concentration of iron and manganese and a very low concentration of dissolved oxygen. These water quality parameters do not correspond to the optimal conditions for breeding and raising these fish (Tab. 1).

Also in relation to trout pond production, the research conducted by Brysiewicz *et al.* (2013) indicates that post-production water discharged from the farm does not cause pollution of surface waters.

INTENSIFICATION OF FISH PRODUCTION SYSTEMS AND THE QUALITY OF POST-PRODUCTION WATER DISCHARGED INTO SURFACE WATER

Fish ponds

In extensive carp farming, fish nutrition is based solely on natural food (plankton and benthos). In intensive farming, fish are fed with natural feed (cereal grains) or granulates. In a low-intensity system, the share of natural food in the carp diet is high and amounts to 50% (95–98% of pond farms in Poland); in a medium-intensive system, the share of natural food is only 9–10%, and in a high-intensity system (industrial fattening), the supply of natural food is minimal, and high-protein fattening granulates are used for feeding (Szarek, Skibniewska and Guziur, 2008).

Organic and inorganic nutrients that have not been used by fish (Terech-Majewska, Pajdak and Siwicki, 2016) and other organisms inhabiting the pond are accumulated in bottom sediments and seasonally in aquatic plants. As a result of feeding, carp separates benthic invertebrates by digging and sifting sediments to a depth of about 3 cm. The effect of this action is the increased availability of oxygen in the bottom sediment, which accelerates the mineralisation of organic matter and stimulates the circulation of elements in the reservoir, simultaneously shaping the abiotic and biotic properties of the water column. In the water above the sediment, there is a decrease in the concentration of oxygen dissolved in water, an increase in the concentration of carbon dioxide, an increase in the mineralisation of organic matter and an increase in the availability of soluble forms of nitrogen and phosphorus, a decrease in pH and a decrease in alkalinity. The concentration of mineral nutrients also increases through carp excretions. Biogenic compounds stimulate the photosynthesis of phytoplankton and indirectly affect the development of zooplankton (Rahman, 2015). With an excessive density of common carp, in medium-intensive and intensive production systems, the physicochemical state of the water reservoir changes from clean water conditions, in which aquatic plants thrive, to a turbid state. In such conditions, the inflow of light to submerged plants is limited, which consequently promotes the development of emerging, floating and free-floating species. Dead plants additionally enrich the ecosystem with decaying organic matter. Draining such water from the pond will result in contamination of the watercourse mainly with nitrogen compounds and slightly with phosphorus compounds (Kufel, 2012), and reconstruction of vegetation communities (Toyama *et al.*, 2020). In such a situation, post-production waters should be cleaned or remedial measures should be introduced to balance the risk of eutrophication caused by carp excrements. In the first case, an ecotone zone could be used. In the second case, Roy *et al.* (2020) propose dietary changes leading to a reduction in the content of phosphorus and nitrogen in faeces or adjusting the feed supply to the thermal conditions of rearing.

In fish farms consisting of different types of breeding ponds, there will be differences in the structure and species composition of aquatic plants, which requires the use of different forms of management. This is not an easy task, because waters taken for carp production are generally rich in biogenic compounds. The selection of aquatic plants for a given type of pond should already take this fact into account, i.e. plant species that prefer a eutrophic environment and are tolerant to large changes in access to nitrogen and phosphorus compounds, and also participate in the accumulation of metals, should be selected.

Recirculation systems in fish farms

Recirculating aquaculture systems (RAS), compared to traditional flow-through and cage aquaculture systems, use and therefore discharge less water, which can be purified efficiently and with lower financial outlays (Lindholm-Lehto, 2023). Additionally, these systems are more resistant to climatic factors (e.g. rainfall fluctuations, floods, droughts, global warming, cyclones, fluctuations in the chemical composition of the collected water) than the previously used ones, which results from the controlled conditions of their operation (Ahmed and Turchini, 2021).

The intensity of the recirculation process in fish farms depends on the amount of water that is recirculated or reused. For example, a traditional flow system for trout with a single water flow before discharge usually uses about 30 m^3 of water per kilogram of fish produced. Reconstruction of such a system into a recirculation system will reduce water consumption by 10 times. In these conditions, the recirculation rate according to the formula below will be 95.9% (the assumptions for the presented calculations are: production of 500,000 kg of fish per year, collection of 4,000 m^3 of water and use of 3,000 m^3 of water to fill tanks with fish and this volume of water is involved in recirculation).

$$\frac{IRF}{IRF + NWI} \cdot 100\% \tag{1}$$

where: *IRF* = internal recirculation flow, *NWI* = new water intake.

When the breeding is carried out in a building, water consumption can be reduced to 0.3 m^3 of new water per kilogram of fish produced, thus achieving a reduction rate of 99.6%. By introducing two-stage water purification from biogenic compounds (phosphorus: mechanical method – drum filter, nitrogen:

biological method – biofilter with a bed), water consumption can be reduced to only 30–40 dm^3 per kilogram of fish produced, which is about 100 times less water than in the traditional system and is characterised by the highest reduction rate – 99.96% (Bregnballe, 2022).

In RAS systems, high requirements for the removal of harmful compounds for fish ensure their proper growth and development throughout the production process. Regardless of the technical solutions used in a given RAS project, its effective operation will be achieved through particulate removal, biological filtration, aeration, pH buffering and disinfection (Ahmed and Turchini, 2021).

Part of the waste generated during mechanical filtration of wastewater (e.g. drum filter) contains significant amounts of solid and organic pollutants (biofilm particles, faeces, feed residues, etc.) and is therefore subject to further neutralisation (Wróbel *et al*., 2023). The resulting hydrated waste and part of the sewage already treated mechanically and biologically (biofilter with a bed) should be directed to the third stage of treatment (Fig. 4).

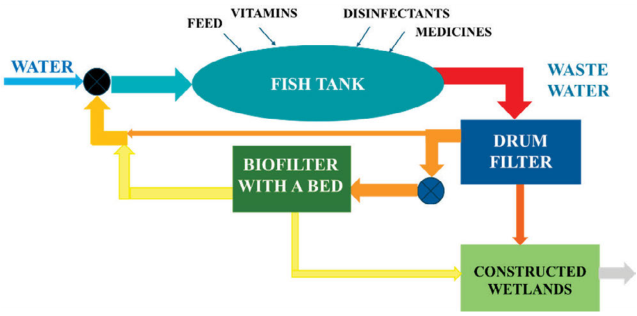

Fig. 4. Simplified diagram of a water recirculation system in the production of salmonids with the discharge of sewage resulting from the cleaning of the drum filter and part of the used water purified by mechanical and biological methods; source: own elaboration

The effectiveness of a similar system was confirmed by studies conducted by Comeau *et al.* (2001). The microscreen reduced the suspended solids content to about 40%, and the constructed wetlands retained more than 95% of the remaining suspended solids and more than 80% of the total phosphorus mass.

PHYTOREMEDIATION AND ITS MECHANISMS FOR WATER PROTECTION IN FISHING FARMS

Phytoremediation

One of the methods used in aquaculture for surface water treatment is phytoremediation (Ghaly, Kamal and Mahmoud, 2005; Gorito *et al*., 2017; Shen, Li and Lu, 2021; Mandal and Bera, 2024). This method also works well in purifying post-production water (Schulz, Gelbrecht and Rennert, 2003; Dalsgaard *et al*., 2018).

Phytoremediation involves the use of plants that are able to grow in a polluted environment and, in addition, affect biological, chemical, and physical processes aimed at removing harmful substances from the biological system. This allows for the effective purification of soils, sewage, groundwater, surface water, sewage sludge, and air (Wróbel, 2007; Gałczyńska, 2012; Jóźwiakowski, 2012; Strzelczyk and Steinhoff-Wrześniewska, 2019; Milke, Gałczyńska and Wróbel, 2020; Shen, Li and Lu, 2021; Liu *et al*., 2024).

In aquaculture, this technology is used to create ecotone (buffer) zones along streams into which post-production water is discharged, to manage the biomass of aquatic plants in ponds and to create constructed wetlands.

Gamrat *et al.* (2016) emphasise that ecotone zones are effective in reducing the adverse impact of agriculture on aquatic ecosystems by reducing the flow of nutrients, protecting against erosion and leaching of soil particles into watercourses, and increasing biodiversity. Therefore, building such zones in aquaculture will also help to counteract the slow eutrophication of post-production water receivers from various fish production systems. *Salix viminalis* 'Jorr' has good phytoremediation capabilities and can be used for planting along the banks of watercourses. Research conducted by Wróbel (2007) indicates that nitrogen, potassium, and magnesium accumulated mainly in leaves, while phosphorus and calcium alternately accumulated in leaves or roots. All these elements were present in the smallest amounts in wood. Data on the accumulation of elements in the organs of various plants allow for the selection of a species that will provide an appropriate level of reduction in the concentrations of macro- and micronutrients.

In turn, in natural or specially constructed aquatic ecosystems, the plants participating in the uptake of macro- and micronutrients are macrophytes representing four groups according to the division of Lacoul and Freedman (2006) – Figure 5.

Techniques used in phytoremediation include: phytodegradation, phytostimulation, phytoextraction, phytostabilisation, rhizodegradation, rhizofiltration and phytovoltalisation (Fig. 5).

Phytodegradation results from the uptake of organic pollutants by the plant, e.g. polycyclic aromatic hydrocarbons (PAHs) from sediments, groundwater or surface water, through metabolism, and their transformation occurs with the participation of enzymatic complexes. These processes also occur in the root zone of plants via rhizosphere microorganisms (rhizodegradation). The decomposition of compounds taken up by the plant is complete to CO_2 and water or partial. Derivatives of partial decomposition can be incorporated into plant structures through lignification (Gałczyńska, 2012). In turn, as a result of phytostimulation through root exudates, the activity of soil microorganisms is stimulated in order to accelerate the transformation of pollutants (Rupassara *et al*., 2002).

The effect of phytoextraction is usually the accumulation of contaminants transported by the root system to the tissues of above-ground organs (Gałczyńska, Gamrat and Ciemniak, 2023). Thanks to rhizofiltration, some aquatic plants adsorb or precipitate xenobiotics on the surface of the roots or take up and accumulate contaminants in the root tissues (Zheng *et al*., 2016). The sorption of contaminants is based on complex physicochemical interactions between the plant and the xenobiotic, mainly through ion exchange and chelation processes. These processes can also occur on dead root tissue. The phytostabilisation technique is simple and occurs through sorption, precipitation, complexation or reduction of the valence of metals and due to these properties is commonly used to remove metals such as arsenic, cadmium, chromium, copper and zinc. Immobilisation of contaminants occurs in the root zone, where they are reduced, not degraded, making them inaccessible to plants. Plants immobilise

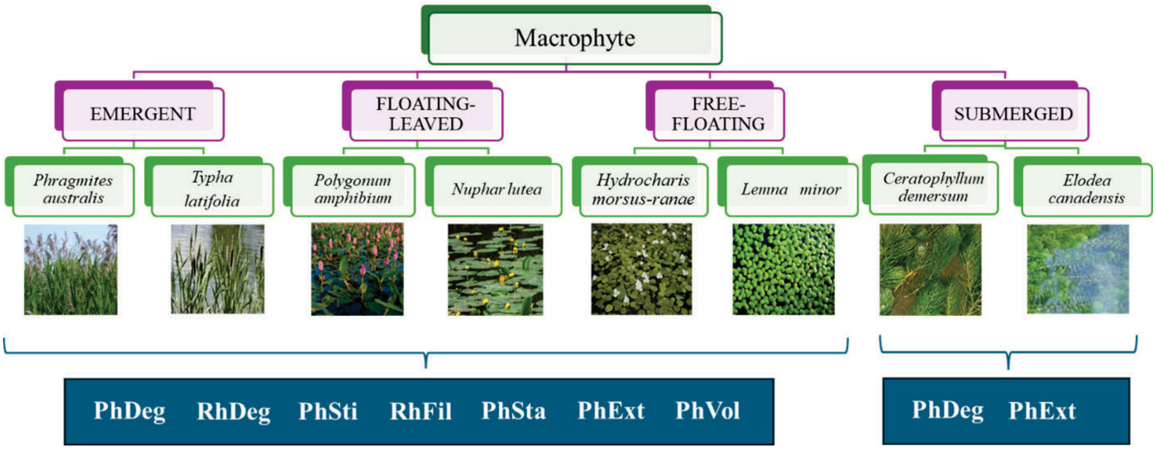

Fig. 5. Simplified diagram of the division of aquatic plants and their phytoremediation mechanisms; PhDeg = phytodegradation, PhSti = phytostimulation, PhExt = phytoextraction, PhSta = phytostabilisation, RhDeg = rhizodegradation, Rhfil = rhizofiltration, PhVol = phytovoltalisation; source: own elaboration based on Gałczyńska *et al.* (2019), Milke, Gałczyńska and Wróbel (2020), Milke and Gałczyńska (2021), and Vymazal (2022)

pollutants, thereby preventing their movement to groundwater or their access to the food chain (Iyyappan *et al.*, 2023). In phytovolatilisation, the collected pollutants can be partially transpired through stomata and evaporated in a modified form. Direct phytovolatilisation of wetland plants due to their adaptive properties, i.e. the presence of specialised tissues that allow O_2 transport to tissues growing in wet conditions, is likely to occur at a higher rate than in phytoremediation with trees. Indirect phytovolatilisation depends on the design of wetland systems, i.e. the type of flow: surface or subsurface. Phytovolatilisation can be carried out not only by metals (e.g. Se, As or Hg) but also by organic compounds such as benzene, trichloroethylene, phenol, nitrobenzene and atrazine (Limmer and Burken, 2016).

The purification potential of macrophytes is determined by the activity of microorganisms, the natural distribution of distinguished groups of aquatic plants in the aquatic ecosystem and the different modes of their activity due to the place of occurrence in the reservoir, conditions and preferences in the uptake of mineral components (Lacoul and Freedman, 2006; Shen, Li and Lu, 2021). Both limited access to light caused by turbidity and lower tolerance to toxic water pollutants favour the development of emerged species compared to submerged macrophytes (Toyama *et al.*, 2020). Individual plant species are also characterised by different phytoremediation efficiency.

Possibilities and limitations of using phytoremediation in aquaculture

Phytoremediation, like any technology, has its advantages and limitations (Fig. 6), therefore taking into account the latest literature data on the conditions of plant functioning in various wetland systems is crucial to maintain the assumed efficiency of wastewater treatment (Fraga-Santiago *et al.*, 2022).

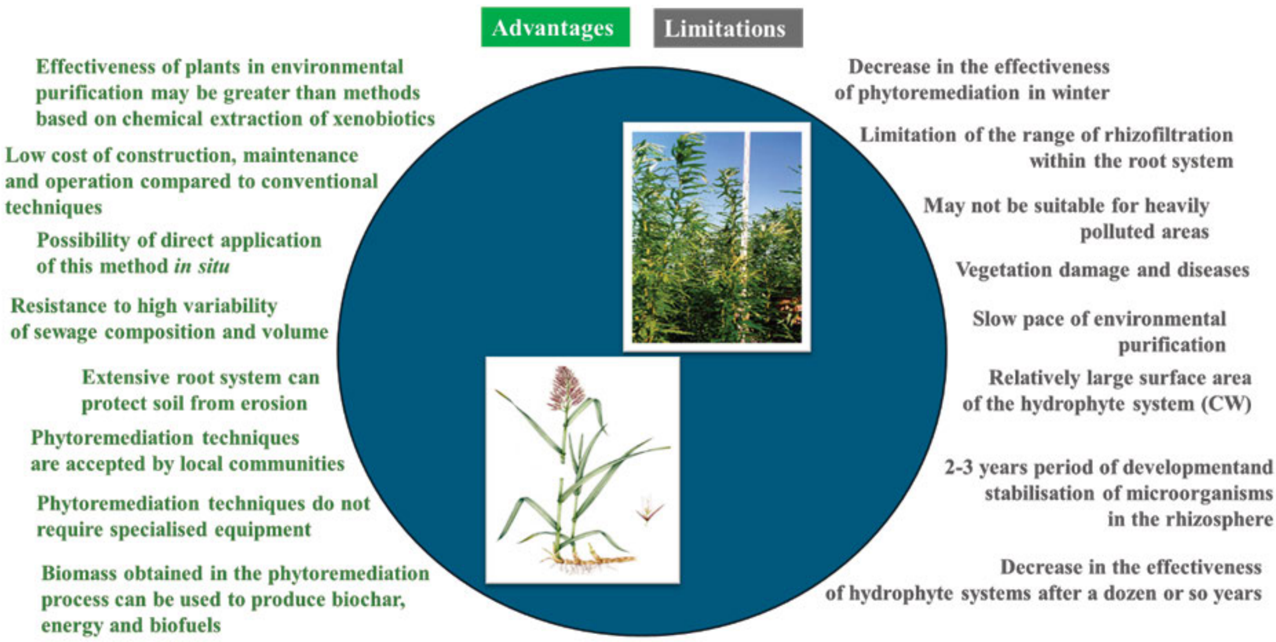

Fig. 6. Advantages and limitations of phytoremediation for emergent macrophyte (*Phragmites australis*) and *Salix viminalis*; CWs = constructed wetlands; source: own elaboration based on Farraji *et al.* (2016), Gałczyńska (2012), Fraga-Santiago *et al.* (2022), Mustafa, Hayder and Mustapa (2022)

Phytoremediation potential can be enhanced by genetic engineering (Fasani *et al.*, 2018), magnetic and electric field applications (Politaeva and Badenko, 2021), natural microbial stimulation, and chemical and natural additives (Kristanti and Hadibarata, 2023). The analyses conducted by Cho, Igliński and Kumar (2024) using biochar are promising and bring significant improvements in water quality.

Constructed wetlands

Constructed wetland (CW) is a complex consisting of: water with dissolved and undissolved chemical compounds, mineral substrate, dead plant parts, living plants, a huge number of microorganisms (bacteria, protozoa, fungi) and animals (invertebrates and vertebrates). Within the relationships between the individual elements of such a system, there is a large number of mechanisms influencing the removal of both inorganic and organic substances from sewage. In the sewage treatment process, the oxidation and reduction processes of chemical compounds are intensified, which are supported by the processes of sorption, sedimentation and assimilation, enabling the treatment of sewage (Li *et al.*, 2024).

When designing a constructed wetland treatment plant, the following are determined separately for each project: the expected volume of sewage, its chemical composition, pH, plant species intended for planting in specific climatic conditions, as well as the type of receiver, its size, shape, depth, bottom type, hydraulic conditions (hydraulic loading rate and hydraulic retention time) or support by additional clarifiers without vegetation, constantly or periodically aerated, and additional features of the selected area (Wu *et al.*, 2023).

Sewage composition

The physicochemical conditions of the fish growth environment in aquaculture result from the adopted system of breeding and raising a given fish species (Tab. 1). The conditions for discharging wastewater to surface waters are specified in the water-law report for each fishing enterprise. Sewage from fish farms is characterised by lower concentrations of biogenic compounds and suspensions than municipal sewage. Nevertheless, the mass of discharged pollutants, mainly from excrements and undigested food by fish, must be reduced (Comeau *et al.*, 2001).

Feeds, vitamins, macro- and micronutrients, and hormones used in fish nutrition affect the variability of the chemical composition of their fresh excrements (Naylor, Moccia and Durant, 1999). Disinfectant residues will also be present in sewage. Their use is intended to maintain cleanliness and hygiene during daily maintenance work on fish farms and for fish health prophylaxis. Currently, probiotics are widely used to combat diseases in aquaculture, especially *Oncorhynchus mykiss* as the most important commercial cold-water fish in the world (Rahimi *et al.*, 2022). Therefore, unused medicines and used chemicals may also appear in sewage in very small quantities. Their concentration in recirculating water is low and this should not pose any problems in the treatment of wastewater in constructed wetlands (Lei *et al.*, 2023).

Selection of plants for constructed wetlands

Macrophytes selected for artificial water and sewage treatment systems are characterised by high biomass growth, a well-developed fibrous root system, a preference for eutrophic sites, i.e. the occurrence of high concentrations of biogenic compounds, but also tolerance to their high variability and the ability to accumulate metals (Milke, Gałczyńska and Wróbel, 2020; Sayanthan, Hasan and Abdullah, 2024).

Due to the composition of wastewater from salmonid fish production (e.g. *Oncorhynchus mykiss*) and the climatic conditions prevailing in Poland, halophytes are the most suitable group of plants for use in constructed wetlands. These plants have a very extensive system of rhizomes with well-developed aerenchyma and can occur in hypoxic conditions. In turn, the tangled network of the root system creates an organic environment with a very large surface area, very quickly inhabited by microorganisms that actively participate in wastewater treatment. In addition, by effectively supplying oxygen to the root zone, they intensify the course of the processes of decomposition of organic matter and transformation of nitrogen and phosphorus compounds (Milke, Gałczyńska and Wróbel, 2020). Soil conditions of the substrate also affect the effectiveness of other phytoremediation mechanisms, such as rhizofiltration of metals.

The most effective halophytes used in hydrophyte lagoons include common reed (*Phragmites australis* (Cav.) Trin. ex Steud.), a species with high biomass (stem height from 2 to 6 m, length of horizontal stolons from 6 to 10 m), dynamic spreading by underground stolons (e.g. one specimen takes over 1 m^2 of surface in a season) and very good adaptive abilities, wide ecological amplitude and resistance to environmental stresses. The plant tolerates variable soil moisture, creating both terrestrial and aquatic reed beds in natural conditions (Milke, Gałczyńska and Wróbel, 2020).

The different growth forms of *Phragmites australis* facilitate the removal of pollutants from both the water column and sediments, depending on their distribution. This plant tolerates water salinisation with chlorides, is resistant to freezing and is characterised by strong biomass growth and high dynamics of vegetative growth through a system of underground, massive stolons. Rhizomes form the greatest density at a depth of 0.5 m. The lifespan of individual rhizomes is on average about 6 years and they can grow within a radius of 10 m at a rate of 1 m per year. *Phragmites australis* grows well on sandy and gravel substrates and peat soils to various types of gyttja and silt (Comeau *et al.*, 2001; Rezania *et al.*, 2019, Milke, Gałczyńska and Wróbel, 2020). In conditions similar to the terrestrial environment, the plant is characterised by a greater increase in biomass, associated with increased uptake of biogenic compounds, especially N, and better-developed mycorrhiza, which supports the plant in the decontamination process.

As the temperature decreases, the metabolic rate of reeds decreases, which leads to slower growth or, outside the growing season, to complete dormancy. The consequence of this is reduced nutrient uptake or cessation of this process (Li *et al.*, 2024). Studies conducted by this confirmed that in winter, wilted plants in CW can effectively remove ammonium nitrogen and participate in the decomposition of organic matter (decrease in *COD* concentration), affecting the abundance of microorganisms (e.g. *Rhodobacter*, *Catellibacterium*, *Hydrogenophaga*, *Geothrix*, and *Aeromonas*) and their community structure (Ding *et al.*, 2021).

Examples of the use of *Phragmites australis* in wetland systems for the treatment of wastewater from nutrients and organic substances, including from *Oncorhynchus mykiss* production, are presented in Table 2. The collected publications document the good effects of phytoremediation also in relation to river waters and aquifers using this plant. *Phragmites australis* effectively removes metallic elements, including heavy metals, from polluted waters (Milke, Gałczyńska and Wróbel, 2020). Both low and high concentrations of heavy metals such as copper or iron in sewage from a fish farm do not pose a threat to the growth and development of *Phragmites australis* in constructed wetlands. Thanks to various phytoremediation techniques (Fig. 5), metals from *Oncorhynchus mykiss* excrements, depending on their toxicity, are retained in the root zone of the plant or accumulated in other organs in the following order: root > rhizome > leaf > stem. This advantage of *Phragmites australis* is important due to the extension of monitoring of surface water quality in relation to copper concentration according to the Regulation of the Minister of Infrastructure of June 25, 2021 (Rozporządzenie, 2021). Additionally, studies by Couto *et al.* (2022) indicate good effects of eliminating various pharmaceuticals by aquatic plants due to their bioadsorption, biodegradation and absorption. In turn, Liu *et al.* (2013) emphasise that *Phragmites australis* can both: absorb and tolerate ciprofloxacin, oxytetracycline and sulfamethazine in the concentration range (0, 0.1, 1, 10, 100 and 1000 $\mu g \cdot dm^{-3}$), which are usually found in sewage. For example, oxytetracycline accumulation occurred via passive absorption and its distribution was consistent with the root > leaf > stem sequence. The results showed that high concentrations of these veterinary antibiotics (>10 $g \cdot dm^{-3}$) had a toxic effect on root activity and leaf chlorophyll, while hormesis occurred at low concentrations (0.1–1 $g \cdot dm^{-3}$). Therefore, it does not seem that the presence of pharmaceutical residues in the wastewater flowing into the constructed wetlands could negatively affect the removal of copper or iron from the constructed wetland system.

Characteristics of constructed wetlands using *Phragmites australis*

Due to the direction of sewage flow in constructed wetlands with *Phragmites australis*, we distinguish such systems (Vymazal, 2022):

1) surface flow system (SF systems) – these include ditches and constructed wetlands;
2) horizontal subsurface flow systems (HSSF systems) and vertical subsurface flow systems (VSSF systems);
3) hybrid systems that are any combination of the above systems.

In SF systems, sewage flow takes place above the ground surface in a layer up to 30 cm thick. *Phragmites australis* is exposed above the water. A small bottom slope of 0.5% or less is recommended to dry the plot for maintenance purposes. Regulating the outflow level also allows sewage to flow.

In subsurface flow systems (SSF), the sewage level is maintained below the ground surface. Sewage flows through a bed filled with sand, gravel or other soil. The depth of the bed, depending on the direction of sewage flow and the type of plants used, is 0.6–1.2 m, the bottom slope is 1–3%, and the slope of the bed bottom should be 2%.

The HSSF systems are recommended, in which sewage feeds the bed using a perforated pipe placed at the system inlet. Sewage flows horizontally through the bed, where it is purified. Purified sewage is discharged through a ditch filled with crushed stone and a device allows for flooding the bed and regulating the outflow. In the summer, a high level of sewage should be maintained, and in the winter – low.

In VSSF, sewage is supplied periodically using a dispenser. They are characterised by a smaller surface area than beds with horizontal flow. The drainage that discharges sewage is located at the bottom of the bed. In order to ventilate and provide greater access to oxygen, exhaust pipes are installed, and placed in rows

Table 2. Examples of applications of *Phragmites australis* and its companion *Typha latifolia* or *Typha orientalis* in constructed wetlands hydrophyte wastewater treatment systems

Plant	Contamination	Specification	Location and source
Ph. a., *T. o.*	biogenic and organic compounds	treatment of wastewater from *Oncorhynchus mykiss* breeding and farming with RAS in two constructed wetlands (an area of 100 m^2 and depth of 0.6 m, each with sand and crushed limestone)	Canada, Comeau *et al.* (2001)
Ph. a.	biogenic and organic compounds	treatment of wastewater from *Oncorhynchus mykiss* breeding and farming in three wetland systems 1.4 × 1.0 × 0.7 m; filling sand particle size 1–2 mm; flow 1, 3 and 5 $dm^3 \cdot min^{-1}$; 20 plants per 1 m^2	Germany, Schulz, Gelbrecht and Rennert (2003)
Ph. a., *T. l.*	metal elements	remediation of river water in three pilot wetland systems (0.18 × 0.050 × 0.050 m)	Taiwan, Yeh, Chou and Pan (2009)
Ph. a.	organic compounds	treatment of wastewater for a period of 24 mo, additionally iron oxide and charcoal were introduced	Germany, Seeger *et al.* (2011)
Ph. a., *T. l.*	organic compounds	pilot studies of wetland systems with an area of 35 m^2, daily flow rate 1 m^3	USA, Ranieri, Gikas and Tchobanoglous (2013)
Emergent and immersed in water	biogenic and organic compounds	treatment of wastewater from *Oncorhynchus mykiss* farming and breeding in a wetland system (area of 5,811 m^2 and volume of 4,139 m^3) with RAS; treated stream 12,960 $m^3 \cdot d^{-1}$ equal to make-up water	Danmark, Dalsgaard *et al.* (2018)

Explanations: *Ph. a.* = *Phragmites australis*, *T. l.* = *Typha latifolia*, *T. o.* = *Typha orientalis*, RAS = recirculating aquaculture systems.
Source: own elaboration based on the literature.

between drainage pipes discharging sewage. The VSSF-type beds can operate all year round.

Wetland systems with vertical subsurface sewage flow are characterised by a higher biodegradation potential compared to systems with horizontal subsurface flow. The efficiency is influenced by better oxygenation of such a system, which results in a greater number of microorganisms responsible for biodegradation processes in the bed. Nitrification processes are more effective in these systems (oxygen forms of nitrogen are the dominant form). In turn, in HSSF systems, conditions are favourable for the denitrification process (ammonium nitrogen predominates) but unfavourable for the nitrification process.

Efficiency of removing nutrients and organic matter

After the introduction of sewage into the constructed wetlands, the concentration of oxygen in the substrate filled with water quickly decreases due to its consumption in the process of decomposition of organic matter. Oxygen flows to the root system through aerenchyma developed in the stems and leaves of *Phragmites australis*. As a result of oxygen diffusion outside the roots, local oxygen microzones are formed around the rhizomes and roots. Behind these microzones there are hypoxic microzones – without O_2, but with NO_3^-, and after them reducing microzones appear – devoid of both O_2 and NO_3^- (Vymazal, 2022). The role of *Phragmites australis* metabolism in the process of decomposition of organic matter depends on the type of sewage treatment system used. The use of biogenic compounds by plants is only of quantitative importance in low-load systems with surface sewage flow. The processes leading to the removal of nitrogen from the system are the release of ammonia into the atmosphere, ammonification, nitrification and denitrification. The processes leading to nitrogen retention in the system are accumulation in biomass and sorption processes in the substrate (Hu *et al*., 2010).

$$\mathrm{2CH_2NH_2COOH + 3O_2{+}2H_3O^+(aq) \rightarrow 2NH_4{}^+(aq){+}4CO_2{+}4H_2O} \quad (2)$$

$$\mathrm{(NH_2)_2CO{+}H_2O \rightarrow 2NH_3{+}CO_2} \quad (3)$$

$$\mathrm{2NH_4{}^+(aq){+}3O_2{+}2H_2O} \\ \rightarrow 2NO_2{}^-(\mathrm{aq}){+}4\mathrm{H_3O^+(aq)}(Nitrosomonas) \quad (4)$$

$$\mathrm{2NO_2(aq){+}O_2 \rightarrow 2NO_3{}^-(aq)}(Nitrobacter) \quad (5)$$

Many heterotrophic bacteria of the genera *Pseudomonas* and *Achromobacter* participate in the denitrification process in conditions of the inflow of large amounts of easily decomposable organic matter.

$$\mathrm{4NO_3{}^-(aq){+}5\{CH_2O\}{+}4H_3O^+(aq) \rightarrow 2N_2{+}5CO_2{+}11H_2O} \quad (6)$$

The second gaseous product that is formed during denitrification in the presence of small amounts of oxygen is nitric oxide:

$$\mathrm{2NO_3{}^-(aq){+}2\{CH_2O\}{+}2H_3O^+(aq) \rightarrow N_2O + 2CO_2{+}5H_2O} \quad (7)$$

Studies conducted by Toyama *et al.* (2016) over a period of 42 days after planting *Phragmites australis* indicated that 31–44% of the total N from the sediment was removed via microbial nitrogen cycling and 56–69% was removed via plant uptake.

Phosphorus in hydrophyte systems is removed both by biotic processes (absorption by higher plants, plankton, periphyton and microorganisms and mineralisation of biomass and organic phosphorus found in the system filling) and abiotic processes (sedimentation and deposition, sorption in soil, precipitation and ion exchange processes between the solid and liquid phases). The greatest uptake of phosphorus by plants occurs during their greatest growth in summer and decreases in winter. Phosphorus accumulation in above-ground parts of plants is usually short-lived. During aerobic and anaerobic decomposition of dead tissues, depending on hydrobiological conditions and the availability of alternative electron acceptors, large amounts of phosphorus are produced. The part of detritus that has not decomposed enriches the soil, which leads to long-term retention of substances contained in it. The impact of phosphorus accumulation by living biomass (macroliths, algae, periphyton) is variable and can lead to both short-term and long-term phosphorus loss in the system. The average removal efficiency of phosphorus compounds in constructed wetlands in biotic processes, regardless of the sewage flow method, does not exceed 20%.

In constructed wetlands, organic substances are collected and retained. The removal of nitrogen and phosphorus accumulated in biomass by collecting above-ground parts of vegetation is small but can be significant for low-loaded wetland beds and is about 100–200 g of $N{\cdot}m^{-2}{\cdot}y^{-1}$ and 10–20 g of $P{\cdot}m^{-2}{\cdot}y^{-1}$ (Hu *et al*., 2010; Vymazal, 2022).

When oxygen and nitrates have been consumed, sulphates can serve as electron acceptors in the oxidation reaction of organic matter:

$$\mathrm{2\{CH_2O\}{+}H_3O^+(aq){+}SO_4{}^{2-}(aq) \rightarrow HS^-{+}2CO_2{+}3H_2O} \quad (8)$$

In the absence of any oxidant, dead organic matter can, however, be oxidised in anaerobic reactions, the final product of which is, among others, methane.

$$\mathrm{\{CH_2O\}{+}5H_2O \rightarrow CO_2{+}4H_3O^+(aq){+}4e^-} \quad (9)$$

$$\mathrm{CO_2{+}8H_3O^+(aq){+}8e^- \rightarrow CH_4{+}10H_2O} \quad (10)$$

Biodegradable organic compounds constitute on average 39% of all organic substances in sewage, and non-biodegradable – approx. 61%. The BOD_5 value decreases in constructed wetlands due to sedimentation, biological decomposition of dissolved organic matter and microbial respiration. The organic matter directly binds heavy metals and is a source of carbon and energy for microbial metabolism (Lee and Scholz, 2007).

Future prospects for the development of phytoremediation in aquaculture

Phytoremediation accompanies and supports aquaculture regardless of the intensity of fish production. In the case of *Cyprinus carpio*, technologies based on intra-pond systems, RAS, biofloc, small ponds, cages and their combinations are being developed, as well as those that are a combination of RAS and small ponds enabling plant growth in the winter (Stanivuk *et al*., 2024). Hydroponic production systems combined with intensive aquaculture systems (aquaponics) are also worth noting, which support the purification of post-production waters and the reuse of mineral nutrients. The effect of combining fish production with hydroculture technology is the preservation of the quality of surface and ground waters and meeting the need to purchase commercial fertilisers (Ghaly, Kamal and Mahmoud, 2005). In turn, integrated multi-trophic aquaculture is a new technology slowly developing in Europe, in which the synergistic culture of aquatic organisms from different trophic levels is integrated. In this system, uneaten food, faeces and excretory products of the fed fish species become food for other organisms such as herbivorous fish and e.g. seaweed. The integrated multi-trophic aquaculture (IMTA) strategy mitigates the effects of intensive aquaculture (Rusco *et al.*, 2024). Biofloc technology is a production system based on microorganisms that maintain water quality, provide a natural source of food for fish and compete with pathogens (Khanjani, Sharifinia and Emerenciano, 2024).

CONCLUSIONS

In this article, we illustrate how different types of solutions based on phytoremediation serve to solve a number of challenges faced by developing aquaculture in relation to the protection of natural resources, the increase of biodiversity and the preservation of good quality of farmed fish.

1. We have shown that macrophytes occurring both in carp ponds and in constructed wetlands, through various mechanisms of phytoremediation (phytostimulation, phytodegradation, rhizofiltration, phytostabilisation, phytoextraction), affect the reduction of the concentration of nutrients and metals in post-production waters discharged into watercourses. Additionally, by using the phytoremediation properties of the *Salix viminalis* in the ecotone zone of watercourses, we can positively influence the quality of aquatic ecosystems, regardless of the fish production system.
2. We have shown that farmed fish in Poland in ponds are not contaminated with heavy metals.
3. We have listed methods that influence the development of phytoremediation technology despite its limitations in terms of its impact on improving water quality, i.e. the use of genetic engineering in relation to macrophytes, magnetic and electric fields, natural microbiological stimulation and chemical and natural additives or biochar.
4. We have indicated that the development of aquaculture based on closed water cycles and at the same time resistance to climate change contributes to the development of new technologies using mineral nutrients that have not been taken up in the fish production process, and these include integrated multitrophic aquaculture, biofloc or the use of aquatic plants to enrich fish feed.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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