

Review

The Importance of Biological and Ecological Properties of *Phragmites Australis* (Cav.) Trin. Ex Steud., in Phytoremediation of Aquatic Ecosystems—The Review

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Abstract: *Phragmites australis* (common reed) is one of the most extensively distributed species of emergent plant worldwide. The adaptive features of this plant show its competitive character. Owing to high intraspecific diversity of common reed, as well as its phenotypic plasticity, the plant shows a broad ecological amplitude. Moreover, the plant exhibits a high capacity for acclimatization to environmental conditions which are considered adverse. This plant has been used for many years in phytoremediation to purify various types of wastewater. *Phragmites australis* has a high ability to accumulate various nutrients, heavy metals, and micropollutants, and in this respect, it is superior to other aquatic plants. This review examines the existing literature on the biological and ecological properties of common reed, the use of common reed in wastewater treatment for removing pollutants and tolerance for metals, and in hydrophyte treatment systems. It seems vital to conduct further research on the physiology and biochemistry of the common reed, with the aim of increasing the plant's efficiency for pollutants removal.

Keywords: *Phragmites australis*; pollutant removal; heavy metals; wastewater treatment; phytoremediation

1. Introduction

Freshwater ecosystems (lakes, ponds, rivers, streams, and wetlands) cover only 2.5 percent of our planet [1] and play a pivotal role in providing a large array of services for a fast-growing human population [2], which is predicted to reach around 9.7 billion by 2050 [3].

However, a significant increase in pollution of aquatic ecosystems due to human activities associated with urbanization, industrial development, and the intensification of agricultural activities was observed in last five decades [4,5]. The decrease of surface water quality is connected with the negative influence of either point or non-point sources of water pollution. Pollutants originating from municipal and industrial wastewater, as well as surface runoffs from arable fields, roads, and highways, were divided into physical (solid material), biological (micro-organisms such as bacteria), and various different chemical pollutants [6–8]. The most dangerous to aquatic ecosystems is chemical pollution, which includes compounds of phosphorus (P) and nitrogen (N) (used as fertilizers and formed as a result of the breakdown of human and animal wastes); radioactive elements (e.g., strontium (Sr), caesium (Cs), and radon (Rn)); heavy metals (e.g., mercury (Hg), cadmium (Cd), lead (Pb), and chromium (Cr)); and natural (crude oil) and synthetic organic chemicals, such as pesticides and other persistent pollutants (e.g., detergents, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, pharmaceuticals, and personal-care products, nanoparticles) [9–15]. Although most aquatic ecosystems

have a natural tendency to dilute pollution to some extent, severe contamination of aquatic ecosystems results in alterations in the fauna and flora of the community [16]. Therefore, particular attention is paid to actions aimed at reducing point and non-point pollution. A good solution is to use the next stage of wastewater treatment or protection of water reservoirs against surface runoff. A very interesting solution to this issue is provided by constructed wetlands (CWs). In many countries, different types of constructed wetlands have been created to improve water quality [17–20]. Regardless of flow type of the polluted water (surface or subsurface flow), CWs generally consist of the following: (1) an impermeable layer (generally clay or geomembrane), (2) a gravel layer that provides a substrate (i.e., an area that provides nutrients and enables development of microorganisms) for the root zone, and (3) an above-surface vegetation zone (emergent plant and aquatic plants) [21]. The impermeable layer prevents infiltration of wastes down into lower aquifers. The gravel layer and root zone are where water flows and bioremediation, as well as denitrification, take place. The aboveground vegetative layer accumulates nutrients and heavy metals in different tissues. Floating Treatment Wetlands (FTWs) constitute the latest version of CWs. These systems consist of a floating element (usually made of a plastic material) on which the plants are established and optically look like floating islands. As in the other CWs types, the plants develop a deep and dense root system within the underlying water column [20].

Constructed Wetlands have the following advantages when compared with the traditional sewage treatment methods:

- a. They are relatively inexpensive to construct and operate and are easy to maintain;
- b. They provide effective and ecologically friendly wastewater treatment;
- c. They can tolerate both great and small volumes of water and varying contaminant levels [22].

Plant species differ in their ability to extract biogenic compounds and metals from wastewater [23–27]. The common reed is a species that is very often used in these systems [28–30]. There are many reasons why reed is often chosen. Firstly, *P. australis*, as an emergent perennial plant, has a very wide geographical range that encompassed many climatic and ecological zones [31–36]. Reed is a typical swamp and aquatic plant species; it inhabits both aquatic and terrestrial ecosystems [37]. It is a cosmopolitan species, widespread in temperate and tropical regions around the world, except for Antarctica [33–35]. The natural range is difficult to determine due to the dilation of this species in many places in the world and its easy placement [38,39]. The plant is extensively distributed in North America, and, with the exception of Alaska, it can be found in all US states, Canadian provinces, and territories, except Nunavut and Yukon [40]. The common reed is a native plant to Puerto Rico and non-native to Hawaii [41]. In North America, the non-native common reed haplotype is extensively distributed [42]. Its occurrence extends from British Columbia to Quebec, and in the south, it is found throughout the contiguous United States [33]. The plant is common in Europe, North Asia, Central and South-West Asia (from the Mediterranean to Pakistan), East Asia, and in Australia [33,43,44]. *Phragmites australis* is found in a belt around the dense forest zone in tropical Africa, from Senegal east to Eritrea, as well as to the south of Ethiopia and Eritrea to Mozambique, Zimbabwe, Namibia, South Africa, and Swaziland. It also occurs in Madagascar [45]. The lineages and genotypes of *P. australis* are diverse both within and among populations. Moreover, genes from relatives from other phylogeographic regions and species can be incorporated into populations [31]. *Phragmites australis* is a cosmopolitan wetland grass which is classified as one species (Figure 1) but consists of three main phylogeographic groups [34,46].

Regardless of its geographical location, this species provides food and habitat for some organisms and serves to stabilize soils against erosion. Secondly, many biological features of this species predispose it to be used as a biological pollution filter [35]. In comparison with other species of emergent aquatic plants, *P. australis* has annual cane-like stems and is characterized by relatively high growth and mass (up to 6 m in height), show variations in diameter from 4 to 10 mm, and has long hollow internodes of 10–25 cm in length, as well as an extensive rhizome system. The perennial rhizomes have

both horizontal and vertical components. The extension of the size of the clone is due to horizontal rhizomes, while the annual upright stems are due to vertical rhizomes. Rhizomes are characterized by an extensive aerenchymatous tissue. Its roots develop from rhizomes and other submerged parts of shoots. Rhizomes form the largest densities at a depth of 0.5 m. The lifespan of individual rhizomes is, on average, about six years, and they can grow within a radius of 10 m, at a rate of 1 per year. It grows well on various types of substrates, from sandy and gravel, through peat soils to various types of gyttia and mules. The leaves are smooth, alternate with narrow-lanceolate laminae 20–70 cm long and 1–5 cm wide. They are closely nerved, and they taper to long slender points [42]. The inflorescence is a terminal panicle, often 30 cm long, lax, with a color from dull purple to yellow, and the main branches bear many spikelets. The smooth branches usually have scattered groups of long silky hairs [47] (Figure 2).

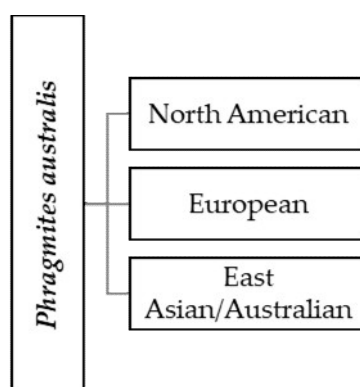


Figure 1. Main phylogeographic groups, sourced from Reference [31].



Figure 2. *Phragmites australis* (Photographers: Justyna Milke and Małgorzata Gałczyńska): (a) inflorescences in the form of panicles, (b) lanceolate leaves, (c) new green, young steams, (d) rhizomes

Thirdly, photosynthesis is the primary physiological process which determines plant growth and crop productivity and influences many other plant processes. There are three different plant systems in nature, viz., C_3 , C_4 , and crassulacean acid metabolism (CAM), characterized by CO_2 trapping mechanisms. However, C_4 and CAM plants are generally found to employ a C_3 pathway to trap CO_2 as the initial step. *P. australis* is a plant that exhibits photosynthetic properties of the C_3 pathway [48,49]. It was also observed that *P. australis* exhibits characteristics of both C_3 and C_4 pathways, because its carbon anhydrase activity is typical of a C_3 plant, while its phosphoenolpyruvate carboxylase activity ratio is indicative of a C_4 plant [50,51]. Table 1 shows the *P. australis* survival strategy in two types of environmental conditions.

The analysis of the information presented in Table 1 allows us to conclude that the phytoremediation process is more effective at low soil moisture than in a typical water environment (floating islands with *P. australis*). In conditions similar to the terrestrial environment, the plant is characterized by a greater increase in biomass, associated with an increased uptake of biogenic compounds, particularly N, and superiorly developed mycorrhiza, which supports the plant in the process of decontamination. The listed biological features of this species and its photosynthetic capacity for different mechanisms

of CO₂ trapping are related to relatively high growth, the possibility of obtaining high biomass in crop, and a highly developed root system—crucial adaptive properties of plants for phytoremediation of aquatic ecosystems.

Table 1. The C₃–C₄ ecotype of *Phragmites australis*. Modified from References [31,51].

The ecotype C ₃ –C ₄	
C ₃	C ₄
Aqueous conditions	Dry conditions
Temperature	
T < 22 °C	T > 22 °C
Photorespiration	
Can exceed 30%	Hardly achieve 5%
Mycorrhization	
Less Mycorrhization	Higher Mycorrhization
Biomass	
Less Biomass Accumulation	Higher Biomass Accumulation
Water use efficiency	
Less efficient	Highly efficient
Nitrogen use efficiency	
Less efficient	Highly efficient
Stomatal conductance	
High	Lower
Greenhouse gases—CO ₂	
Lower	High
Greenhouse gases—CH ₄	
High	Lower

Furthermore, even though *Phragmites australis* (Cav.) Trin. Ex Steud. is considered native to Europe, the adaptive features of this plant show its competitive character. Owing to high intraspecific diversity and phenotypic plasticity, the common reed shows an extensive ecological amplitude, as well as great acclimatization capacity to adverse environmental conditions. *Phragmites australis* grows in soils with various salinity [52–55], fertility [56], textures [57], and of different pH [28,58] and attains high productivity under different climatic conditions [10,32,59]. It is a highly adaptable emergent macrophyte, with a broad range of tolerance to flooding regimes [60–65]. Being a native species, *P. australis* shares many characteristics with invasive species [66–70].

The purpose of the present review article was to show the following: (1) The reed is a versatile and adaptable species and can therefore be implemented in constructed wetlands for phytoremediation in various geographical regions (wide geographical range, biological features of this species, and ecological background—the first section); (2) an overview of how well the reed can remove different pollutants from wastewater, in comparison to other aquatic species (the second section and fourth section); (3) presentation and summary analysis of the usefulness of applying the reed in different types of constructed wetlands to remove a number of frequently occurring pollutants (radar charts).

These characteristics aim at presenting the current research progress concerning the potential of *P. australis* for removing nutrients, heavy metals, and other chemical substances in wastewater treatment systems.

2. The Potential for Heavy Metal Absorption by Common Reeds Compared to Other Aquatic Plants

2.1. The Absorption of Heavy Metals by Plants

The contamination of aquatic environments is one of the most important global problems, because they are irreplaceable, and most of them, having exceeded certain concentrations of pollutants, have a toxic effect on living organisms. Reclamation of water ecosystem is the main priority for all ecologists worldwide. Even though metals are one of the largest categories of pollution, it is worth noting that they are perfectly removed by aquatic plants [71].

Metals with a high density ($\geq 5 \text{ g/cm}^3$) are often regarded as heavy metals. These metals are introduced into aquatic systems with agricultural runoff or industrial discharge. Increased levels of heavy metal contaminants in water have a negative effect on the ecological function of water, including recycling and primary production of nutrients. Moreover, the health of wildlife and humans is affected through bioaccumulation in the food chain, with the lasting impact of developing metal tolerance among certain organisms, even at a very low concentration [72]. Heavy metals are removed from the environment by aquatic plants through the following three processes [73,74]:

- (1) Plants attach the heavy metals to their cell wall;
- (2) The roots accumulate heavy metals and then translocate them to the shoots;
- (3) Hyperaccumulation (the ability to accumulate metals at very high concentrations in aboveground tissues, without phytotoxic effects).

Some heavy metals are needed for the upkeep and growth of aquatic plants. However, when the concentrations become excessive, the plant may be at a risk of heavy metal toxicity, both directly and indirectly [72]. Therefore, aquatic plants have developed defense mechanisms that allow toxic metals to survive [75–77]. Avoidance mechanisms constitute a strategy for extracting roots from the root cells out of the rhizosphere, e.g., compounds that heal metal ions [78] metal cations, including micronutrients, are primarily taken up by plant roots. According to Kushawha et al. [79], it is possible to attribute the cellular mechanism of detoxification and tolerance to metals to the following: (1) immobilization by mycorrhizal associations; (2) heavy metal restriction by binding to a plant cell wall (3) heavy metals chelation by root exudates, e.g., sugars and polysaccharides, organic and amino acids, peptides, and proteins; (4) reduced heavy metals influx by the plasma membrane; (5) active heavy metals efflux; (6) chelation by various ligands, i.e., phytochelatins, metallothioneins, and organic and amino acids.

In plants, heavy metals uptake takes place through the root system, but also through leaf blades. The easiest way for plants to take up metals from the soil is in the form of free ions, while the metals occurring in the form of complexes can be mobilized by active substances secreted by plant roots and then collected by plants [80,81]. The effectiveness of the phytoremediation process increases due to interactions between the plant's roots and the microorganisms in the rhizosphere.

2.2. The Role of Microbial Interactions with Common Reed in Heavy Metal Uptake

To a great extent, plant growth and development depend on the activity of soil microorganisms found in the rhizosphere. These microorganisms influence the shaping of plants in various ways [82], and the mutualisms between the plants and their microbiome are common and facilitate plant invasion processes [83]. *Phragmites australis* is a macrophyte that is very productive, and its root zone is rich in dissolved oxygen [84] and organic carbon [85], providing suitable conditions for the colonization of microorganisms. Bacteria and mycorrhizal fungi found in the rhizosphere play an important role in phytoremediation through degrading metals, organic pollutants, radionuclides, and xenobiotic compounds [83–91]. Soil microbes participate in mobilization of metals for plant uptake or immobilization of metals in the rhizosphere to restrict leaching. They help in these processes through acidification, chelation, and reduction of metals in the soil (for example, *Pseudomonas fluorescens*

produces citric acid, but *Rhodococcus* sp. Reduces Arsenic (As) (VI) to As (III) [92]. For example, in the rhizosphere of *P. communis*, the most abundant acidophilic bacterium *Gp6* and the dominant heterotrophic microorganism *Gp7* were important members of soil microbes. Zhao et al. [89] pointed out that As and Nickel (Ni) promoted the growth and reproduction of *Gp6* and *Gp7*. In turn, the dominant bacteria such as *Gp6* and *Longilinea* were involved in metabolizing multiple carbohydrates and amino acid in the soil. Aerobic tissues in the stems of *P. australis* enable the roots to release oxygen and other primary and secondary metabolites into the rhizosphere [85,93], and they consequently create an oxygen-enriched sediment microhabitat. In their research, Chaturvedi et al. [86] have shown that the rhizosphere of *P. australis* contains many aerobic microorganisms, such as *Microbacterium hydrocarbonoxydans*, *Achromobacter xylosoxidans*, *Alcaligenes faecalis* and species that belong to the genus *Bacillus* and *Pseudomonas*. Fifteen culturable bacterial species were grown on effluent-supplemented medium as a sole carbon source, resulting in the reduction of the levels of distillery effluent pollution with heavy metals. The latest research provides information on the impact of the winter or summer season on the diversity and composition of the microbiome [94], which, in addition to slowing cane vegetation, may additionally determine the rate of the phytoremediation process.

Arbuscular mycorrhizal fungi (AMF) also play a major role in decontamination of the rhizosphere. They are ubiquitous, obligatory plant symbionts. Fungi provide nutrition, particularly for plants. These microbes make plants more efficient in absorbing environmental resources, interact with indigenous microbes, and enhance the plant's tolerance to stress, by promoting the secretion of glycoproteins into the rhizosphere. The expansion of the mycelium can greatly extend the area of influence of the rhizosphere. Increasing the rhizosphere means an increase in the bacterial population, which can also contribute to the bioremediation process. Arbuscular mycorrhizal fungi have been reported to occur in the association with wetland plants, too. The community structure of AFM is characteristic for specific plant species [90]. Huang et al. [95] suggested that AMF symbiosis with roots of *P. australis* can result in a marked tolerance to Cd via accumulating Cd with a shorter exposure treatment time. The decrease in phytotoxicity was mainly accomplished by increasing enzyme activities and levels of thiolic compounds in roots. In another research, Wu et al. [91] pointed out that AMF could effectively improve the growth and physiological activity of *P. australis* under copper stress. Excess copper accumulation in *P. australis* leads to a decrease in photosynthetic enzyme activity, yet the inoculation AFM of *Rhizophagus irregularis* can alleviate this adverse effect. Regardless of copper concentration, the response of *P. australis* after AMF addition is closely related to intracellular energy transfer. In turn, Malicka et al. [90] reported a negative affect by the presence of polycyclic aromatic hydrocarbons and phenol on the roots' mycorrhizal colonization and AMF biomass in the soil.

2.3. Arrangement of Heavy Metals in Various Parts of Common Reed

The amount of metals taken in by plants is determined by the type of metal, their content in the soil, the forms in which they occur, and plant species [96]. Cell walls of individual root tissues form a barrier limiting migration of trace elements to the aboveground parts of plants. Bonanno et al. [97] reported that belowground organs were the primary areas of Cd, Cr, Copper (Cu), Hg, Manganese (Mn), Ni, Pb, and Zinc (Zn) accumulation. In particular, determined metal concentrations in *P. australis* organs show a decrease in the order of root > rhizome > leaf > stem.

Toxic effects of metals are associated with their excessive concentrations in the cell [98]. These concentrations cause disturbances in the functioning of membranes [99] in photosynthetic and mitochondrial electron transport, and also affect the inactivation of many enzymes involved in the regulation of basic cell metabolism, e.g., nitrate reductase [100], which in turn leads to a reduction in the energy balance of cells. Other specific effects include chlorosis and leaf necrosis, followed by traces of senescence and abscission, which lead to lower nutrient uptake and interfere with the biomass acquired [72].

Aquatic plants are natural absorbers of heavy metals and other nutrients; therefore, for many metals, there is a simple relationship between their content in the environment and the amount

accumulated in plants [101]. In addition, based on biochemical composition, habitat, species, abundance, and environment, these macrophytes manifest the ability to absorb the said pollutants at various rates and with different efficiencies [102]. Heavy metals concentrations in individual parts of aquatic plants (roots, stem, and leaves) are varied and depend on the species, environmental conditions, metal uptake, transport mechanisms, and interactions between metals [103]. The rate of photosynthetic activity and plant growth play a role in removing small to medium amounts of pollutants during the implementation of phytoremediation technology [104].

Phragmites australis is one of the most studied aquatic plants for removing heavy metals because of its high potential for metal removal and fast growth, as well as its accumulation of metal in aboveground and belowground biomass [69]. This plant tends to release excessive metal ions by transpiration, reducing toxic concentrations in leaf tissues [105]. It is also considered to be an "accumulator", that is, it accumulates metals in the roots [106]. Rzymiski et al. [6] noted the accumulation of Cr, Cd, Cu, Cobalt (Co), Iron (Fe), Pb, Mn, Ni, and Zn in the roots of *P. australis*, as well as the translocation of Cd and Pb in the leaves. Peltier et al. [107] observed high accumulations of Zn and Mn in the roots of *P. australis*.

Table 2 shows concentrations of heavy metals in the organs of *P. australis*, in studied mesocosms and water ecosystems.

Kastratović et al. [108] investigated the accumulation of Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn, Sr, and V in sediment, water, and different organs of *P. australis*. The plants were collected from Lake Skadar, Montenegro, in different seasons of 2011. The concentrations of five (Cd, Cu, Mn, Zn, and Sr) out of the ten metals under analysis were found to be higher in the plant than in sediment during, as well as after, the growing season. At the same time, metal concentrations determined in the plants were found to be much higher than those identified in the water. This indicates that the sediment is the major source of the metals absorbed by the plant roots. Prica et al. [113] analyzed the concentrations of heavy metals (Fe, Mn, Ni, Zn, Pb, Cd, Co, and Cu) in *P. australis* plants spontaneously growing in shallow water of several mine tailing ponds. It was revealed that behavior of the metals within the plant and their toxicity are not merely a function of their total concentrations but also depend on the plant species and mechanisms involved in sequestration and translocation of particular metals within the plant. The study by Bonanno [111] showed bioaccumulation of trace elements in three wetland plants located around the worldwide: *Typha domingensis*, *P. australis*, and *Arundo donax*. The purpose of the study was to demonstrate which species shows superior potential for the removal and monitoring of the following elements: Al, As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, and Zn. It was found that all species have the potential to be used as biomonitors of trace element contamination in sediment; however, only *P. australis* and *A. donax* exhibited a correlation with water. Many studies indicate that, in *P. australis*, the concentration of accumulated metals is higher in belowground organs than in ground organs. Other studies show the following order of metal accumulation: roots > leaves > stems [29,123,124]. In their research, Klink et al. [122] showed that the roots of the *P. australis* were correlated with the highest Mn, Fe, and Cu concentrations. The highest Pb, Zn, and Cd concentrations were identified in *Typha latifolia* roots. Despite the differences in the ability to accumulate trace metal between the studied species, the concentrations of Fe, Cu, Zn, Pb, and Ni in the *P. australis* and *T. latifolia* followed the accumulation pathway: roots > rhizomes > leaves > stems. Mn concentration decreased according to the following order: root > leaf > rhizome > stem. There are some common characteristics of wetland plants, e.g., high tolerance to toxic element levels, capacity of phytostabilization, and different element concentrations in various organs [97]. Despite some ecological and morphological similarities, different plant species respond differently to heavy metals exposure. This may result from an ability of a given species to accumulate and detoxify various metals rather than differences in their ecological and morpho-anatomical characteristics [115]. In the study by Chernykh et al. [121], the regularities of accumulation of heavy metals (Fe, Cu, Zn, Cd, and Pb) and As in various types of aquatic vegetation were studied, with respect to season and the levels of pollution of the Srepok River (Vietnam). The results show that the concentrations of Fe, Cu, Zn, As, Cd, and Pb in all studied areas of the river were higher in the roots of water hyacinth and common reed than in the stems.

Table 2. Heavy metal concentrations in the organs of *P. australis* (mg/kg, standard deviation SD).

Element	Organs				Type of Systems	Climatic Conditions						References
	Root	Rhizome	Stem	Leaf		Climate Zone	Aquatic Ecosystem Type	°C	Precipitation (mm)	Flow (m ³ /s)	Month	
Cr	6.87 min 3.32 max 10.3	-	1.77 min 1.05 max 2.68	0.66 min 0.28 max 1.24	natural	subtropical climate with a Mediterranean variety	lake	8.7	1245	-	April June August October	[108]
	5.32 min 3.81 max 6.84	5.32 min 3.81 max 6.84	0.571 min 0.241 max 0.901	0.571 min 0.241 max 0.901	natural	moderate warm climate	lake	8.7	397.1	-	April	[8]
	11.06 ± 0.52	-	8.82 ± 0.09	-	natural	Mediterranean climate	wetland	13.6	-	-	-	[109] *
Co	2.805 min 0.60 max 5.57	-	0.112 min 0.06 max 0.14	0.302 min 0.14 max 0.46	natural	subtropical climate with a Mediterranean variety	lake	-	-	-	April June August October	[108]
	1.1	-	0.22	0.31	natural	subtropical continental climate	wetland	-	1280	-	April	[110]
	6.72 ± 0.20	-	5.09 ± 0.036	-	natural	Mediterranean climate	wetland	13.6	-	-	-	[109] *
Ni	4.78 ± 0.67	3.89 ± 0.56	0.79 ± 0.06	2.59 ± 0.18	natural	Mediterranean subtropical climate	shallow water coastal	12.0–18.0	400–1000	-	-	[97]
	8.36 ± 0.98	0.79 ± 0.06	-	2.21 ± 0.36	natural	Mediterranean subtropical climate	river	19.3	622	1.0	October	[111]
	41.2 min 23.5 max 63.1	12.03 min 1.8 max 31.4	9.65 min 2.5 max 24.9	12.31 min 2.9 max 28.3	natural	extremely dry climate	wetland	25.4	111	-	March	[112]
Cu	298.6 ± 2.1	24.9 ± 3.8	12.6 ± 0.15	11.3 ± 1.05	natural	moderate warm climate	mine tailing pond	11.3	631	-	season summer	[113]
	18.8 min 11.2 max 26.4	18.8 min 11.2 max 26.4	22.3 min 12.0 max 12.3	22.3 min 12.0 max 12.3	natural	moderate warm climate	wetland	21	690	-	August	[114]
	67.08 min 12.3 max 138.6	14.38 min 7.1 max 24.8	13.41 min 7.2 max 21.5	14.5 min 10.9 max 17.4	natural	extremely dry climate	wetland	25.4	111	-	March	[112]

Table 2. Cont.

Element	Organs				Type of Systems	Climatic Conditions						References
	Root	Rhizome	Stem	Leaf		Climate Zone	Aquatic Ecosystem Type	°C	Precipitation (mm)	Flow (m ³ /s)	Month	
Zn	135 ± 15.7	-	21.4 ± 3.32	66.5 ± 8.43	natural	Mediterranean subtropical climate	coastal wetland	18.0	-	0.50–2.0	April October	[115]
	76.0 min 55.0 max 131.0	-	49.0 min 27.0 max 69.0	39.5 min 39.0 max 106.0	natural	dry tropical climate	lake	21.3	18	-	-	[116] *
	-	21.85 min 17.28 max 27.93	15.46 min 9.10 max 21.02	17.89 min 14.38 max 20.45	natural	moderate warm climate	river	11.3	631	-	September	[117]
Cd	1.13 ± 0.08	1.00 ± 0.08	0.68 ± 0.06	1.05 ± 0.10	natural	Mediterranean subtropical climate	river	11.8–26.8	430	-	August September	[118]
	5.64 ± 5.64	0.54 ± 0.09	0.0 ± 0	0.05 ± 0.02	natural	moderate warm climate	mine tailing pond	11.3	631	-	season summer	[113]
	5.63 min 1.8 max 4.3	2.3 min 0.5 max 3.8	2.18 min 0.5 max 4.6	1.8 min 0.3 max 3.8	natural	extremely dry climate	wetland	25.4	111	-	March	[112]
Hg	3.06 ± 0.55	-	0.97 ± 0.04	1.84 ± 0.21	natural	Mediterranean subtropical climate	river	19.3	622	1.0	October	[111]
	0.91 ± 0.11	0.74 ± 0.09	0.27 ± 0.03	0.54 ± 0.06	natural	Mediterranean subtropical climate	shallow water coastal	12.0–18.0	400–1000	-	-	[97]
	0.230 min 0.189 max 0.321	0.055 min 0.011 max 0.089	-	0.0342 min 0.019 max 0.067	natural	moderate warm climate	shallow coastal lagoon	14.4	1178	-	-	[119]
Pb	8.45 ± 1.12	-	0.66 ± 0.07	2.05 ± 0.24	natural	Mediterranean subtropical climate	coastal wetland	18.0	600	0.50–2.0	April October	[115]
	117.3 ± 11.7	17.5 ± 2.1	11.2 ± 2.0	5.8 ± 0.9	natural	moderate warm climate	mine tailing pond	11.3	631	-	summer season	[113]
	272.4	263.1	257.5	255.9	natural	extremely dry climate	drainage	25.4	111	20–80	July	[120]

Table 2. Cont.

Element	Organs				Type of Systems	Climatic Conditions						References
	Root	Rhizome	Stem	Leaf		Climate Zone	Aquatic Ecosystem Type	°C	Precipitation (mm)	Flow (m ³ /s)	Month	
As	2.85 ± 0.34	-	0.23 ± 0.04	0.44 ± 0.66	natural	Mediterranean subtropical climate	coastal wetland	18.0	600	0.50–2.0	April October	[115]
	9.09 ± 2.89	-	6.06 ± 1.55	-	natural	moderately climate zone warm	river	-	-	-	March October	[121]
	-	2.97 min 0.53 max 6.56	0.97 min 0.23 max 1.78	0.49 min 0.00 max 0.98	natural	moderate warm climate	river	11.3	631	-	September	[117]
Mn	784 ± 240	76.3 ± 23.3	61.1 ± 18.7	509 ± 156	natural	moderate warm climate	lake	8.4	551	-	July August	[122]
	181.1 min 85.7 max 378	34.2 min 5.00 max 75.0	36.1 min 7.3 max 93.0	108.5 min 16.7 max 248.2	natural	extremely dry climate	wetland	25.4	111	-	March	[112]
	558 ± 84.3	157 ± 24.6	44.5 ± 7.23c	336 ± 56.2	natural	Mediterranean subtropical climate	shallow water coastal	12.0–18.0	400–1000	-	-	[97]
Fe	1481 ± 438	709 ± 205	41.6 ± 12.0	101 ± 29.3	natural	moderate warm climate	lake	8.4	551	-	July August	[122]
	459.7 ± 23.02	-	31.3 ± 4.3	122.9 ± 9.2	natural	subtropical continental climate	wetland	-	-	-	December	[123]
	4303 min 3003 max 5688	440.2 min 299.9 max 667.9	260.6 min 122.7 max 333.3	326.8 min 200.3 max 380.3	natural	extremely dry climate	wetland	25.4	111	-	March	[112]
Al	3153 ± 264	513 ± 64.21	67.30 ± 8.55	389 ± 27.31	natural	Mediterranean subtropical climate	river	18.1	430	-	August September	[29]
	2570 ± 420	-	86.6 ± 10.3	345 ± 29.8	natural	Mediterranean subtropical climate	river	19.3	622	1.0	October	[111]
	2394.20 ± 74	-	706.7 ± 55.6	-	natural	Mediterranean climate	wetland	13.6	-	-	-	[109] *

Table 2. Cont.

Element	Organs				Type of Systems	Climatic Conditions						References
	Root	Rhizome	Stem	Leaf		Climate Zone	Aquatic Ecosystem Type	°C	Precipitation (mm)	Flow (m ³ /s)	Month	
Se	<0.50	<0.50	<0.50	<0.50	natural	Mediterranean subtropical climate	river	18.1	430	-	August September	[29]
	-	1.12 min 0.89 max 1.44	1.25 min 1.91 max 0.86	1.26 min 1.04 max 1.61	natural	moderate warm climate	river	11.3	631	-	September	[117]
V	9.09 ± 0.98	-	<0.14	0.46 ± 0.1	mesocosm	Mediterranean subtropical climate	constructed wetland	-	-	-	May September	[124] *
	-	0.75	-	-	natural	subtropical continental monsoon climate	river	16.0	820	-	July September	[125]
	3.01 min 0.29 max 6.91	-	0.25 min 0.00 max 0.18	0.05 min 0.00 max 0.15	natural	subtropical climate with a Mediterranean variety	lake	8.7	1245	-	April October	[126]
B	17.60 ± 2.52	37.40 ± 4.93	11.0 ± 0.88	25.90 ± 2.94	natural	subtropical climate	river	18.1	430	-	August	[29]
	-	0.00	0.00	0.81 min 0.16 max 2.10	natural	moderate warm climate	river	11.3	631	-	September	[117]

Legends: standard error (SE)*. Aluminum (Al), Selenium (Se), Vanadium (V), Boron (B).

The present review of the literature allowed us to develop a graph in which metal arrangement in common reed organs was marked (Figure 3). In accordance with environmental standards for waters in Poland (Regulation of the Minister of the Environment of July 21, 2016, on how to classify the status of surface water bodies and environmental quality standards for priority substances), the elements leading to deterioration of surface waters are marked in red.

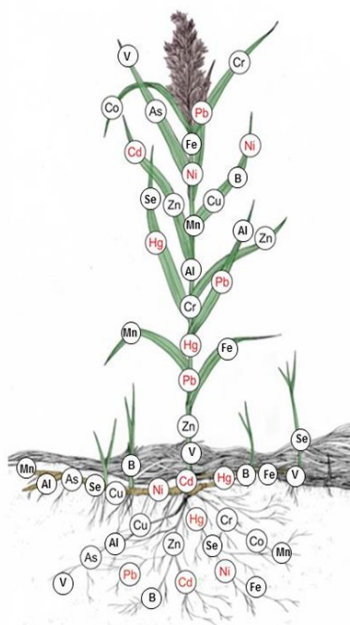


Figure 3. Arrangement of heavy metals in various parts of *P. australis*, own study.

2.4. Comparison of Removal of Heavy Metals by Common Reed and Other Aquatic Plants

The review of scientific papers published between 1995 and 2020 was carried out in relation to three terms: phytoremediation, aquatic plants, and heavy metals found in the title and keywords of articles. The total number of records was 7617 (Figure 4). *Phragmites australis* appeared in 25.4% scientific papers. The selection of other species to compile the data in Table 3 was also based on the percentage share of other aquatic plant species in the phytoremediation of aquatic ecosystems contaminated with heavy metals. The list of plant species includes the diversity of their habitat (emergent: *T. latifolia*—14.2% all articles, *Hippuris vulgaris*—0.3%; submerged: *Ceratophyllum demersum*—9.3%; floating aquatic plants: *Lemna minor*—18.8%, *Eichornia crassipes*—18.6%, *Pistia stratiotes*—9.7%, *Hydrocharis morsus-ranae*—0.5%). Other species described in the literature accounted for 3.2%. Among the floating aquatic plants, there are data on a high capacity of *H. morsus-ranae*. This species, especially in Canada, creates compact floating mats and, since it is invasive, reduces the biodiversity of local aquatic ecosystems [127]. The fight against this species brings positive effects because the mechanical removal of this plant from reservoirs contributes to reducing the concentration of heavy metals in water. Another species little described in the literature is *H. vulgaris*. Information on its heavy metal uptake capacity is given in Table 3, below, as this species can be used in the treatment of municipal wastewater not only in Europe, but also in Asian countries, such as China. In addition, this plant occurs in various forms, as terrestrial, wetland, and underwater.

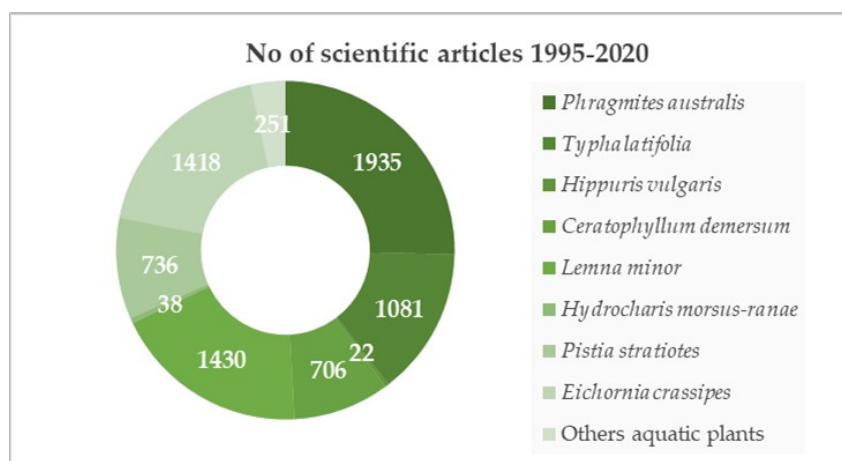


Figure 4. Number of scientific articles from 1995 to 2020 on aquatic plants used in phytoremediation with respect to heavy metals.

Table 3. Comparison of removal of metals by some water plants.

Metal	Aquatic Plants	Removal Rate	Concentration Metal in the Environment mg/L	pH	References
Cu	<i>Phragmites australis</i>	Cu—96.4%	0.041–0.051	7.24–8.34	[128]
	<i>Typha latifolia</i>	Cu—67.73%	0.240	7.11–8.48	[101]
	<i>Hippuris vulgaris</i>	Cu—0.8–34.2%	0.120	7.2	[12]
	<i>Ceratophyllum demersum</i>	Cu—79.8%	40	-	[129]
	<i>Lemna minor</i>	Cu—87%	0.067 ± 0.002	7.17–7.52	[130]
	<i>Hydrocharis morsus-ranae</i>	Cu—85%	0.120	6.3–7.2	[131]
	<i>Pistia stratiotes</i>	Cu—53.20%	5	-	[26]
	<i>Eichhornia crassipes</i>	Cu—78.6%	0.001	7.4	[132]
Pb	<i>Phragmites australis</i>	Pb > 99%	0.890	4.2–7.5	[133]
	<i>Typha latifolia</i>	Pb—83.83%	10	-	[25]
	<i>Hippuris vulgaris</i>	Pb—0.3–6.7%	0.600	7.2	[12]
	<i>Ceratophyllum demersum</i>	Pb—48.54%	0.210	6.2	[134]
	<i>Lemna minor</i>	Pb—78%	0.830	7.9	[135]
	<i>Hydrocharis morsus-ranae</i>	Pb—95%	0.600	6.3–7.2	[131]
	<i>Pistia stratiotes</i>	Pb—43.02–76.66%	0.860	8.4	[136]
	<i>Eichhornia crassipes</i>	Pb—36.09–84.41%	0.860	8.7	[136]
Cd	<i>Phragmites australis</i>	Cd—89.12%	5	-	[137]
	<i>Typha latifolia</i>	Cd—89.12%	5	-	[25]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cd—82%	0.360	7.0	[138]
	<i>Lemna minor</i>	Cd—44.93%	0.023	<7	[139]
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Cd—47.4%	0.190	6.5–7.7	[140]
	<i>Eichhornia crassipes</i>	Cd—20%	10	6.8–7.5	[141]

Table 3. Cont.

Metal	Aquatic Plants	Removal Rate	Concentration Metal in the Environment mg/L	pH	References
Cr	<i>Phragmites australis</i>	Cr—96.61%	15	-	[25]
	<i>Typha latifolia</i>	Cr—78.07%	0.150	7.1–8.4	[101]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cr—56.4%	0.210	6.20	[134]
	<i>Lemna minor</i>	Cr—72–91%	0.062	6.5–7.5	[142]
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Cr—77.3%	2	-	[143]
	<i>Eichhornia crassipes</i>	Cr—80.9%	2	-	[143]
Zn	<i>Phragmites australis</i>	Zn—98%	0.100	>12	[144]
	<i>Typha latifolia</i>	Zn—66.2%	0.945	7.3	[132]
	<i>Hippuris vulgaris</i>	Zn—15.6–29.2%	2.400	7.2	[12]
	<i>Ceratophyllum demersum</i>	Zn—58.65%	1.850	6.2	[134]
	<i>Lemna minor</i>	Zn—83%	1.470	7.9	[135]
	<i>Hydrocharis morsus-ranae</i>	Zn—95%	2.400	6.3–7.2	[131]
	<i>Pistia stratiotes</i>	Zn—26.99–79.57%	1.670	8.4	[136]
	<i>Eichhornia crassipes</i>	Zn—62%	4.050	7.0–7.8	[145]
Hg	<i>Phragmites australis</i>	Hg—37.8–92.9%	5.920	8.36	[146]
	<i>Typha latifolia</i>	Hg—46.63%	0.050	-	[147]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cannot be found in the available literature			
	<i>Lemna minor</i>	Hg—82.84%	2	7.48	[148]
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Hg—62.14%	5	-	[26]
	<i>Eichhornia crassipes</i>	Hg—16.52%	0.450	5.5	[27]
As	<i>Phragmites australis</i>	As > 99%	2.030	4.2–7.5	[133]
	<i>Typha latifolia</i>	Cannot be found in the available literature			
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cannot be found in the available literature			
	<i>Lemna minor</i>	As—70%	0.500	-	[149]
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Cannot be found in the available literature			
	<i>Eichhornia crassipes</i>	As—74%	0.596	7.4	[132]

Table 3. Cont.

Metal	Aquatic Plants	Removal Rate	Concentration Metal in the Environment mg/L	pH	References
Ni	<i>Phragmites australis</i>	Ni—98%	0.100	>12	[144]
	<i>Typha latifolia</i>	Ni—76%	1.210	7.9	[135]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Ni—52.5%	2	7	[150]
	<i>Lemna minor</i>	Ni—76%	0.112	<7	[139]
	<i>Hydrocharis morsus-ranae</i>	Ni—91.4%	0.057	6.9–7.2	[131]
	<i>Pistia stratiotes</i>	Ni—28.96–68.79%	1.310	8.4	[136]
	<i>Eichhornia crassipes</i>	Ni—25.68–81.56	1.830	8.7	[136]
Co	<i>Phragmites australis</i>	Co—76.86%	0.044	6.6	[151]
	<i>Typha latifolia</i>	Co—82.2–84.2%	0.004	7.0–7.5	[152]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cannot be found in the available literature			
	<i>Lemna minor</i>	Co—87%	0.0002	-	[153]
	<i>Hydrocharis morsus-ranae</i>	Co—98.6%	0.0286	6.9–7.2	[131]
	<i>Pistia stratiotes</i>	Cannot be found in the available literature			
	<i>Eichhornia crassipes</i>	Cannot be found in the available literature			
Mn	<i>Phragmites australis</i>	Mn—96.9%	2.560–3.750	7.3	[154]
	<i>Typha latifolia</i>	Mn—65.24%	0.150	7.1–8.4	[101]
	<i>Hippuris vulgaris</i>	Mn—10.4–37.9%	1.200	7.2	[12]
	<i>Ceratophyllum demersum</i>	Mn—81%	0.050	6.2	[134]
	<i>Lemna minor</i>	Mn—94.3%	5	6.29–7.7	[155]
	<i>Hydrocharis morsus-ranae</i>	Mn—90%	1.200	6.3–7.2	[131]
	<i>Pistia stratiotes</i>	Mn—94.3%	5	6.29–7.7	[155]
	<i>Eichhornia crassipes</i>	Mn—22%	4.050	7.0–7.8	[145]
Fe	<i>Phragmites australis</i>	Fe > 98%	61.540	4.2–7.5	[133]
	<i>Typha latifolia</i>	Fe—70.09%	0.950	7.1–8.4	[101]
	<i>Hippuris vulgaris</i>	Fe—4.2–104.2%	2.400	7.2	[12]
	<i>Ceratophyllum demersum</i>	Fe—67.5%	0.020	6.28	[156]
	<i>Lemna minor</i>	Fe—77%	1.170	7.9	[135]
	<i>Hydrocharis morsus-ranae</i>	Fe—88%	2.400	6.3–7.2	[131]
	<i>Pistia stratiotes</i>	Fe—83.20%	5	-	[26]
	<i>Eichhornia crassipes</i>	Fe—61%	0.320	7.4	[132]

Table 3. Cont.

Metal	Aquatic Plants	Removal Rate	Concentration Metal in the Environment mg/L	pH	References
Al	<i>Phragmites australis</i>	Al—96%	1	8.7	[124]
	<i>Typha latifolia</i>	Al—96%	1	8.8	[124]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Al—95.89%	3	7.0	[157]
	<i>Lemna minor</i>	Cannot be found in the available literature			
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Al—73%	0.320	7.4	[149]
	<i>Eichhornia crassipes</i>	Al—63%	4.050	7.0–7.8	[145]
V	<i>Phragmites australis</i>	V—50%	0.095	-	[124]
	<i>Typha latifolia</i>	Cannot be found in the available literature			
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	V—50%	0.095	-	[124]
	<i>Lemna minor</i>	Cannot be found in the available literature			
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Cannot be found in the available literature			
	<i>Eichhornia crassipes</i>	Cannot be found in the available literature			
B	<i>Phragmites australis</i>	B—40%	1	8.7	[124]
	<i>Typha latifolia</i>	B—12.5–21.4%	25	6.0	[124]
	<i>Hippuris vulgaris</i>	Cannot be found in the available literature			
	<i>Ceratophyllum demersum</i>	Cannot be found in the available literature			
	<i>Lemna minor</i>	B—12%	32	7.8	[158]
	<i>Hydrocharis morsus-ranae</i>	Cannot be found in the available literature			
	<i>Pistia stratiotes</i>	Cannot be found in the available literature			
	<i>Eichhornia crassipes</i>	Cannot be found in the available literature			

Despite the large number of publications on phytoremediation, it was not possible to document the effectiveness of wastewater treatment by several plant species for some metal concentrations in wastewater. Nevertheless, the data in Table 3 may provide useful information on the high degree of wastewater treatment, with varying metal concentrations through the common reed and other biofilters.

Depending on the concentration of heavy metals in polluted waters and information on the efficiency of their removal, it can be indicated, with some probability, which species of aquatic plants, under given conditions, are most suitable for phytoremediation. High efficiency of this process, over 90 percent gives the possibility of using only one species for water purification. The construction of multi-species biological systems is associated with many problems. One of them is the possibility of inter-species competition, which, over time, can lead to the dominance of one species. The next problem may be the ease of transferring pathogens between co-growing plant species. Moreover, not less important is having the knowledge and skills to perform various care treatments in relation to these species. The positive effect of using, for example, two or three species is the ability to reduce even very high metal concentrations in treated waters. By analyzing the combination of the efficiency of removing a given metal from water by selected plant species, it can be determined which of them,

one by one, could be reduced by absorption of the concentration of this metal in water. For example, for Hg (Figure 5), such a sequence would look like the following:

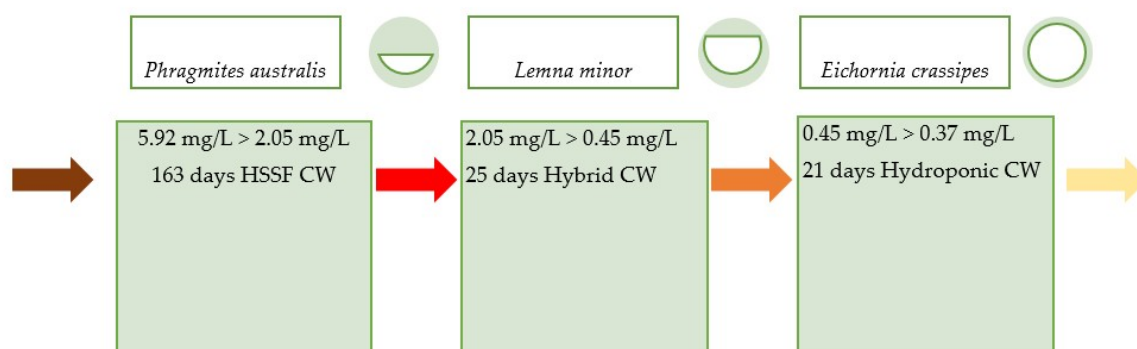
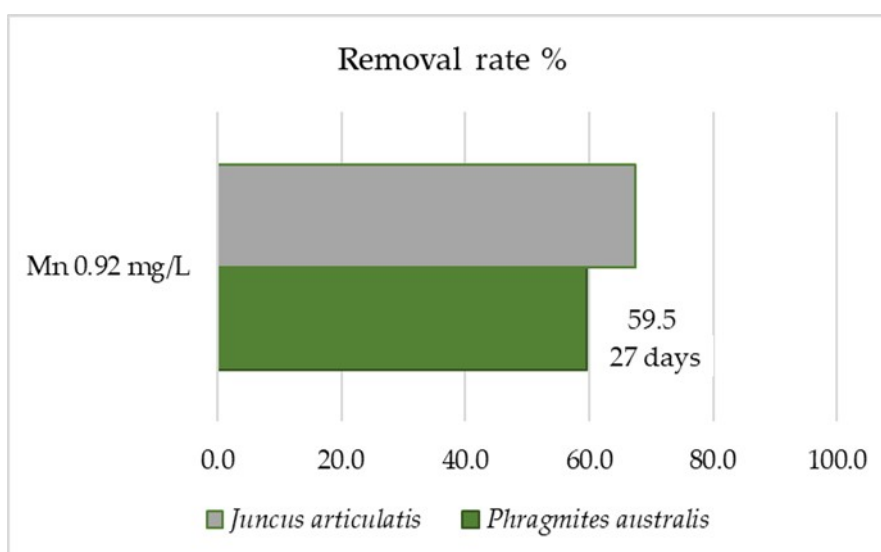


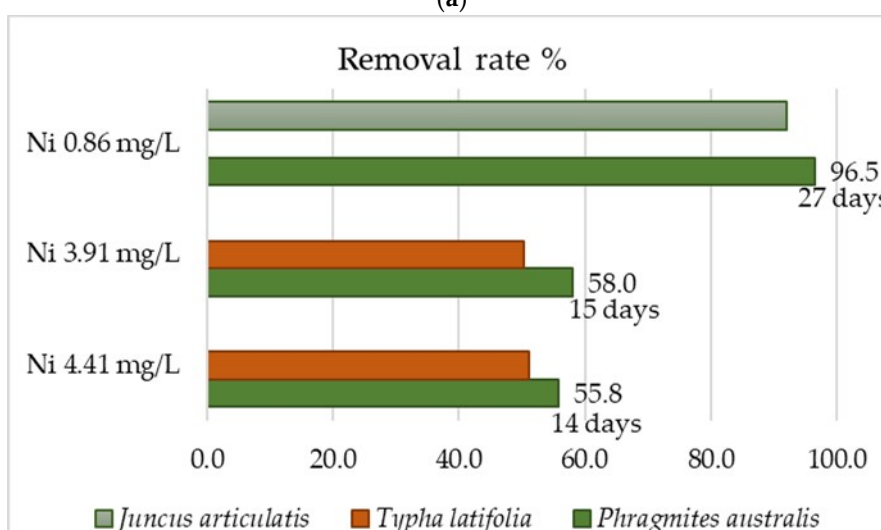
Figure 5. Plant sequence as biosorbents and the effect of reducing Hg concentration in water.

In this combination, with a high level of pollution 5.92 mg Hg/L, the first species that could participate in phytoremediation would be *P. australis* (mean rate efficiency 65%), followed by *L. minor* (82.84%), and finally, after acidification of the environment to pH 5.5, *E. crassipes* (16.52%). The entire biosorption system could potentially remove this toxic metal to 0.37 mg/L, which is a 93.75% reduction in concentration. This hypothetical arrangement of consecutive plots of constructed wetland with the listed plant species and wastewater retention time is a proposal that requires testing. However, this gives grounds for the composition of constructed wetlands with a high degree of mercury removal in wastewater treatment.

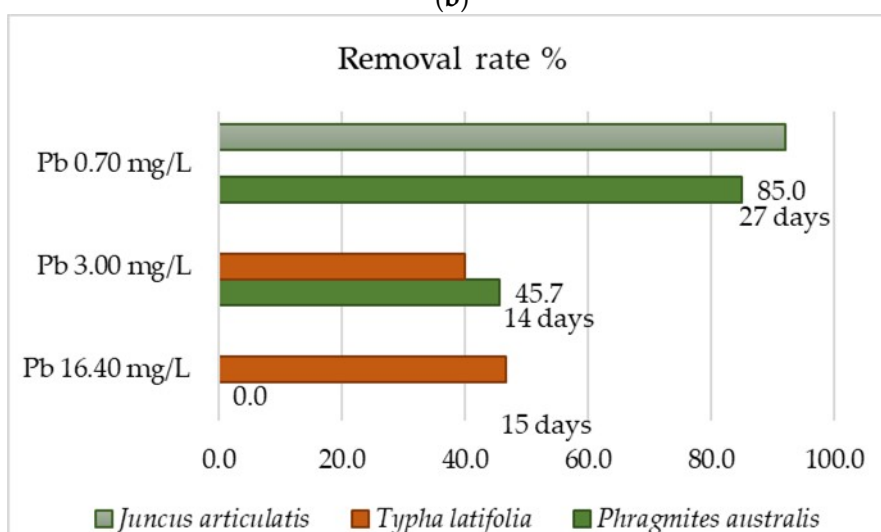
The data in Table 3 do not indicate that *P. australis* has always been the most effective species for use in phytoremediation. Several scientific articles have been found in which the removal efficiency of this plant and other emerging aquatic plant species (*P. australis*, *T. latifolia*, *Phalaris arundinacea*, *Vetiver zizanioides*, *Acorus calamus*, *Juncus effuses*, and *Helianthus annuus*) was compared at the same metal concentration. These emergent aquatic plants play a very important role in the removal of heavy metals from municipal or industrial wastewater [159–165]. The conducted researches indicate high efficiency for *P. australis*, but also for other species at the same metal concentrations. These data are presented in Figure 9 for eight heavy metals (nickel, cadmium, iron, chromium, lead, manganese, zinc, and copper). They indicate the general regularity that the higher metal concentration in the wastewater led to the lower its removal efficiency (Figure 9b,e). In addition, some of the data of rate removal of metals are very similar to each other, even though they show the results from different studies. This indicates the repeatability of the results obtained, and thus their reliability. *Phragmites australis* has a higher removal efficiency of Ni and Cd than *T. latifolia* and *J. articulatis* in all of these metal concentrations [159,160]. In the case of Pb and Fe, it occurs that the common reed removes these metals better at higher, than at a lower, concentrations (Figure 9c,d).



(a)

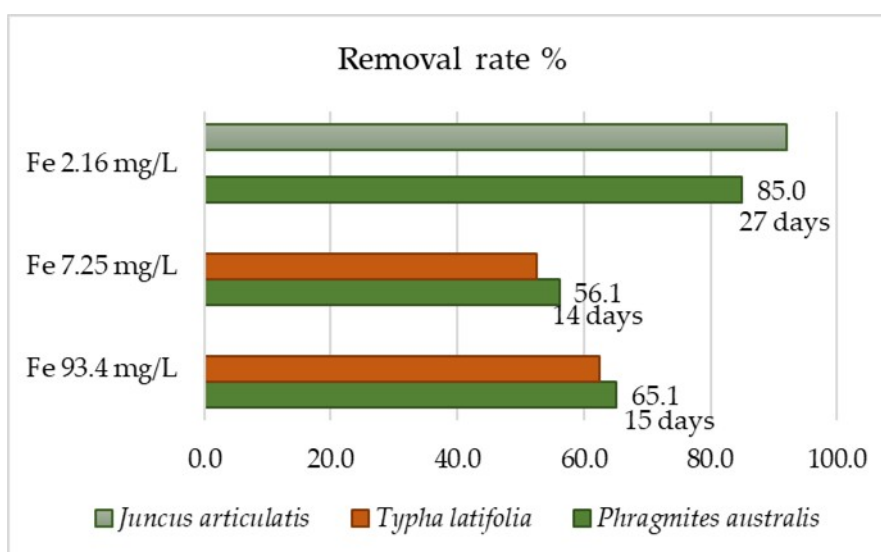


(b)

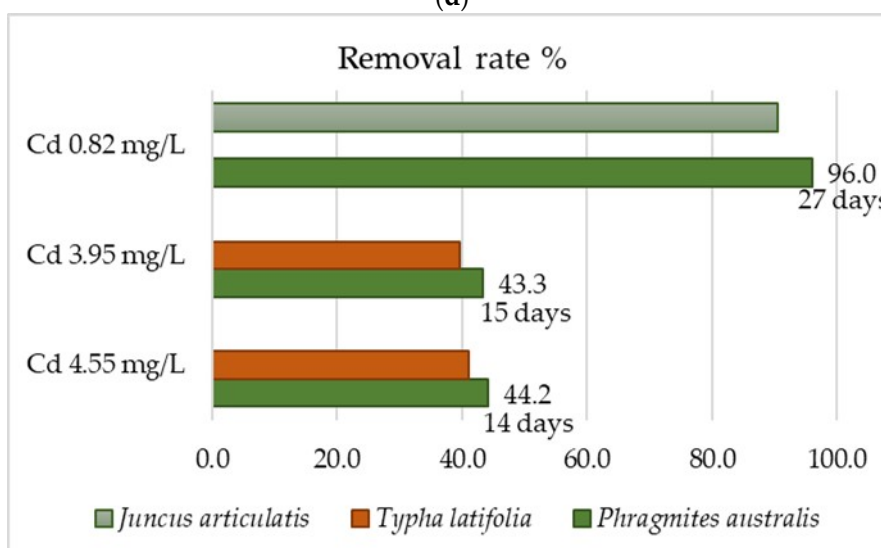


(c)

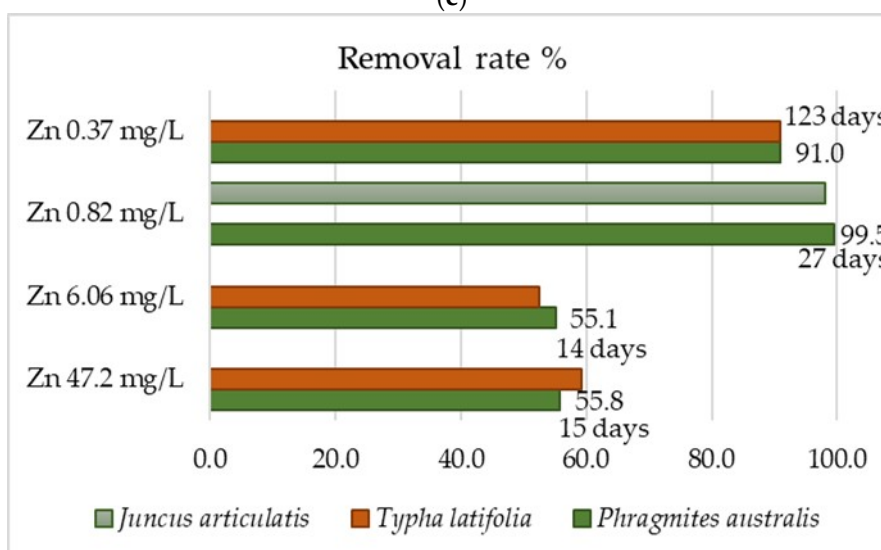
Figure 6. Cont.



(d)



(e)



(f)

Figure 6. Cont.

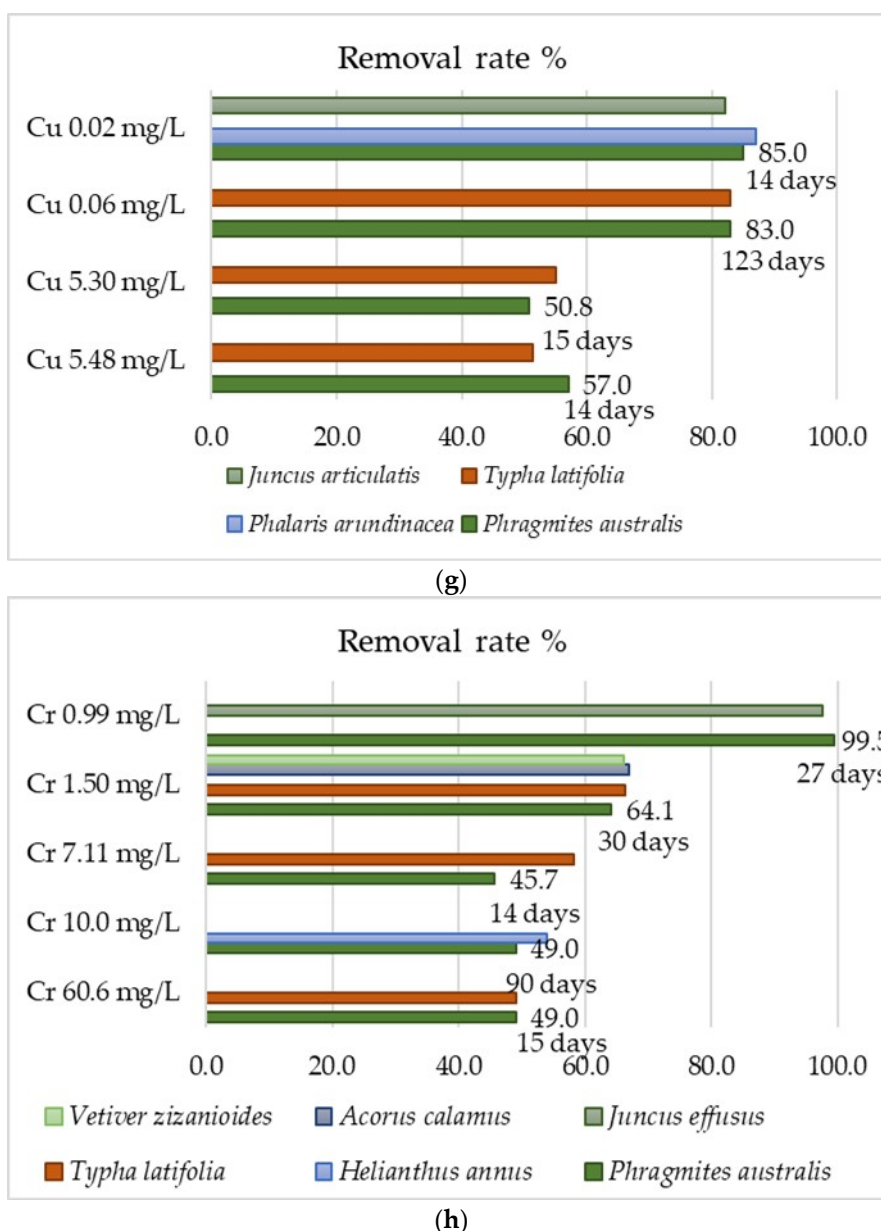


Figure 6. Heavy metals removal rate % for *P. australis* and the others emergent aquatic plants: (a) Mn, (b) Ni, (c) Pb, (d) Fe, (e) Cd, (f) Zn, (g) Cu, (h) Cr.

3. Removal of Other Contaminants by the Common Reed

The widespread use of pharmaceuticals, medicines, and personal-care products is becoming an increasing threat to water management. *Phragmites australis* additionally removes salts and works well in phytodesalination of soil and water. The presence of drugs in the aquatic environment may have an adverse effect on organisms living in the aquatic and terrestrial environment and cause a decrease in the diversity of algae and immunization of organisms to antibacterial agents. *Phragmites australis* is also used for removing different types of compounds—silicone, dyes, pesticide, pharmaceuticals, personal-care products, and illicit drugs—from wastewater [15,166,167]. For example, *P. australis* degrades ibuprofen (IBP) from water after 21 days of exposure and is therefore suitable for use in constructed wetlands, for the purpose of cleaning wastewater effluents containing IBP [168]. *Phragmites australis* is used for phytoremediation of veterinary medicines, and their removal is 94% with respect to enrofloxacin and 75% for tetracycline observed from enriched water [169]. Lv et al. [170] found that *P. australis* was able to remove 96.1% of tebuconazole and 99.8% of imazalil from the aquatic

medium. Pesticide removal from the hydroponic solution was not enantioselective. However, tebuconazole degradation was enantioselective both in the roots and shoots. Imazalil was also enantioselectively translocated and degraded inside *Phragmites*: R-imazalil translocated faster than S-imazalil. Jie-Ting et al. [14] showed that, by using *P. australis* in laboratory-simulated vertical wetland systems, it is possible to remove 36.9% of polycyclic aromatic hydrocarbons in continuous and intermittent feeding.

The influence of antibiotics (enrofloxacin and ceftiofur) on removing metals by constructed wetlands was investigated in mesocosms planted with *P. australis*. More than 85% removal of Fe, Cu, and Zn was achieved. It was also noted that ceftiofur improved metal uptake by *P. australis* and showed no adverse impacts of antibiotics [171]. The research conducted by Verlicchi et al. [172] shows that *P. australis* was more effective than *T. angustifolia* in the removal of pharmaceutical compounds, including ibuprofen, diclofenac, and caffeine. The effectiveness of wastewater removal compounds such as salicylic acid, IBP, naproxen, diclofenac, and caffeine was respective for the VF-CW type deposit, 98%, 99%, 89%, and 73%, and for the HF-CW type, 96%, 71%, 85%, 15%, and 97%. Plants (*Juncus*, *Typha*, *Berula*, *P. australis*, and *Iris*) increase the process of microbial degradation, owing to oxygen availability. Similarly, higher hydraulic residence times and macrophyte covers were found to improve the removal efficiencies of androstenedione, carbamazepine, caffeine, diclofenac, estrone, IBP, paracetamol, propranolol, and triclosan in a CW treating hospital wastewater [173]. Kankılıç et al. [174] investigated the removal of methylene blue (MB) from aqueous solutions by using the reed species *P. australis* as an adsorbent. It was found that the adsorptive capacity of crude *P. australis* increased significantly by modification reaction. The results showed that both *P. australis* and its modified forms have the potential as an ecological adsorbent for removing MB from the volatile substance.

The increase in water pollution with nutrients affects the accelerated process of their eutrophication. Therefore, in the assessment of surface water quality, in addition to mineral forms of N and P, total nitrogen (TN) and total phosphorus (TP) are also determined. These parameters are also of key importance in assessing the efficiency of wastewater treatment. Total organic carbon (TOC) is one of the most important parameters for the knowledge of water and wastewater quality, because it concerns theoretically all organic compounds. Chemical oxygen demand (COD) and biological oxygen demand (BOD) are other parameters widely used in indicating organic pollution, with respect to both wastewater and surface water. Biological oxygen demand is defined as the oxygen requirement of microorganisms to carry out biological decomposition of dissolved solids or organic matter in wastewater, under standard temperature, after five days. Chemical oxygen demand is an indispensable parameter in the analysis of the quality of water, since it provides an index to assess the impact of discharge on the receiving water body. Another parameter of wastewater that is just as frequently monitored is total suspended solids (TSS).

There are also scientific reports that indicate a significant effect of microorganisms in the rhizosphere on increasing the capacity of common reed to remove organic compounds. Fifteen culturable bacterial species were grown on effluent-supplemented medium as a sole carbon source, resulting in the reduction of the levels of distillery effluent pollutants with heavy metals and their color by 75.5% [86]. Concomitantly, there was a reduction in, for example, phenol sulfate. The presence of certain microorganisms also depends on the chemicals released by the reed. Toyama et al. [85] found that *P. australis* root exudates containing phenolic compounds supported growth and degrading activity of the *Mycobacterium gilvum* strain. Mycobacterium-root exudate interactions can accelerate pyrene and benzo[a]pyrene degradation. The results by Dan et al. [87] also determine the effect of selected phenolic compounds (namely p-hydroxybenzoic acid, p-coumaric acid and ferulic acid) on enriching the composition of bacteria (including *Luteolibacter*, *Reyranella*, *Asticcacaulis*, *Pseudomonas*, *Novosphingobium*, and *Rhodococcus*), degrading p-tert-butylphenol, as well as its chemical decomposition. The microbial degradation in the rhizosphere of *P. australis* ranged from 17 to 44%.

4. Common Reed in Constructed Wetlands

Macrophytes constitute the essential part of constructed wetland and manifest distinguished properties with respect to specific wastewater treatment processes. Among those are morphological adaptations to develop in water saturated soils, an extensive lacunar system facilitating substantial oxygen transport to the well-developed roots of the plant and rhizosphere, high growth rate, and the ability to incorporate biomass [24]. Currently, thousands of constructed wetlands are used for treatment purposes in polluted waters, since they constitute a low-cost alternative with respect to maintenance, operation, and construction. Additionally, constructed wetlands can be employed in different design and component combinations for different types of wastewater and concentrations of pollutants [175–177]. Through using constructed wetlands, the following objectives can be achieved: domestic wastewater treatment and agricultural runoff, industrial wastewater treatment, treatment of landfill leachate, flood treatment and urban runoff, post-treatment of wastewater, eutrophic lakes restoration, and treatment of water polluted by nutrients such as nitrate and phosphate [7,21,178–180]. The hydrophyte systems are used for wastewater treatment after a mechanical (preliminary) or biological first stage of wastewater treatment, often conducted in conventional wastewater treatment plants. For the purpose of effective treatment of wastewater in the artificially constructed wetlands horizontal flow (HF), vertical flow (VF), and hybrid constructed wetlands (Figure 7) are used worldwide [9,18,181–183]. Surface-flow wetlands are very similar to natural wetlands. The combined-technique approach is another innovation in recently developed constructed wetlands. It consists of employing two or more techniques (VF and HF systems) for the treatment of different wastewaters. This type of treatment shows higher efficiency and less infrastructure requirements, as well as low energy consumption [184].

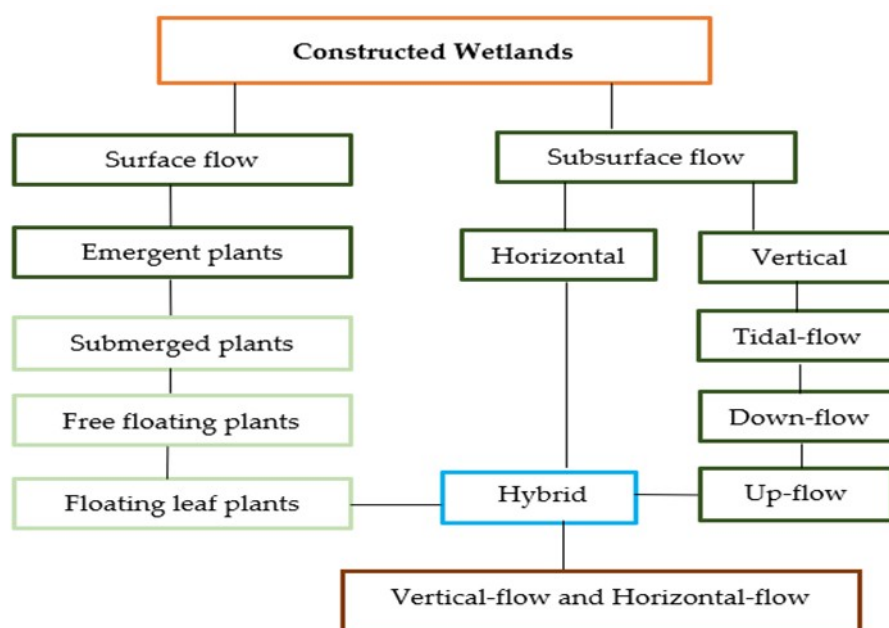


Figure 7. Classification of constructed wetlands for wastewater treatment, sourced from References [185–188].

High efficiency in removing various types of contaminants, such as organic matter, detergents, pharmaceuticals, N and P compounds, heavy metals, suspended solids, and trace elements, e.g., Cu, Zn, Al, etc., in constructed wetlands in many continents (Europe, Canada, Australia, and most parts of Asia and Africa), confirmed the potential ability of common reed to undisturbed development in an environment with a high concentration of pollutions and sewage treatment [189]. The review of scientific articles published in the years 1995–2020 in the field of the use of *P. australis* in constructed

wetlands (Figure 8) indicates that this species has been used to a greater extent in systems with subsurface flow of contaminated waters than with surface flow (1504 records from 2754 records). This is due to the photosynthetic properties of the CO₂ pathway for this species. In a typically aquatic environment, as compared with a terrestrial environment, lower biomass growth and a smaller N removal effect are obtained.

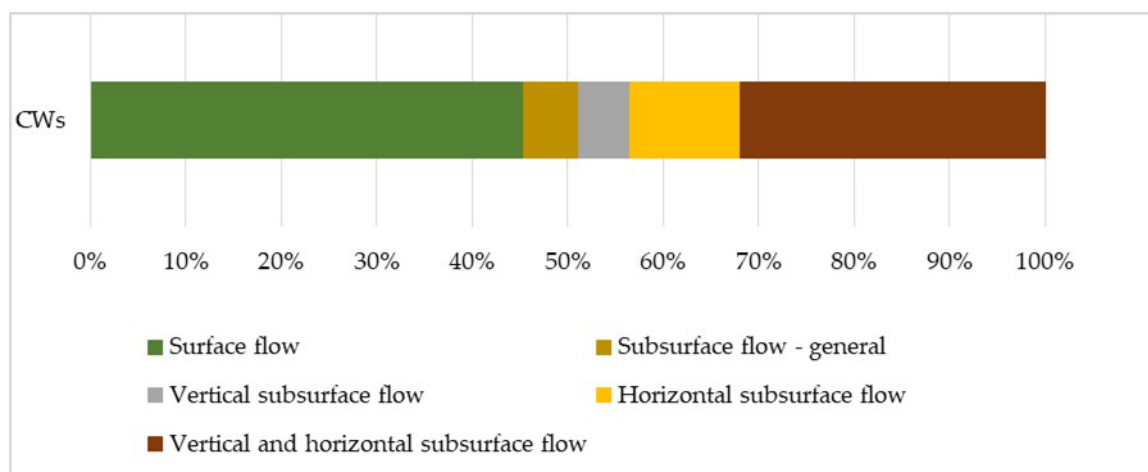


Figure 8. Percentage rate of articles, from 1995 to 2020, about constructed wetlands with common reed.

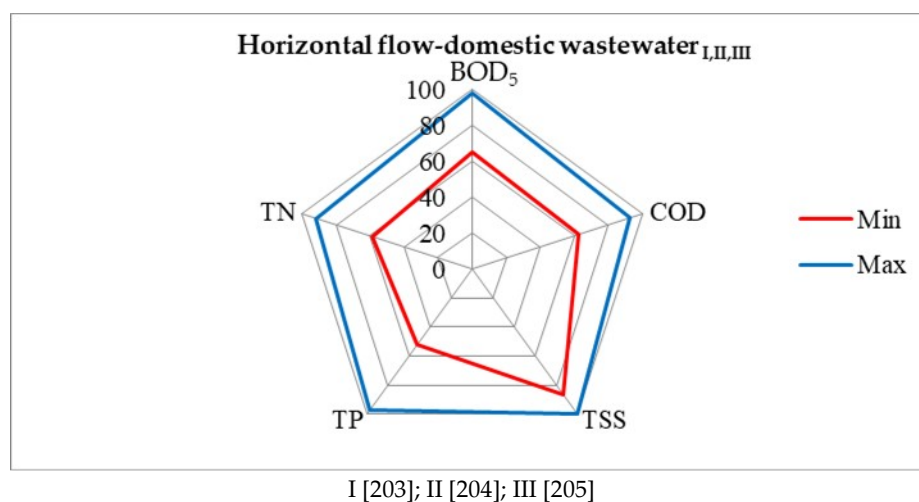
The analysis of the functioning of constructed wetlands is associated with an assessment of the effectiveness of removing impurities (Figure 9). This is of great importance for ensuring the purity of natural aquatic ecosystems to which treated wastewater is discharged. Various elements of these systems are tested. In the literature, some of the most important issues that are considered and often described relate to the following: the impact of vegetation on the uptake of metals and biogenic compounds by common reeds and individual organs of this plant; the control of the purification process due to the introduction of other species of flora and fauna to the hydrophyte system; and, in recent years, a detailed description of the role of microorganisms inhabiting the rhizosphere on the efficiency of removing organic compounds. Genetic research is becoming increasingly more important to accurately describe the mechanisms of bacterial decontamination of contaminants and facilitative arbuscular microbial fungi. The examples of the effects of the most interesting scientific studies related to the above issues are presented below, based on the recent literature [13,87,190–194]. Mulkeen et al. [195] analyzed the seasonal variations of metals and nutrients in *P. australis* in a CWs treating municipal wastewater. Investigations of uptake and seasonal variations in storage capacities of nutrients in *P. australis* were also taken in CWs under Irish climatic conditions [196,197]. Vymazal and Březinová [198] assessed the amount of heavy metals absorbed in aboveground biomass *P. australis* and found that their amount in plant tissues in constructed wetlands is highly variable. The amount of heavy metals accumulated in the aboveground biomass of *P. australis* (aboveground standing stock) represents often only small fraction of the inflow annual load, but in some studies, this fraction was quite high, especially for Zn (up to 59%), and more rarely for Cd (55%) and Cr (38%).

The investigation of the growth dynamics and nutrient and heavy metal shoot accumulation of the two dominating macrophytes, *P. australis* and *Bolboschoenus maritimus*, was conducted on constructed wetland of the Venice lagoon watershed [199]. In order to assess the effects on vegetation, the research was carried out in a vegetative season in three locations, characterized by different distance to the inlet points. It was shown that the said distance had no effect on shoot biomass, nor on the nutrients (N, P, Potassium, and Sodium (Na)) or heavy metals (Cr, Cu, and Zn) shoot content. In comparison with *B. maritimus*, the concentrations of nutrient and heavy metals, however, with an exception of Na, was found to be higher in the shoots of *P. australis*. The obtained results confirm that *P. australis* shows a superior efficiency.

According to results by Toscano et al. [200], *P. australis* shows superior removal capacity in comparison with *Vetiveria zizanioides*, *Miscanthus x giganteus*, and *Arundo donax*. Furthermore, it confirms that this plant is a superior plant species to be used in constructed wetlands for wastewater treatment. Importantly, the vegetation growth positively affects NH_4 growth. This particularly is the case with *Phragmites*, as 60% of the variable NH_4 load is due to vegetation growth. This confirms that the changes in vegetation affect other processes in nutrients removal.

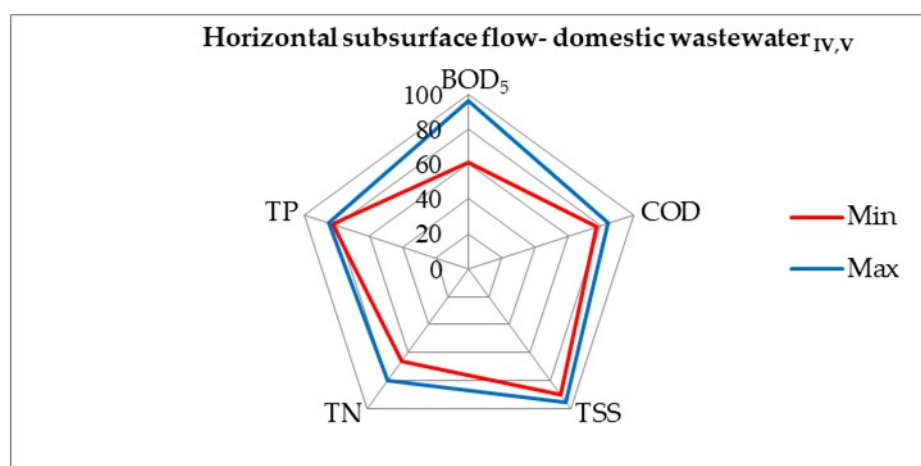
Massoudinejad et al. [201] evaluated the effectiveness of constructed wetland suburban flows (horizontal subsurface flow constructed wetlands) by the *Gambusia* fish and *P. australis* (sewage treatment plant) in municipal wastewater treatment. The presence of *P. australis* and *Gambusia* fish demonstrated the maximum removal efficiency. In the spring and summer season, the respective mean concentration of ammonium was 14.37 and 19.7 mg/L. Additionally, the presence of *P. australis* in wetlands resulted in the highest removal of ammonium. According to the results of this study, *P. australis* and *Gambusia* fish—when used simultaneously—show the superior properties in removal of COD and BOD_5 . As the results suggest, it could be a viable alternative to treatment of wastewater in small communities.

Tara et al. [202] presented the performance of a pilot-scale system, carrying *P. australis* in combination with three plant growth promoting and dye-degrading bacteria (*Acinetobacter junii* strain NT-15, *Rhodococcus* sp. strain NT-39, and *Pseudomonas indologens* strain NT-38) for the purpose of treating textile industry wastewater. High removal capacity of organic and inorganic pollutants was determined for the vegetated tanks. The combined application of plants and bacteria showed a superior removal performance, i.e., COD reduction to 92%, BOD_5 to 91%, color to 86%, and trace metals reduced to approximately 87% in the wastewater. The augmented bacteria displayed persistence in water, as well as in the roots and shoots of *P. australis*, suggesting a potential partnership with the host toward enhanced performance.



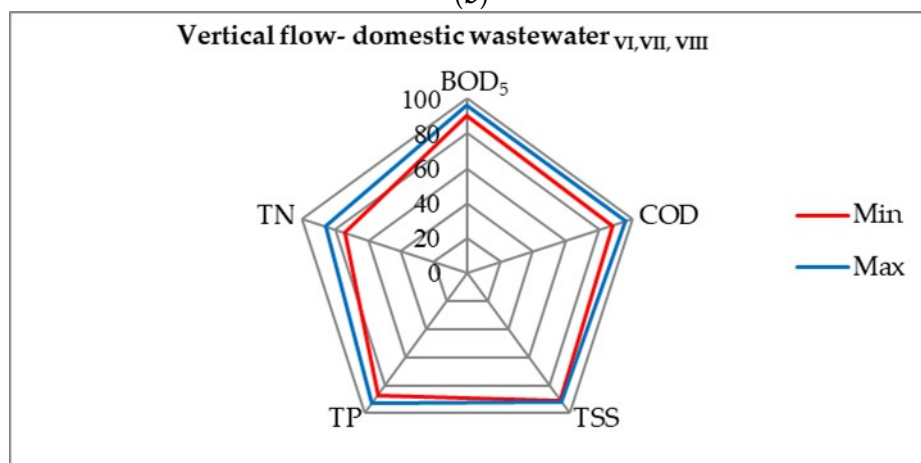
(a)

Figure 9. Cont.



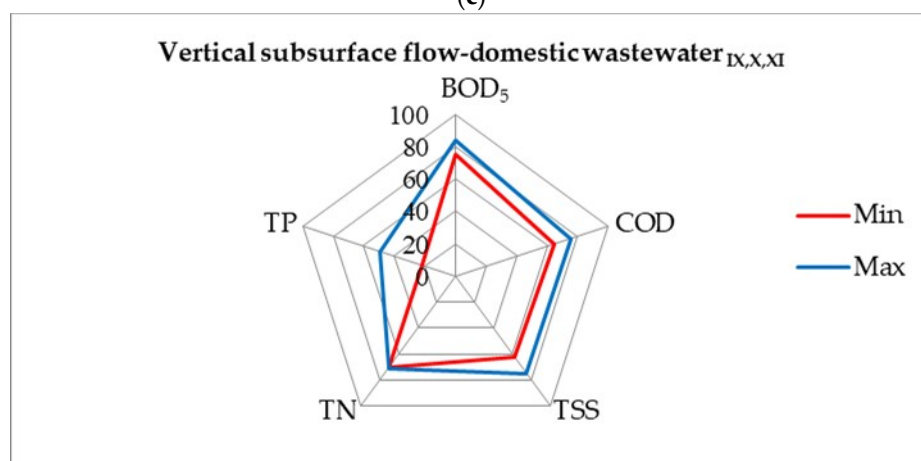
IV [206]; V [207]

(b)



VI [208]; VII [209]; VIII [210]

(c)



IX [211]; X [212]; XI [213]

(d)

Figure 9. Cont.

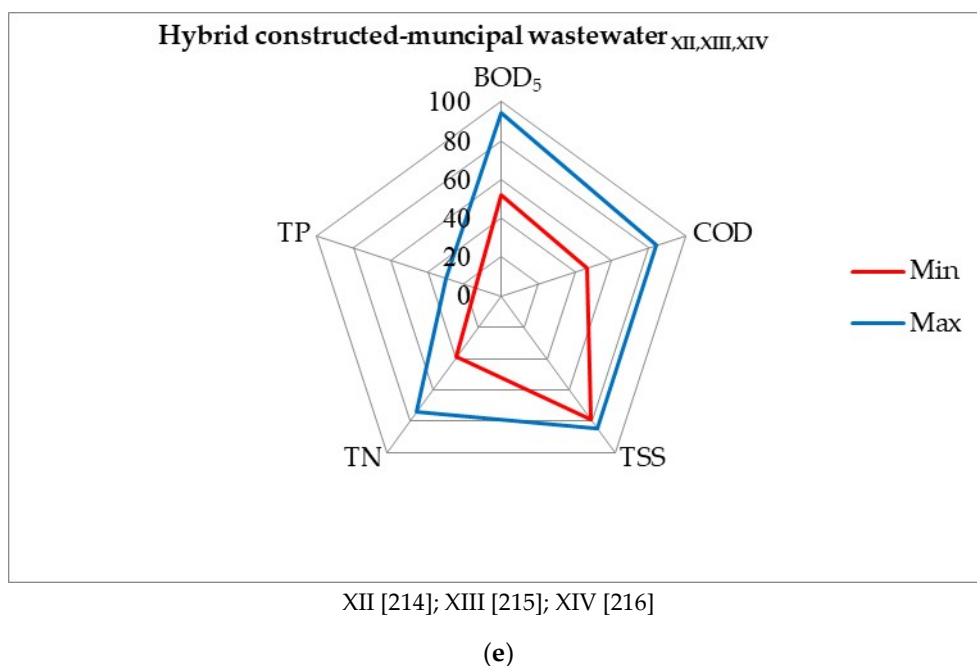


Figure 9. Evaluation of the effectiveness of wastewater treatment systems using *P. australis*: (a) horizontal flow—domestic wastewater, (b) horizontal subsurface flow—domestic wastewater, (c) vertical flow—domestic wastewater, (d) vertical subsurface flow—domestic wastewater, (e) hybrid constructed—municipal wastewater [203–216].

Phragmites australis stimulates bacteria-degrading hydrocarbons to do so in water. The results show that the floating treatment wetlands efficiently removed hydrocarbons from water, and that bacterial inoculation further enhanced its hydrocarbons degradation efficacy. The maximum reduction in hydrocarbons (95.8%), COD (98.6%), BOD₅ (97.7%), TOC (95.2%), and phenol (98.9%), as well as toxicity, was analyzed in a combination of both plants and bacteria. The augmentation of hydrocarbons degrading bacteria in floating treatment wetlands was found to be a superior option for treating diesel polluted water [180]. Figure 9 shows the removal percentages of BOD₅, COD, TSS, TP, and TN of wastewater treatment systems, using *P. australis*.

5. Conclusion and Future Outlook

Phragmites australis is a naturally robust and vigorous primary species in many wetland environments worldwide. This plant grows in different environmental conditions and can uptake, translocate, and accumulate a wide range of pollutants in both belowground and aboveground tissue. The ability of the plant to develop and grow in the waste sewage ecosystems allowed for the use of reeds in many types of sewage treatment plants. To increase the efficiency of phytoremediation of a polluted natural or artificial aquatic ecosystem and to estimate the required purification time and accelerate the rate of its reclamation, the interaction processes between common reeds and soil microbes, metal accumulation, and ionic homeostasis in the hydrophyte purification systems should be further tested. The researches of especially research carried out by interdisciplinary teams (plant physiologist, biochemist, geochemist, microbiologist, and agriculture and genetic engineer) in a short time can advance the efficiency of removing both metals and organic impurities.

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