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REVIEW ARTICLE

Phytoremediation potential and control of *Phragmites australis* as a green phytomass: an overview

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Abstract

Phragmites australis (common reed) is one of the most extensively distributed emergent plant species in the world. This plant has been used for phytoremediation of different types of wastewater, soil, and sediments since the 1970s. Published research confirms that *P. australis* is a great accumulator for different types of nutrients and heavy metals than other aquatic plants. Therefore, a comprehensive review is needed to have a better understanding of the suitability of this plant for removal of different types of nutrients and heavy metals. This review investigates the existing literature on the removal of nutrients and heavy metals from wastewater, soil, and sediment using *P. australis*. In addition, after phytoremediation, *P. australis* has the potential to be used for additional benefits such as the production of bioenergy and animal feedstock due to its specific characteristics. Determination of adaptive strategies is vital to reduce the invasive growth of *P. australis* in the environment and its economic effects. Future research is suggested to better understand the plant's physiology and biochemistry for increasing its pollutant removal efficiency.

Keywords *Phragmites australis* · Heavy metals · Nutrients · Phytoremediation · Soil · Sediment · Value-added products

Introduction

Phytoremediation is defined as the use of plants to remediate contaminated water, soil, and sediments. Phytoremediation has environmental and socioeconomic merits over other physical and chemical cleanup methods. This technology is subdivided into different categories based on their mechanisms of contaminant removal such as phytoextraction in which pollutants are transferred into the shoot and leaves of plants (Lee 2013; McSorley et al. 2016) and phytostabilization/phytoimmobilization, which is the transformation of toxic compounds into nontoxic or less toxic forms that lead to reduce the mobility of contaminants through accumulation by roots or immobilization within the rhizosphere (Yadav et al. 2018). The selection of plants for phytoremediation is also based on their ability and tolerance to uptake a wide range of pollutants and to maintain high growth in contaminated sites (Darajeh et al. 2017; Kushwaha et al. 2018). Constructed wetlands (CWs) are an artificial yet natural-like wastewater treatment system with the potential of removing both heavy metals and nutrients (Maucieri et al. 2017). CWs are based on the interaction of plants, soil, water and microorganisms under the synergies of the physical, chemical, and biological elements in the system (Wang et al. 2018). Vymazal (2013), Rezania et al. (2015), and Rezania et al. (2016a) suggest that a wide range of aquatic plants have the ability to absorb pollutants from aquatic environments. In other words, wetland plants can uptake, translocate, and accumulate heavy metals from water and sediments in their tissues (Bonanno et al. 2018). Aquatic plants are divided into three categories according to their morphology such as free-floating (e.g., *Eichhornia crassipes*), submerged (e.g., *Myriophyllum* sp.), and emergent (e.g., *Phragmites australis* and *Typha domingensis*) (Rezania et al. 2016b; Rezania et al. 2016c; Valipour and Ahn 2016). *P. australis* has been the most

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frequently used wetland plant for phytoremediation in the past few years (Zhang et al. 2010).

Habitat, growth, and morphology of *P. australis*

The geographic distribution of *Phragmites* sp. extends from cold temperate regions to the wetlands of hot and moist tropics in almost all continents, especially Asia and Europe (Vymazal 2013). The plant is mostly dominant in Europe, but also widespread in North America and various regions of South America and Australia (Mykleby et al. 2016; Srivastava et al. 2014). In terms of country distribution, *Phragmites* sp. is found in the UK, Egypt, Taiwan, Morocco, Australia, Poland, the USA, Japan, Italy, and Hungary.

P. australis has a resilient rhizome system with high propagation ability, long growth period, strong adaptability, and strong resistance to pollution (Fraser et al. 2004; Liu et al. 2012). The seeds of *P. australis* proliferate in wet conditions such as wetlands (Meng et al. 2016). Bonanno (2013) determined the morphological characteristics of *P. australis* as a large perennial grass with 2–6 m stems and 6–10 m horizontal runners. Vymazal (2013) also stated that *P. australis* is perennial, which can penetrate to a depth of 0.6–1.0 m through an extensive rhizome system. Moreover, the stems are rigid with hollow internodes. Less than 0.5 m to 4–5 m, *P. australis* has a distinct seasonal cycle (Saeed and Sun 2012). The length of the stem can grow up to 6 m with the ability to survive in high concentrations of toxic contaminants (Bragato et al. 2009). However, Hurry et al. (2013) found that in the Gippsland Lakes, a high level of salinity (27% and 33%) had a negative effect on the growth of *P. australis*. They also found that 40% of the stem length decreased in high salinity than in low salinity while 30% of the leaves' width and length decreased in similar conditions. Figure 1 shows the morphology of *P. australis*.

Engloner (2009) stated that by increasing the salinity, the density, basal diameter, shoot, and height of *P. australis* decreased. However, the relative growth rate increased with nutrient availability, which confirmed that nutrients can significantly enhance the growth of *P. australis*. For instance, the addition of NO_3^- and PO_4^{3-} positively increases the biomass production of *P. australis* (Uddin and Robinson 2018). Water level variation could also have an effect on *P. australis* growth in terrestrial zones because the averages were higher for stem lengths (26.3–27.5%) and diameters (7.2–12.0%) than those in submerged zones (Zhao et al. 2013). Shuai et al. (2016) reported that the dry biomass yield of *P. australis* was in the range of 0.38–3.6 kg/m^2. They found that factors such as soil pH, nitrogen availability, and wetland location significantly influenced the biomass yield. The re-growth of the shoots and leaves of *P. australis* biomass are also affected by the harvesting time (Tanaka et al. 2016). For instance, the nitrogen content and dry matter yields could greatly increase if harvesting time occurred at intervals of approximately 60 days (three harvests per year). However, this practice may negatively affect the growth in the following year (Tanaka et al. 2017). Table 1 shows the growth rate and biomass production of *P. australis* in other studies.

The distribution between above- and belowground of *P. australis* plant parts vary in natural and CWs (Vymazal and Březinová 2016). The above ground biomass in eutrophic natural stands can reach the maximum in 3 to 5 years (Vymazal and Krőpfelová 2005). Mulkeen et al. (2017) found that the highest accumulations of metals and nutrients were recorded between April and November. Additionally, while the weight and length of shoots increase over time, the shoots of *P. australis* decrease after the second growing season (Barbera et al. 2014).

According to González-Alcaraz et al. (2012), decreases in soil organic carbon content are an important parameter for the high production of *P. australis*, which is caused by several cultivations and continuous harvesting. The presence of fresh organic carbon in the rhizosphere of *P. australis* results in a high release of N_2O during the later stage of elongation and shows the coupled nitrification–denitrification processes in sediments (Gu et al. 2015). During growth stages, *P. australis* could exert an additional positive influence on N_2O emissions from rhizosphere sediments. As reported by Roley et al.

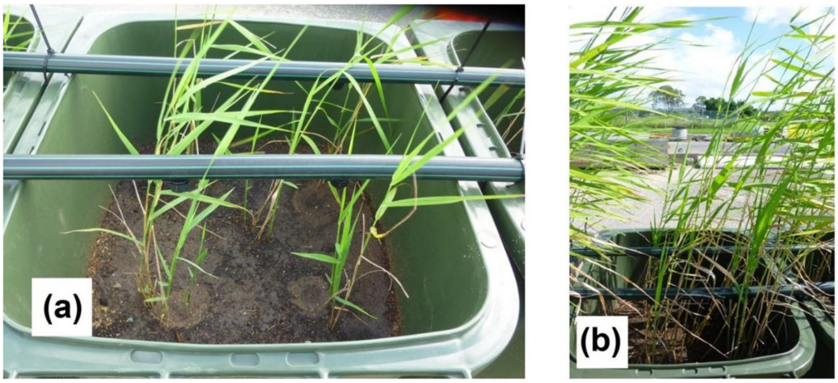

Fig. 1 Morphology of *P. australis*: **a** initial stage and **b** growth after 2 weeks. Soil type: sandy loam; location: Brisbane, Australia

Table 1 Growth rate and biomass production of *P. australis*

Parameters	Season/time period	Location	Amount	Remarks	Reference
Maximum growth	April to August	Czech Republic	5.070 kg/m^{-2} (fresh biomass)	Biomass rate in natural stands is higher than CWs	Vymazal and Krőpfelová (2005)
Biomass production	April to October	Turkey	0.1537 DW kg/m^{-2}	The maximum and minimum temperature were 25.7 °C and − 1.9 °C, respectively	Türker et al. (2016a)
Maximum height			54 cm		Türker et al. (2016b)
Growth rate	Natural stands	Czech Republic	1 and 2 kg/m^{-2}	–	Vymazal and Březinová (2016)
Highest biomass rate	Summer		1.05 kg/m^2	–	Choi et al. (2012)
Highest aboveground biomass	August	Ireland	1.636 ± 507 kg/m^{-2}	Lowest aboveground biomass was 0.835 kg/m^2 in June	Mulkeen et al. (2017)
Dry biomass production	December to September	Greece	0.36 DW kg/plant 10.1 kg fresh weight	Average temperature was 13.6 °C in March to 26.8 °C in August	Fountoulakis et al. (2017)
Dry biomass	December to September	Czech Republic	3.1 kg/m^{-2}	–	Vymazal and Březinová (2018)

(2018), the average contribution of coupled nitrification–denitrification to total nitrification was 4% in sediments of *P. australis* and 2% in unvegetated sediments.

Wetlands could also contribute to the global warming through greenhouse gas emissions (GHGs) such as nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) (Yang et al. 2017; Wu et al. 2017). This can be affected by abiotic and biotic factors like oxygen availability and microbial community composition. The source of the emission could be related to the depth of water bodies, in which N_2O emissions increases due to the biomass allocation to rhizomes and fine roots. According to Gu and Chen (2016), the N_2O emissions increased with an increase in water depth from 0.084 ± 8 at 20 cm to 0.131 ± 18 mg/mol N_2O m^{-2} day^{-1} at 100 cm. Gu et al. (2015) reported that N_2O emissions were influenced by plant height, belowground biomass, and fine-root biomass rather than relative growth rate total biomass and root activity. As found by Álvarez-Rogel et al. (2016), the highest N–N_2O emission by *P. australis* was 8.15 mg m^{-2} h^{-1} in the long-term experiment at week 30. Recently, Yang et al. (2017) evaluated the atmospheric concentrations of GHGs such as CO_2, CH_4, and N_2O in the wetland cultivated by *P. australis*. The emitted daily average flux from *P. australis* marsh was 517 to 438 for CO_2, 15.4 to 20.5 for CH_4, and 810 to 720 mg m^{-2} h^{-1} for N_2O.

Pollutant removal from wastewater, soil, and sediment

The ability of *P. australis* for nutrient removal from different types of wastewater has been examined since 1970s (Mason and Bryant 1975). However, based on a review of the recent literature, there is no published paper that focuses on the ability of *P. australis* in the removal of different types of compounds in the past 6 years. Therefore, we focus on the potential of *P. australis* for the treatment of various types of pollutants in wastewater, soil, and sediment. The control methods and management of *P. australis* are also discussed.

Removal of nutrients from water and soil

According to Bhatia and Goyal (2014), *P. australis* can be used in the treatment of primary, secondary, and tertiary wastewater, which originates from domestic sources and industries due to the easy cultivation and high removal efficiency of *P. australis*. The required time for wastewater treatment in CWs with *P. australis* is less than the time without *P. australis* (Rehman et al. 2017). This could be due to the different accumulation patterns and translocation of N, P, and C in the tissues of the plant. The concentration of these three elements may change with the seasonal variation. Toumpeli et al. (2013) found higher C/N levels in mature plants while the levels of total phosphorous (TP), total nitrogen (TN), and potassium (K) were higher in younger plants. According to Březinová and Vymazal (2015), the concentration of N varies in different parts of *P. australis*. For example, the biomass weight percentages were 33%, 19%, and 18.8% in the lower stem, middle stem, and leaves, respectively. In contrast, N content was 38% in the upper leaves and 3.7% in the stem bottom.

El Shahawy and Heikal (2018) recently used the dried biomass of *P. australis* for adsorbing organic pollutants and they measured chemical oxygen demand (COD) and biochemical oxygen demand (BOD) from oily industrial wastewater effluents. They found that by increasing the pH from 4 to 7, the removal efficiency of COD and BOD increased from 77.35 to 91.05%. Meanwhile, increase of the organic load increased COD and BOD removal from 6.24 to 36.81%.

In a system with sufficient oxygen, *P. australis* can immobilize huge amounts of phosphorus in a short time (Lan et al.

2018). Karstens et al. (2015) reported that the high sorption capacity in *P. australis* is due to excessive iron. In addition, the rhizosphere of *P. australis* is capable of bioremediation of sediments, which shows growth-promoting activities of bacterial communities in contact with plants (Borruso et al. 2017).

The rhizosphere soil of *P. australis* contains different types of bacteria that can enhance wetland performance and plant growth (Abed et al. 2018). The concentration of nutrients and accumulation in the aboveground parts of the reed is mostly related to sediment and nutrient loading at the water surface rather than the variation of water level.

Nitrogen (N) sequestration in plant biomass is a small fraction of the total N abatement in the vegetated areas. Although, the synergistic action of bacterial communities and macrophytes via denitrification is mostly responsible for N sequestration (Castaldelli et al. 2015). Moreover, denitrification performed by biofilms on stems of *P. australis* occurs during the vegetative season in the cold period. It should be noted that the oxidizing conditions of the rhizosphere of *Phragmites* can increase nitrification and ammonification processes with limitations in the denitrification rate in the wastewater (Rodriguez and Brisson 2016).

As found by Soana et al. (2018), the denitrification capacity of *P. australis*, based on biofilms performance reduced up to 25% of the incoming NO_3^- load per linear kilometer. They also found that denitrification rates of dead stems of *P. australis* ranged as 94–292 and 63–231 (μmol N m^{-2} h^{-1}) in dark and light condition, respectively.

According to Toyama et al. (2016), N removal, microbial populations, and their activities increased by the functions of microorganisms and *P. australis* in the sediment. They obtained 31–44% of total N removal by microbial nitrogen cycling and 56–69% removal via absorption by *P. australis* in 42 days experiment.

In addition, *P. australis* enhanced the denitrification in the outdoor typical of low-gradient water bodies. Multiple interfaces in the rhizosphere were observed which support the activity and development of bacterial communities cause NO_3^- dissipation in the range of 61–90% (Castaldelli et al. 2018). Moreover, the diffusive flux of NH_4^+ from the sediments into the water column was lower in the vegetated condition that shows plant increases N retention by assimilatory uptake (Roley et al. 2018).

According to Li et al. (2014), availability of N and P in water and sediments had a positive correlation in comparison with the whole plant. Zhao et al. (2013) reported that the maximum N storage in the terrestrial zone was 74.5 g/m^2 with higher nutrient loading. Al-Isawi et al. (2017) showed that matured *P. australis* cultivated in wetlands was more effective in removing NH_4^{-N} and PO_4^{-P} than ponds. Similarly, Willson et al. (2017) reported higher N removal efficiency in vertical flow CWs. This could be due to the higher N uptake ability of *P. australis*, which enhances microbial activity around the rhizome.

Fountoulakis et al. (2017) evaluated the removal of nutrients from domestic wastewater using *P. australis*. COD concentration decreased from 224 ± 41 to 47 ± 12 mg/L in the effluent using reeds, resulting in a 78–79% average removal efficiency. In addition, the N content decreased from 70–100 to 45–75 mg/L and showed 20 to 30% removal efficiency during the 8-month experiment from March to October. Meanwhile, the P concentration in an inlet was from 8 to 13 mg/L, which reduced to 3 to 6 mg/L with the highest efficiency at 70% in July.

Liang et al. (2017) reported that a mixture of *P. australis* and other emergent and floating plants are able to remove between 40 and 80% organics such as COD, BOD, and ammonia from saline wastewater. Gong et al. (2017) reported that $MgCl_2$-modified biochar from *P. australis* removed 30 mg g^{-1} NH_4–N and 100 mg g^{-1} PO_4^{-P} from eutrophic water. Valipour et al. (2014) investigated the ability of *P. australis* for the treatment of domestic wastewater once cultured with soil. The maximum removal was 80.31% COD, 90.04% BOD, 24.51% of total dissolved solids, and 69.42% of total suspended solids (TSS) after 45 days. The growth of *P. australis* also highly depends on the soil type (Lan et al. 2018). Table 2 shows the removal of various nutrient by *P. australis* from different types of wastewater and soil.

Removal of heavy metals from water, soil, and sediment

P. australis is able to uptake high levels of metals due to their typical tissue system and defense mechanism (Huang et al. 2018). The concentrations of heavy metals generally decrease in the order of roots > rhizomes >leaves > stems in various parts of *P. australis* that grow in CWs and natural wetlands (Vymazal and Březinová 2016). Parzych et al. (2016) also reported that *P. australis* is able to accumulate heavy metals (except Mn) in the rhizomes. Moreover, high concentrations of heavy metal could occur in the leaves of *P. australis*.

As reported by Rocha et al. (2014), *P. australis* is a suitable candidate for phytostabilization, due to its ability to accumulate contaminants by belowground tissues and the resistance to metal toxicity. Bonanno (2013) compared the capacity of heavy metal removal using *Typha domingensis*, *P. australis*, and *Arundo donax*. They found that among these different species, *P. australis* had greater bioaccumulation and removal efficiency. The heavy metal uptake by different parts of *P. australis* was at the roots (Al > Mn > Zn > Cu > Pb > Ni > Cr > Hg), stems (Al > Mn > Zn > Cu > Pb > Hg > Cr > Ni), and leaves (Al > Mn > Zn > Cu > Ni > Hg > Pb > Cr). Astel et al. (2014) found that the metal concentration in *P. australis* was in the order of Ca > Na > Mg > K > Fe > Mn > Zn > Pb > Cr > Ni > Co > Cu > Cd and in the order of chromium > mercury > vanadium > arsenic as reported by Jiang et al. (2018).

Table 2 The removal of nutrients by *P. australis* from soil and wastewater (>2012)

Polluted area	CW type	Location	Nutrients	HRT	pH	Inflow (mg/L)	Outflow (mg/L)	Total dry biomass (kg/m$^{-2)}$	Removal rate (%)	Remarks	Reference
Wastewater	Subsurface vertical flow	China	COD, TP, TN, NH_4–N	4 months	3.7–8.0	COD: 284.13 TN: 23.42 NH_4–N: 14.32 TP: 2.20	COD: 161.67 TN: 8.89 NH_4–N: 5.71 TP: 0.89	3.81	COD = 47.96 TN = 68.94 NH_4–N = 68.36 TP = 63.10	Root zone was the most active area of nutrient removal in wetlands	Liu et al. (2012)
Municipal wastewater treatment	Vertical flow	Egypt	BOD, COD, TKN, NH_3, TP, TSS	2 years	7	COD: 335 BOD: 175 NH_3: 18.3 TKN: 30.7 TP: 3.15 TSS: 94	COD: 30.6 BOD:11.16 NH_3: 7.9 TKN: 17.8 TP: 0.4 TSS: 5	3.26	COD = 88 BOD = 90 NH_3 = 87 TKN = 74 TP = 93 TSS = 92	32.55 g/m^2 TP and 68.10 g/m^2 TKN were accumulated in the plants	Abou-Elela and Hellal (2012)
Swine slurry composting wastewater	Vertical flow	Spain	TSS, COD, BOD TN	7 months		NH_3–N: 459 TKN: 904 TSS: 9.2 COD: 17.9 BOD: 4.8 TN: 1.9 NO_3–N: 178	NH_3–N: 16 TKN: 904 TSS: 9.2 COD: 17.9 BOD: 4.8 TN: 1.9 NO_3–N: 10	–	TSS = 95 COD = 94 BOD = 99 NH_3–N = 97 TN = 79	Nitrification occurred at the initial stages of plant growth; complete denitrification was obtained after 3 months	Vázquez et al. (2013)
Soil profile	Fluctuated flooding condition	Spain	P	1 year	8.7	1.95–19.5	0.5	–	90	Various compounds were the main contributors in the retention of P in the soil compartment	del Carmen Tercero et al. (2017)
Synthetic wastewater	Floating hydroponic root mat	Germany	TN	6 months	7	NH_4–N: 26	NH_4–N: 1.15 ± 0.4	7.73	78	*P. australis* root mats were superior in size and had significantly more aboveground and more belowground dry biomass	Saad et al. (2016)
Domestic wastewater	Subsurface horizontal flow	Turkey	BOD, COD, TSS	3 years	–	BOD: 243.0–456.7 COD: 371.7–556.0 TSS: 113.4–186.6	BOD: 67–180 COD: 130–283 TSS: 14.2–28.9	–	TSS = 86.3 BOD = 64.9 COD = 62.5	Applied hydraulics and loading levels were the key factors for the rates of removal of the system	Çakir et al. (2015)
Synthetic wastewater	Vertical flow	Pakistan	COD, BOD	25 days	6.5	COD: 600–680 BOD: 380	COD: 15 BOD: 8	1.5	BOD and COD 97	Plant biomass was affected by the temperature and light intensity	Rehman et al. (2017)
Domestic wastewater	Vertical flow	UK	COD, BOD, NH_4–N, NO_3–N, PO_4–P, TSS	5 years	4–9.5	COD: 281.3 BOD: 151.8 NH_4–N: 39.6 NO_3–N: 4.1 PO_4–P: 13.3 SS: 157.6	COD: 112.3 BOD: 34.7 NH_4–N: 12.6 NO_3–N: 1.23 PO_4–P: 5.2 SS: 14.1	–	COD = 58.6–70.8 BOD = 74.9–81.3 NH_4–N = 62.0–79.2 NO_3–N = 23.7–107.6 $PO_4 - P$ = 59.8–64.7 SS = 91.3–92.4	NO_3N removal was negative due to the N source rather than pollution	Al-Isawi et al. (2017)
Domestic wastewater	Horizontal surface flow	Spain	BOD, COD, TSS, TN, TP	1 year	7.2	BOD: 300–700 COD: 600–1300 TSS: 130–210 TN: 110–150 TP: 18–23	BOD: 16.5 ± 3.3 COD: 100.3 ± 12.6 TSS: 30 ± 1.3 TN: 16.1 ± 3.3 TP: 2	–	BOD = 97.8 ± 1.2 COD = 92.7 ± 3.7 TSS = 99.8 ± 1.7 TN = 91.5 ± 5.3 TP = 96.9 ± 1.7	Improved HF-CW achieved similar or better reduction than hybrid systems	Andreo-Martínez et al. (2017)
Synthetic wastewater	Vertical subsurface flow	Spain	BOD, COD, TOC	4 months	7	BOD: 368 COD: 300 TOC: 194	BOD: 12–33 COD: 85–31 TOC: 17–46	–	BOD = 81 COD = 67 TOC = 72	Reduction of total nitrogen was highest in saturated vertical flow	Sgroi et al. (2018)

TP total phosphorus, *TKN* total Kjeldahl nitrogen, *TOC* total organic carbon

Rzymski et al. (2014) observed the accumulation of Cr, Cd, Cu, Co, Fe, Pb, Mn, Ni, and Zn in the roots of *P. australis* while Cd and Pb were translocated to the leaves. The accumulation of heavy metals in *P. australis* was in the order of roots > shoots > leaves (Ganjali et al. 2014). As reported by Southichak et al. (2006), *Phragmites* sp. biomass can be used as a biosorbent for high sorption performance even at a low concentration of heavy metals. Klink (2017) found that some parameters such as limited mobility, translocation of trace metals, and high bioaccumulation capacity showed *P. australis* as an attractive species for the phytostabilization of trace metals such as Zn, Mn, Pb, and Cu.

Bhatia and Goyal (2014) stated that around 41% of CWs are vegetated with *P. australis* solely or in combination with other plants. For instance, a mixture of *P. australis*, *Typha angustifolia*, and *Eichhornia crassipes* are able to remove about 60–80% of Fe, Cu, Mn, Zn, Ni, and Cd from pulp and paper wastewater (Arivoli et al. 2015). Marchand et al. (2014) reported total Cu removal ranged from 7 to 90% in CW planted with three macrophytes: *P. australis*, *J. articulatus*, and *Phalaris arundinacea*. García-Mercadoa et al. (2017) obtained 58–66% reduction in Hg levels from the soil during a 36-week experiment using *P. australis*. Willson et al. (2017) found that low levels of iron [Fe(II)] increase biomass, shoot length, and the production of leaves and shoots in greenhouse conditions. Meanwhile, Fe removal depends on the quantity of the iron plaque formed on *P. australis* roots.

Phytoremediation strategies for the uptake of heavy metals from the soil are dependent on several different factors, such as soil pH, metal type, temperature, and depth of the contamination (Ashraf et al. 2017; da Conceição et al. 2016). Recently, Pérez-Sirvent et al. (2017) found that *P. australis* is capable of phytostabilizing contaminated soils with a wide range of heavy metals in combination with selected species such as *Juncus effuses* and *Iris pseudacorus*. In addition, *P. australis* and *T. latifolia* have higher metal accumulation abilities than other species (Feng et al. 2015). This is due to the different uptake levels and transport systems with distinct metal-affinity patterns. Recently, Dan et al. (2017) found high removal rates of Zn, Cr, Ni, Cd, Fe, and Pb for the treatment of synthetic leachate using *P. australis* and *J. effusus*.

Grisey et al. (2012) examined the ability of *P. australis* and *T. latifolia* for heavy metal accumulation in the phytomass. They found that heavy metal removal was more effective in *P. australis* than *T. latifolia* from season to season. In contrast, Fountoulakis et al. (2017) found that the heavy metal accumulation in *P. australis* was lower than three halophytes: *Atriplex halimus*, *Juncus acutus*, and *Sarcocornia perennis*.

In another study, Guo et al. (2014) examined the heavy metal accumulation in reeds grown in an acid mine drainage site. The authors concluded that the Fe, Mn, and Al concentrations in the belowground tissues of *P. australis* had strong positive correlations with the soil concentrations. Similarly, Esmaeilzadeh et al. (2017) reported significant positive correlations between the concentrations of metals in the sediments of *P. australis*. Minkina et al. (2018) confirmed that there were significant positive correlations between the Zn, Pb, Cd, and Mn content and their accumulation in *P. australis*. Table 3 shows recent studies on the removal of heavy metals from different wastewater and soil using *P. australis*.

In the case of heavy metal removal from sediments, *P. australis* showed good potential for the uptake of Co, Ni, Mo, Cd, Pb, Ba, Cr, Cu, Fe, Mn, and Zn with belowground tissue for up to 10 years (Cicero-Fernández et al. 2017). However, the removal of As and Se needs longer periods of treatment for low concentrations. He and Yongfeng (2009) stated that heavy metals in sediments were mostly immobilized in the roots of *P. australis* with little translocation to the aboveground plant parts. The bioaccumulation of metals in roots was in the order of $Al\,(OH)_3 > Al_2O_3 > Fe_3\,O_4 > MnO_2 > FeOOH$. In another study, the removal efficiency for Pb, Mg, and Cr were 15.4%, 79.7%, and 97.9%, respectively, using *Phragmites*, *Chrysopogon nigritana*, and *Canna indica* (Badejo et al. 2015). A significant correlation between metal concentrations in roots and sediments also confirmed that the roots of *P. australis* could be used as a bioindicator for Fe, Cu, Cd, and Ni. Similarly, Mulling et al. (2013) obtained 82% of Mn from sediments using *P. australis*. Shaheen et al. (2019) calculated accumulation factor (AF) for common reed based on mg element kg^{-1} plant/mg to total-element kg^{-1} in sediment. They found common reeds can uptake different heavy metals such as Mn, Ni, Zn, As, Al, Co, and Fe in the range of 0.03 and 18.7 (AF) from sediment-contaminated sites.

Sludge mineralization and dewatering using *P. australis*

Sludge treatment wetlands or sludge drying reed beds are defined as new sludge treatment systems that are based on wetlands (Puigagut et al. 2007; Uggetti et al. 2010). In comparison to conventional sludge methods, sludge treatment reed beds (STRBs) are considered an eco-friendly, energy-efficient, and feasible technology for sludge treatment and stabilization before final land disposal. This method does not require any type of chemicals and can reduce sludge volume (Uggetti et al. 2012; Nielsen and Larsen 2016). However, in long-term experiments, the dry matter content of the sludge reached to 10–12% after several months due to the inefficient drainage of water from the bed, which leads to the poor growth of reeds (Brix 2017).

For many years, *P. australis* has been considered as the most widely used species in the treatment of wetlands from sludge. Hardej and Ozimek (2002) showed the high adaptation capacity of *P. australis* for the treatment of sewage sludge. In this condition, shoot density was more than two times higher than in natural systems. By providing a sufficient

Table 3 Heavy metal removal from wastewater and soil by combination of *P. australis* with other wetland plants (2013 and onward)

Type of wastewater	Vegetation	Location	Heavy Metals	HRT (days)	pH	Removal rate (%)	Remarks	Reference
Vertical–horizontal subsurface flow	*P. australis*, *L. salicaria*, *A. calamus*, *T. minima*	China	Mn, Cr, Zn, Cu	35	–	70 to 80	Plants could accumulate heavy metals (Cr, Fe, Cu, and Zn) aboveground and underground	Sun et al. (2013)
Irrigation water	*P. australis* and *Helianthus annuus*	Brazil	Cr	90	4.5–8.5	Cr removal was 54% for *P. australis* and 70% for *H. annuus*	Cr in the roots of *H. annuus* and *P. australis* was 2730 and 1800 mg Cr/kg/dry tissue, respectively	Ranieri et al. (2013)
Synthetic soil	*P. australis*	Tunisia	Cd	70	6.4	65	Plant biomass was inhibited 89% and 92% in the low and high Cd concentrations	Hechmi et al., (2014)
Secondary treated wastewater	*P. australis*, *T. latifolia*, and combination	India	Fe, Pb, Zn, Cu, Cd, Cr, Ni	15	7.5	Cr = 66.2 ± 3.5%, Fe = 70.6 ± 1.2%, Zn = 71.6 ± 3.9%; combination of *P. australis* and *T. latifolia*	*P. australis* had higher accumulation capacities for Cu, Cd, Cr, Ni, Fe, and Pb	Kumari and Tripathi (2015a)
Vertical flow CW and municipal wastewater	*P. australis* and *Typha latifolia*	Italy	Al, As, Be, Mn, Fe, Co, Ni, Cu, Zn, Cd, Pb, Se, V, B	365	8.5	High removal efficiency for Al (96%), Cu (91%), Pb (88%), and Zn (85%) and lower for Fe (44%), Co (31%), and B (40%)	Both plants had a TF < 1 for almost all the elements except for Mn and B	Morari et al. (2015)
Urban sewage mixed with industrial effluents	*P. australis*, *Typha latifolia*, and combination	India	Cu, Cd, Cr, Ni, Fe, Pb, Zn	14	7.5	High removal for the combination of *P. australis* and *T. latifolia* Cu = 78.07 ± 1.2%, Cd = 60.07 ± 1.2%, Cr = 68.17 ± 0.4%, Ni = 73.87 ± 0.6%, Fe = 80.17 ± 0.3%, Pb = 61.07 ± 1.2%, Zn = 61.07 ± 1.2%	*P. australis* performed better than *T. latifolia* for removal of Cu, Cd, Cr, Ni, Fe, Pb, and Zn	Kumari and Tripathi (2015b)
Urban waste leachate	*P. australis*	Malaysia	Mn, Cu, Ni, Fe	3	6.1	The removal rates for the optimized factors were 25.04 mg/kg Fe, 9.62 mg/kg Mn,	*P. australis* was an effective accumulator plant	Mojiri et al. (2015)

Table 3 (continued)

Type of wastewater	Vegetation	Location	Heavy Metals	HRT (days)	pH	Removal rate (%)	Remarks	Reference
						6.11 mg/kg Cu, 0.90 mg/kg Ni		
Synthetic wastewater	*P. australis*	Italy	Zn, Pb	21	–	112.6 ± 17.8 mg of Zn and 82.8 ± 19.3 mg of Pb accumulated in plant biomass	Accumulation of metals was in the rhizomes and the roots of *P. australis*	Bernardini et al. (2016)
Synthetic wastewater	*P. australis*	Saudi Arabia	Cd, Pb, Ni	180	4, 7, 10	Cd = 89 Pb = 90 Ni = 93	Highest concentration of metals was in the order of roots > shoots > leaves	Bello et al. (2018)

amount of oxygen, common reed can promote carbon respiration and organic nitrogen mineralization, which leads to nitrate formation and organic matter stabilization (Bianchi et al. 2011; Chen et al. 2016). Some studies show the potential of common reed for sludge dewatering and mineralization.

Gagnon et al. (2013) compared *P. australis* to *Typha angustifolia* and *Scirpus fluviatilis*. *P. australis* was more efficient for sludge dewatering and mineralization of organic matter and had the highest reduction in sludge volume. The sludge volume reduced from 0.59 m^3 m^{-2} to 0.07 m^3 m^{-2} during the experiment. In addition, TP content decreased from 2.4% in the fresh sludge to 2.3% in the *P. australis* sludge. In another study, *P. australis* removed 5.7% of TP and between 70 and 98% of TKN and NH_4^-N in the STRB system (Gagnon et al. 2012). Nielsen and Bruun (2015) found that the sludge residue achieved up to 26% dry solid, depending on the sludge quality and STRB system dimension. They also stated that the concentration of heavy metals and hazardous organic compounds in the sludge residue was below the limit values of Danish and EU legislation after 10- to 20-year treatments. Due to the high nutrition content, the sludge can also be used as a substitute for commercial fertilizer in land applications.

Removal of other compounds from wastewater

P. australis is also used for the removal of different types of compounds silicone, dyes, and pesticides. Some studies reported the potential of *P. australis* for the removal of pharmaceutical compounds from wastewater. For example, Carvalho et al. (2012) found *P. australis* was able to remove 75% of tetracycline and 97% of enrofloxacin from an aquatic medium. As stated by Wang and Chi (2012), *P. australis* removed phthalic acid esters during the growing season. However, the removal rate was greater once cultured with *Theileria orientalis*. In another study, *P. australis* showed the ability to adsorb 839 mg kg^{-1} of boron (B) (Wang et al. 2015). The lower B-accumulating capacity of sediments was achieved by cultivation of polyculture wetland plants with *T. latifolia*, *Juncus gerardii*, and *P. australis* (Türker et al. 2016a). In another study, Türker et al. (2016b) stated that the concentration of B in the leaves of *P. australis* (251.09 mg/kg) in both monoculture and polyculture CWs was higher than stems (175.4 mg/kg) and roots/rhizomes (153.2 mg/kg).

Interestingly, *P. australis* peroxidase removed 93% of amaranth and 87% of amido black in 120 h reaction time, which confirms its ability for dye decolorization. The important parameters for dye removal are reaction time, pH, temperature, initial dye, and enzyme concentrations (Haddaji et al. 2015). In lab-simulated vertical wetland systems, 36.9% of polycyclic aromatic hydrocarbon was removed using *P. australis* under continuous and intermittent-flow feeding modes (Jie-Ting et al. 2015). Even the above ground biomass of *P.*

australis could be used to produce high-quality compost in terms of concentrations of metals (Sochacki et al. 2015). Table 4 shows the removal of different types of pollutants using *P. australis*.

Value-added products

After phytoremediation, *P. australis* has the potential to be used as a source of value-added products due to its specific characteristics. For instance, the high yield and low input requirements of this plant are the main advantages in biofuel production (Ahmed 2017). Reeds are considered as suitable candidates to produce high-grade activated carbon (Guo et al. 2016). They have high cellulose (33–36%) and hemicellulose (20–22%), which can be hydrolyzed into monosaccharides and then fermented into alcohols (Gao et al. 2014; Cavalaglio et al. 2016; Shuai et al. 2016; Zhang et al. 2018), butanol production (Gao et al. 2014), and high-quality roughage for ruminants (Tanaka et al. 2016). Table 5 shows different value-added products that can be produced from *P. australis*.

Control methods and management of *P. australis*

P. australis is considered a prime candidate as a biomonitor species due to several basic features such as high pollutant bioaccumulation and widespread distribution (Bonanno 2013). However, due to the rapid growth characteristics of *P. australis*, wetlands may become dominated by this species. The consequence of this change to ecosystem processes has harmful impacts on the native wildlife. This invasive plant blocks water flow and consequently deteriorates CW water quality. Frequent harvesting can mitigate these problems with large amounts of biomass waste being discarded in the process (Wang et al. 2015). Although the harvested biomass has become a problem in many places, it is considered to be a vegetation management choice in CWs for the purpose of improving nutrient removal. For the management and remediation of eutrophication in shallow lakes, water level variation and nutrient loadings should be considered (Zhao et al. 2013).

Table 4 Removal of different types of pollutants using *P. australis*

Type of pollutant	Reference
Veterinary drugs	Almeida et al. (2017), Carvalho et al. (2012)
Medical drug (praziquantel) (ibuprofen)	Marsik et al. (2017) He et al. (2017)
Phthalic acid esters	Wang and Chi (2012)
Antibiotics	Liu et al. (2013)
Silicon	Schaller et al. (2013)
Dye decolorization	Haddaji et al. (2015)
Polyhydroxyalkanoates	Jie-Ting et al. (2015)
Methylene blue (dye)	Kankılıç et al. (2016)
Boron	Türker et al. (2016b)
Pesticides (tebuconazole and imazalil) (pentachlorophenol)	Lv et al. (2016) Hechmi et al. (2014)
Tetracycline	Topal (2015)

Table 5 Various value-added by-products from *P. australis*

Product	Reference
Methane	Risén et al. (2013)
Paper	Risén et al. (2013)
Butanol	Gao et al. (2014)
Roughage for ruminants	Tanaka et al. (2016)
Activated carbon	Ahmed (2017)
Lignin	Angelini et al. (2017)

The management methods for invasive populations of *P. australis* usually consist of chemical, biological, grazing, and mechanical control (Mal and Narine 2004; Tanaka et al. 2016). For instance, mechanical control is the easiest way to remove *P. australis*. Mechanical control includes crushing, excavation of entire plants, mowing or cutting, hand-pulling, and burning (Hazelton et al. 2014).

Large-scale management of the *P. australis* wetlands helps maintain the biodiversity, sequesters carbon, creates jobs, and improves economic development of the local people. To address the problem of control of *P. australis* in North America, biological methods were classified in terms of regional requirement (Casagrande et al. 2018).

Brix et al. (2014) reported several efforts that have been implemented to increase the yields of the paper industry by the rehabilitation of *P. australis* fields infested with weeds. According to Mykleby et al. (2016) and Srivastava et al. (2014), the removal of invasive *P. australis* from wetlands and riparian zones in semi-dry regions had a significant impact on the water balance. On the other hand, *P. australis* can release phenolic compounds, which have effects on neighboring plants. In the context of global invasion of *P. australis*, these findings have important ecological implications through the improvement of understanding the process involved in its invasiveness (Uddin and Robinson 2018).

As suggested by Hazelton et al. (2014), *Phragmites* management should shift to inland management units or coastal watershed-scale efforts. Future management efforts could focus on the restoration of native plant communities rather than the eradication. However, the identification of ecosystems in *Phragmites* management is necessary and has positive benefits.

In a plan to manage *Phragmites* in North America, a model was developed based on components that positively affect the spread of this invasive plant, such as germination and recruitment, seed quantity, gene diversity, and seed viability. The results confirmed that germination and recruitment are central points for increasing genetic diversity while increases in seed quantity or seed viability resulted in higher recruitment rates (Hazelton et al. 2014).

In an economical context, the invasive characteristics of *P. australis* lead to substantial damage to the environment. For instance, the USA spends $25 billion annually for the management of invasive species (Pimentel et al. 2005). Kelly et al. (2013) stated that the annual cost for the control of invasive species in Ireland was £207.5 million and £1.8 billion in the UK. Among the different control methods, herbicides are typically used as the primary technique to control excess growth. Quirion et al. (2018) suggested that early detection and rapid response to small populations of *P. australis* invasion is implementable. In contrast, in many regions, invasive *P. australis* is not feasible to control excess growth. However, suppression and containment strategies are necessary.

In a recent survey by Rohal et al. (2018), 97% of the managers used herbicides for control of *P. australis*, followed by burning (65%), livestock grazing (49%), and mowing (43%). Glyphosate and imazapyr are the two most effective herbicides for the control of *P. australis*. The selection of these herbicides provides a wider range of options for the control of this plant. Typically, the appropriate time for the application of either glyphosate or imazapyr is during the late stages of flowering (summer) or seed filling (fall), and the best application is by aerial spraying from an airplane or a helicopter (Knezevic et al. 2013). Herbicide application during the vegetative stage can also be a viable option. Knezevic et al. (2013) used a mixture of three types of herbicides (glyphosate, imazapyr, and imazamox) either alone with two applications or as two-way mixtures on various growth stages of *P. australis*. They found that imazapyr and glyphosate had the highest control level (90%) at the end of the first growing season. However, imazamox and glyphosate had the lowest control level (< 30%) at the first application (Knezevic et al. 2013). This suggests that broad partnerships can be implemented between ecologists, managers, and policy makers in order to address the improvement of management methods and to solve the existing challenges of *Phragmites* invasion (Hazelton et al. 2014).

Concluding remarks and future perspectives

P. australis can be considered as a suitable candidate for phytoremediation of contaminants from wastewater, soil, and sediment. *P. australis* grows in different environments with various environmental conditions and can uptake, translocate, and accumulate a wide range of pollutants in below and aboveground tissue.

In terms of heavy metal pollution by *P. australis*, full-scale investigations of the long-term phytoremediation of contaminated sediments is needed to evaluate the influence and the bioavailability of contaminates. These investigations can help researchers to estimate the required time for phytoremediation of a contaminated site (Cicero-Fernández et al. 2017).

Besides, nutrient management may also limit the intensive growth of *P. australis* in wetlands, which could reduce invasion through competitive advantages over other native plants (Uddin and Robinson 2018). Further research and development on the physiology, biochemistry, and contamination removal efficiency based on the uptake of nutrients and heavy metals of *P. australis* is recommended (da Conceição et al. 2016). In general, future research on *P. australis* as an invasive plant is crucial. Long-term research related to the invasiveness and effects of *P. australis* on invaded communities may help to develop a feasible control method.

The following conclusions of the literature review are summarized:

- The highest aboveground biomass is obtained during the summer (especially in August) ranged from 1 to 10 kg/m^{-2} (fresh biomass).
- A few studies on pollutant uptake from soil and sediments have been published. The studies showed higher removal of *P. australis* than other aquatic plants.
- Many studies used the combination of *P. australis* and *T. latifolia*. However, *P. australis* has better nutrient and heavy metal removal performance.
- A higher rate of organic and inorganic pollutants can be removed by the combination of *P. australis* and a wide range of aquatic plants than the solo use of *P. australis*.
- The increase in initial organic load, contact time, and pH has a positive effect on pollutants removal efficiency by *P. australis*.
- After phytoremediation, the biomass of *P. australis* can be used for the production of value-added by-products such as biofuel and animal feedstock.
- Biological and chemical control methods are effective. However, the suitability and cost-effectiveness of these methods based on environmental conditions should be considered.

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