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Chapter 12

Phytoremediation using aquatic plants

12.1 Introduction

Freshwaters are affected by a diverse range of pollutants which increases the demand for effective remediation. Aquatic phytoremediation is a nature-based solution that has the potential to provide efficient, spatially adaptable and multi-targeted treatment of polluted waters using the ability of macrophytes to take-up, sequester and degrade pollutants. This chapter considerers the primary phytoremediation mechanisms that macrophytes employ to remove inorganic, organic and biological waterborne pollutants before highlighting some of the common macrophyte accumulators that have been studied. Three common macrophyte planting systems (i) constructed wetlands (CWs), (ii) wild macrophyte planting/harvesting and (iii) floating treatment wetlands (FTWs),are considered to understand how macrophytes are deployed for targeted aquatic phytoremediation.

Important practical considerations for implementing aquatic phytoremediation include the use of invasive species, the optimal harvesting time and frequency for pollutant removal with macrophyte biomass, and the full extent of the role that microbial biofilms play in phytoremediation. In this chapter, these issues are unpacked and recommendations for future programmes of research and development are made. Finally, the opportunities to generate 'added value' from expanding aquatic phytoremediation in terms of the provision of ecosystem services and the potential for resource recovery are outlined.

12.2Water contamination and water security

Surface waters are vital for supporting people and ecosystems; however, freshwater availability is under increasing pressure due to a growing human population requiring access to safe water(Heathwaite, 2010). Global freshwater resources comprise 2.5% of the total global water budget, although only 0.0072% (93,120km^3) of the total global waters are available for drinking, energy, food production and the industry sector(Lawford et al., 2013; Zimmerman et al., 2008).Tilman *et al*.(2011) predicts that crop production will need to increase by 100-110% by 2050 to feed the growing population, leading to a global freshwater deficit of approximately 2,400km^3 per year (Rockström et al., 2014).

Many surface waters are currently of sub-optimal standards due to a range of stressors impacting freshwaters such as point source and diffuse pollution, land-use change and climate change, which further compounds the challenge of providing water security (Ormerod *et al.*, 2010; Berger *et al.*, 2017).One of the major pressures on water quality in the United Kingdom is nutrient enrichment from diffuse pollution (Ulénet al., 2007), whereas elsewhere in countries such as China,additional issues of heavy metal pollution are also prominent (Cheng, 2003). Interactions between different stressors in space and time can also lead to additive effects(Heathwaite, 2010), for example, increased land-use change towards intensive agriculture and a potential increase in storm frequency may increase the delivery of nitrogen (N) phosphorus (P) and fine sedimentto receiving water(Dunn et al., 2012).

Table 12.1 summarises the surface water pollutants that are of concern and where remediation solutions are being developed. Water pollutants can be broadly categorised as either: organic, e.g. hydrocarbons, pesticides and algal toxins, orinorganic,e.g. metals or syntheticand manure-based fertilisers containing excess amounts of N and P,or biological,e.g. pathogens and algal toxins.The mobilisation and effects of different pollutants have been discussed extensively elsewhere (Heisler et al., 2008; Ohe et al., 2004; Liess & Carsten Von Der Ohe, 2005; Edwards, 2015; Lintelmann et al., 2003). However, different pollutants may have multiple sources, for example, N and P can be released from agriculture, aquaculture and urban waste water streams.

Managing waterborne pollutants through *in-situ* best management practices (BMPs) that target the source of pollution is the principal approach to improving water quality(Lam et al., 2011). However, lag times associated with the improvement of water quality and subsequent ecological recovery of receiving watersfollowing mitigation may range from 1 to >50 years(Meals et al., 2010). The 'legacy effect' is one such component delaying water quality improvements in spite of BMPs being in place(Haygarth et al., 2014). Water bodies, such as those with long residence times, may become reservoirs for pollutants over time, meaning that although source management is in place, the receiving waters remains high in pollutant levels for significant amounts of time(Meals et al., 2010). Therefore, developing management systemsthat combine BMPs with other methods of remediating waters with high levels of pollutants, both at source and throughout the catchment,is needed to sustainablyimprove water quality.

The pollution of water with inorganic elements such as N, P and metals also provides an opportunity to recover elements as part of a 'circular economy' approach(Masi et al., 2017; Quilliam et al., 2015). Energy-intensive mining for macronutrients such as P and potassium (K) are exhausting finite supplies of nutrientsfor the production of agricultural fertilisers(Jones et al., 2013), whilst liquidfertilisers and nutrient-rich solid manures applied to agricultural land are readily transferred to receiving waters.Coupling systems that remediate water pollution and enable the capture of these resources may help close the loop on nutrient loss (Quilliam et al., 2015). Therefore, macrophyte phytoremediation has the potential to be employed for both the sustainable remediation of surface waters and as a management strategy for recovering nutrients.

12.3Aquatic phytoremediation

Aquatic phytoremediation isaphytotechnologyused for the removal of pollutants from surface waters and the restoration of impacted water bodies (rivers, streams, lakes, ponds). Within surface watersplants can be cultured to remove pollutants from both the water column and the sediment (Newete & Byrne, 2016; Miretzky et al., 2004), and can be deployedat either the point source, or within waterbodies where diffuse pollution is problematic(Lu *et al.*, 2011). Aquatic phytoremediation specificallyuses macrophytes (i.e.freshwater adapted angiosperms, pteridophytes and ferns) for removing and degrading pollutants within aquatic environments(Rai, 2009). This definition does not include microalgae species. Macrophytes can be broadly classified into three primary growth forms: floating, submerged and emergent (Figure 12.1). Floating macrophytes occupy the water surface and include genera such as *Lemna* (duckweeds), *Hydrocharis* (frogbit) and *Nymphaea* (water-lilies) which may be free-floating or rooted. Submerged macrophytes grow primarily below the water surface and may be anchored to the substrate, although*Ceratophyllum* (hornworts) are a widespread genus of unrooted submerged plants. Emergent macrophytes occupy the margins of water bodies and are rooted into the substratebut have significant shoot growth above the water level, e.g.*Typha* (reedmace) and*Phragmites* (common reed). These different growth forms facilitate the removal of pollutants from both the water column and the sediment depending on the way in which they are deployed(Newete and Byrne, 2016).

Macrophytes have significant capacity for uptake of nutrients and other substances from their growth medium, and can thus lower the pollution concentration of a target water body(Dhote and Dixit, 2009). Macrophytes can remove and degrade pollutants using the key mechanisms of rhizo/phyto-filtration, phytoextraction, phytovolatilization and phytodegradation(Table 12.2). Emergent and floating macrophytes primarilytake up nutrients and other contaminants (whether from the substrate or water column) through their roots, whereasstem tissue can also be an important pathway for removal from the water column for submerged macrophytes(Denny, 1972;

Gabrielson, Perkins and Welch, 1984; Dhote and Dixit, 2009). Specific mechanisms for pollutant removal and degradation by macrophytes depend primarily on the type of pollutant (nutrient, heavy metals, organic pollutants, biological), and the location of the pollutant within the surface water body (water column, lake or streambed sediment)(Miretzky, Saralegui and Cirelli, 2004; Padmavathiamma and Li, 2007; Vymazal, 2011; Xing *et al.*, 2013; McAndrew, Ahn and Spooner, 2016; Polechońska and Samecka-Cymerman, 2016).Different mechanisms for removing various classes of pollutant from surface water systems by macrophytes are considered below.

Macronutrients

It is important to note that elements targeted for phytoremediation may exist in a dissolved phase, or in a particulate phase adhered to suspended material in the water column or bound to sediment, which means there are different mechanisms for removal(Perk, 2006).Macronutrients, including Nand P, are essential elements required in relatively large concentrations for plant metabolism (Hawkesford et al., 2011). Therefore, when aquatic system are enriched with N and P,phytoextraction (uptake and sequestration) is an important mechanism(Eid et al. 2012; Mkandawire & Dudel, 2005). Particulate pollutants in the water column, such as P,can be stabilised by phytofiltration(Tanner and Headley, 2011a; Olguín and Sá Nchez-Galvá, 2012), whereplant roots may excrete exudates that assist phytoextraction of adsorbed elements(Jackson, 1998; Verkleij *et al.*, 2009; Akeel, 2013). For N removal, phytodegradation may also be important in the water column and sedimentas the oxygen and energy supplied to the root zone from macrophytes may support nutrient-degrading microbial communities, including the simultaneouspresence ofboth nitrifyingand denitrifying bacteria (Table 12.2)(Lu et al., 2018).

Micronutrients/metals

Micronutrients are essential elements that are required by plants in relatively small quantities, e.g. to regulate redox reactions, metabolism and cell integrity (Broadley et al., 2011). Essential micronutrients include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum

(Md) and boron (B); beneficial but non-essential micronutrients include sodium (Na), silicon (Si), cobalt (Co), selenium (Se); while there are elements that can be found in plant tissue but are not thought to be beneficial such as aluminium (Al) vanadium (V), titanium (Ti), lanthanum (La)and cerium (Ce)(Broadley et al., 2011)(Table 12.1). Some of these elements may be enriched by industrial pollution but can be reduced by phytoextractionthrough repeated harvesting of plant tissue, following uptake in the water column through hydroponic growth (e.g. in FTWs) or where plants are rooted in sediment(Ali et al., 2013)(Figure 12.2). The efficiency of phytoextraction asa phytoremediation strategydepends upon thespecific degree of essentiality of each element for plant metabolism and is determined by specific mechanisms for uptake and translocation into plant tissue(Dhir, 2013). Hyperaccumulators are plants that have a high affinity for certain elements and through enhanced phytoextraction can sequester high concentrations of metals (Sarma, 2011; van der Ent *et al.*, 2013). Phytofiltration is important for soluble and particulate pollutants with absorption/adsorption to plant roots (Olguín and Sá Nchez-Galvá, 2012), and in some cases metals can be bound and/or precipitated on the plant roots(Xian *et al.*, 2010; Gomes *et al.*, 2016) (Figure 12.2).

Organic pollutants

Organic pollutants are compounds containing carbon that are primarily synthetic, environmentally persistent and potentially toxic. They include products such as pesticides,solvents and pharmaceuticals and personal care products (PPCPs) (El-Shahawi et al., 2010)(Table 12.1). Phytometabolism and rhizodegredation within the water column and sedimentare integral processes in the aquatic phytoremediation of organic compounds(Reinhold et al., 2010). Phytometabolism can occur if organic compounds are more hydrophilic meaning they pass more readily through the plant epidermis into plant cells (Lintelmann et al., 2003; Dettenmaier, Doucette and Bugbee, 2009; Yamazaki et al., 2015) (Figure 12.2). Sequestered compounds undergo chemical modification through oxidation, reduction or hydrolysis which makes them chemically more reactive within plant cells; theless harmful metabolite is then conjugated/bound to sugars, amino acids or glutathione to reduce its toxicity and hydrophobicity(Macek et al., 2000; Geissen et al., 2015). Thesebound metabolites may then be eitherstored within the vacuole orexcreted from the plant, or can become insoluble by being covalently boundwithin the cell wall (Zhang et al., 2014). Rhizodegradationcan take place within sediment,andmore hydrophobic compounds can serve as a microbial carbon source whereemergent macrophytes supply oxygen to the root zone (Figure 12.2). The advantage of these two phytoremediation processes is that there is no need for repeated harveststo extract the pollutant and thus disturbance to the aquatic system is reduced.

Microbial pollutants

Microbial water pollutants such as the bacteria *Escherichia coli* O157, the protozoan parasite *Cryptosporidium*spp.and viruses such as norovirus can cause harm to humans and animals (Haack etal., 2016; Fuhrimann et al., 2017) (Table 12.1). The ability of plants to directly take up microbial pollutants is limited; however, there are some accounts of pathogens entering plant tissue through the process of internalisation, although whether this is an active or passive process is unclear and likely depends on the type of pathogen, plant and the local abiotic conditions(Hirneisen et al, 2012). The primary mechanisms for removal of microbial pollutants from water are either, chemical, e.g. oxidation, photodegradation, exposure to plant root biocides and adsorption to organic material and biofilms; physical, e.g. through filtration and sedimentation; or biological, e.g. predation, natural die-off, antibiosis and other biolytic processes(Decamp and Warren, 2000; Karathanasis et al, 2003; Karim et al., 2004; Wand et al., 2006; Makvana and Sharma, 2013).Macrophyte planting systems, particularly CWs, may promote these mechanisms and thus facilitate the degradation of microbial pollutants.

12.4 Macrophytes used in aquatic phytoremediation

12.4.1 Macronutrients

Macrophytesuptake and sequester N primarily in the form of nitrate (NO_3^-) and ammonium (NH_4^+), while P is taken up as phosphate (PO_3^{4-}).Studies vary in their focus on total amounts (i.e. including particulate) versus the dissolved fraction of macronutrients,which makes comparing optimal macrophyte accumulator specieschallenging(Table 12.3). Macrophytes that have the greatest biomass production and/or fastest growth rates are some of the most effective nutrientphytoremediators(Keenen and Kirkwood, 2015), for example, *Eichhornia crassipes*, *Lemna sp*. and *Typha latifolia* have growth rates of 60-110 t/ha/yr, 6-26 t/ha/yr and 8-61 t/ha/yr, respectively(Gumbricht, 1993).

Emergent species have received considerable attention in nutrient phytoremediationand are often deployed in CWs, with *Canna* spp. and *Cyperus* spp. showingsome of the highest removal efficiencies for ammonium (NH_4^+) of between 74-100% (Table 12.3). *Typha latifolia*, *Lolium multiflorum* and *Polygonum hydropiperoides* showed high TP removal efficiency of 81-90% (Table 12.3).For floating macrophytes*Eichhornia crassipes*, *Lemna gibba* and *Pistia stratiotes* show good potential for nutrient removal:*E. crassipes*can remove up to 92% NO_3^- and 81% NH_3^- whilst *L. gibba*can remove 100% $NO_3^-$and 82%NH_3^-(Table 12.3). The same two species were also effective at removing total phosphorus (TP) (Table 12.3). Submerged plants have received less attention for their nutrient phytoremediation capacity(Table 12.3). This may reflect the difficulty of cultivating and harvesting submerged macrophytes, and thepotentially lower biomass generated compared to emergent plants(Du et al., 2017). *Ceratophyllum demersum* and *Myriophyllum aquaticum*are potential candidates for the targeting of total nitrogen (TN) and TP with removal rates >41% (Table 12.3). *Potamogeton crispus*was deployed as part of a hybrid FTW experiment and was found to have enhanced effects over the FTW comprised of only emergent plants; however, the individual removal contribution from *P. crispus* was not quantified(Guo *et al.*, 2014). Most submerged species are rooted in sediment and may also remove nutrients from the water column through foliar absorption (Eichert and Fernández, 2011). Hence they offer the dual ability to remove nutrients from water and sediment,allowing the simultaneous remediation of sediments that have a pollutant legacy and which may continue to release nutrients to the water column via internal loading even after external loads have been reduced. However, the disturbance caused during harvesting can re-suspendsediment-bound elements, and alter the macrophyte-equilibrium state to a potentially undesirable phytoplankton-dominated state(Kuiper et al., 2017).

The phytoremediation potential of a macrophyte is influenced by biotic factors such as competition, predation anddevelopmental stage (Quilliam et al., 2015), and abiotic factors such as temperature, pH, light availability, seasonality and nutrient loading (Ansari et al, 2014). For example, Ayyasamy et al.(2009)found that the removal efficiency of by*E. crassipes*increased between concentrations of 100mg/l to 300mg/l of NO_3^-, but decreased at higher concentrations of 400 and 500 mg/l of NO_3^-. Similarly, a mesocosm-based study of the effect of different temperature regimes on N and P removal by*Nasturtium officinale* and *Oenanthe javanica* found that maximum net accumulation of TN and TP occurred at an air temperature of 22°C but deteriorated thereafter(Hu et al., 2010). Given the wide range of factors that may influence the ability of macrophytes to remove contaminants, understanding the performance of some of the key macrophyte accumulators under different environmental conditions is prudent in order to optimise species selection.

12.4.2Metals

Macrophytes canalso remove micronutrients(henceforth referred to as metals (Rai, 2009))from water and sediments, and hyperaccumulators are most appropriate for the phytoremediation of metals(Ali et al., 2013). The search for hyperaccumulator species has been one of the primary foci within the field given the widespread prevalence of past and current metal industrial effluents and the ecological risks they carry(van der Ent et al., 2013); however,metal bioavailability can be reduced by sedimentation and adsorption to clay particles (Kumar et al., 2008). Studies based on mesocosm-scale CW experiments have been carried out on synthetic solutions with elevated metal concentrations in domestic and industrial wastewaters to assess the potential of macrophytes of different growth forms to act as hyperaccumulators (Fu & Wang, 2011; Kamal et al., 2004; Rai, 2009;

Rezania et al., 2016)(Table 12.4). Many species also have the capacity to take up multiple types of metals meaning that some species could be more beneficialin phytoremediation (Table 12.4).

Macrophytes that have often been cited as hyperaccumulators with high biomass potential are free-floating plants, such as members of the Lemnaceae (e.g. *Lemna minor*), *Pista stratiotes*, *Eichhornia crassipes* and those from the genera*Salvinia* (Table 12.4). For example, *L. gibba*has been reported to concentrate between 14,000mg/kg dry weight of Cd, whilst *E. crassipes* can concentrate 10,000mg/kg Zn (Low et al., 1994; Mkandawire et al., 2004). Furthermore, *Typha latifolia* and *Cetatophyllum demersum L.* have also shown good potential (Osmolovskaya & Kurilenko, 2005; Sunita et al., 2015). The main limitation for macrophyte metal uptake is the toxicity of the target metal pollutant at higher concentrations(Landesman et al., 2011). However, detoxification mechanisms also allow species to avoid the negative effects of these metals (Deng et al., 2004); for example, more than 50% of the Ca, Cd, Co, Fe, Mg, Mn, and Zn recovered in the roots of *Pistia stratiotes*were actually attached to the external surfacesindicating theability of the plant to exclude metals and thus maintain tolerable levels internally (Lu et al., 2011). Newete & Byrne(2016) also state that the extent of the root system affects the ability of macrophytes to remove metal pollutants, with fibrous root systems being superior due to their large surface area.Physio-chemical factors are also important for uptake and accumulation of metals with temperature, light, pH and salinity all having been shown to influence remediation performance (Rai, 2009).

12.4.3Organic pollutants

Table 12.5 shows the wide range of studies that have been carried out in relation to the phytoremediation of organic pollutants and some of the key macrophytes that may be utilised. For pesticides, *Lemna minor* removed 95% of 2,4,5-trichlorophenol, whereas for isoproturon and glyphosate *L. minor*its removal efficiency was poor(25% and 8% respectively; Table 12.5). *Eichhornia* *crassipes* also shows good phytoremediation potential, removing up to 81% of ethion within a water mesocosm experiment(Table 12.5). The removal of DDTby macrophytesshows promise.For the DDT isomers *o,p'*-DDT and *p,p'*-DDT: *Spirodela oligorrhiza* can remove 66% and 50% respectively; whilst*Myriophyllum aquaticum* can remove 76% and 82% respectively (Gao et al., 2000). *Elodea canadensis*also has the ability to remove 48% to 89% of *p,p'*-DDT(Gao *et al.*, 2000; Garrison *et al.*, 2000). *Lemna gibba, L. minuta* and *Potamogeton crispus* have been demonstrated to be very efficient at removing phenols from water (Barber et al., 1995; Hafez et al., 1998). However, *P. crispus* is less efficient at removing twoPAHs, phenanthrene (removal 18-34%) and pyrene (removal 14-24%) (Meng et al., 2015).

There is great potential for phytoremediation of a wide variety of PPCPs such as anti-inflammatory, hormonal replacement and anticonvulsant products (Zhang et al., 2014). CWs(section 12.7.1) planted with *Phragmites australis* demonstrated very efficient removal of the hormones Estrone, 17 beta-estradiol and 17 alpha-ethinylestradiol from water (Table 12.5). In CWsthe water column/plant sediment matrix adepthof *c*.7.5cm provided more efficient PPCP removal than deeperdepths of 30cm(Zhang et al., 2014). This highlights the importance of oxygen for the removal of waterborne hormone pollutants with vertical mixing from the surrounding atmosphere increasing the aeration of plant roots and (Zhang et al., 2014). Plants such as *Typha latifolia* with more extensive roots and rhizomes system may be favourable for deployment due to their capacity to oxygenate water(Makvana and Sharma, 2013).

Scirpus validus displays mixed ability to remove anti-inflammatory pharmaceuticals with very efficient removal of naproxen, compared to very poor removal of diclofenac (Zhang et al., 2012; Zhang et al., 2013a). *Typha angustifolia*removed 27-91 % of anti-inflammatory drugs in a study by Zhang et al.(2011). Chen et al.(2016) found that there is large variability in planted rural CWs in terms of their removal efficiency of PPCPs with 11-100% removal of anti-inflammatories, 37-99% for β-blockers and 18 - 95% for diuretics. Understanding this variability and identifying macrophytes for the removal of PPCPs through laboratory studies and at the field-scale is important given the need for lowcost removal solutions, especially in developing countries. There has been little focus on the use of novel macrophyte planting systems(e.g.FTWs) for the removal of organic chemicals, and future work on these systems would build flexibility into the deployment of different aquatic phytoremediation schemes for tackling the problem of PPCP pollution. Importantly, the distribution and storage of organic chemicals within plants, especially for PPCPs, requires further study in orderto avoid the problem of transferring pollutant from one place to another(sections 12.8 and 12.9).

12.4.4 Microbial pollutants

Most studies on the removal of microbial pollutants and their indicators of the presence (e.g. *E.coli*,faecal coliforms and faecal streptococci)are focused on macrophytes within CWs, therefore the following examples will mainly refer to this planting type (see section 12.7.1).Furthermore most studies show that CW planting systems removemicrobial pollutants from watervia a combination of chemical, biological and physical mechanisms.A study of 12 CWs found that over a year vegetated CWs removed between 95-97% of faecal coliforms and 93-98% of faecal streptococci (Karathanasis et al., 2003). Similarly, in an experimental CW system,Makvana & Sharma(2013)demonstrated removal rates of 94%, 87% and 94% for *Salmonella*, *Shigella* and *Vibrio,*respectively. However, the removal of *Salmonella* and *E. coli*from water in unplanted control mesocosms versus mesocosms containing*Typha latifolia*, *Cyperus papyrus*, *Cyperus alternifolius* and *Phragmites australis*showed no significant difference in the removal rates (>98 %) between the two treatments; furthermore,in general, unplanted mesocosms reached their maximum removal rate before the planted mesocosms(with the exception of the*C.alternifolius*mesocosm) suggesting that plants provide little additional benefit for removing biological pollutants over and above the effect of standing water conditions(Kipasika et al., 2016). Similarly, a review comparing *Lemna sp*. treatment ponds against unplanted treatment ponds showed that the latter had greater removal rates of *E.coli*facilitated by the greater exposure of the water to UV light and the subsequent photodegradation and microbial die-off (Ansa et al., 2015). However, Decamp & Warren (2000)have shown that gravel beds planted with *Phragmites australis*remove *E.coli* more quickly compared to unplanted soil beds, possibly as a result of the impact of antagonistic root exudates from *P. australis*on *E. coli*survival.

The variability of the results obtained between planted and unplanted experiments suggests that for each treatment system different mechanisms of microbial pollutant removal become dominant. Within unplanted facultative systems or lagoons it is likely that oxygenation and phytodegradation from UV light are the dominant methods of removal (Ansa et al., 2015). Conversely, biological and chemical process may become more important within planted systems, for example, *Pistia stratiotes*facilitates presence of protozoa by providing structural habitat, which can increase predation on *Salmonella*(Awuah, 2006). Conversely, predation from protozoa seemed to have a negligibleeffect in systems planted with *Spirodela polyrhiza* (greater duckweed),highlighting that removal mechanismsare probably related to below-ground morphological attributes, with more extensive roots/rhizomes providing superior habitat for grazers (Awuah and Gyasi, 2014).Increased root zone surface area also facilitates greater microbial biofilm growth which is thought to be a key removal structure for bacterial adsorption and predator microbial proliferation(Decamp and Warren, 2000). Therefore,smaller grasses such *Festuca arundinacea* may have limited potential for microbial pollutant removal compared to large emergent such as*Typha latifolia*(Decamp and Warren, 2000). Futureresearch investigating the ability of different macrophytes to remove microbial pollutants from water, especially outside of CWsystems, is clearly merited. Direct deployment of macrophytes for pathogen removal would be highly beneficial in developing countries where low-cost options for remediation could provide accessible water treatment.

Of the few experimental studies investigating potential for macrophyte removal ofmicrobial pollutants outside of CWs, Saeed et al.(2016) demonstrateda 72 % reduction of *E.coli* in FTWs planted with *Phragmites australis* and *Canna indica*. However, during times of high *E.coli* loading, induced by experimental 'shock phases' where hydraulic loading was increased between 5 to 14-fold to simulate low frequency and high magnitude discharge events, the removal of *E. coli*was reduced significantly to levels varying between 6-45%. The effect of hydraulic retention time is also important for pathogen survival and die-off (Reinoso et al. 2008)and may have implications for the use of phytoremediation (with FTWs) in lakes and rivers given the difference in hydraulic retention times.

12.5Macrophyte phytoremediationcommunities

There has been considerablework focusing on the ability of individual plant species to remove single pollutants from water(e.g. Zhou & Wang 2010), with the design of CWs also focusing on monocultures of macrophytes(Kadlec, 2009). Conversely, there has been a lack of studies that explicitly explore the ability ofmixedplant assemblages to simultaneously take-upand degrade multiple pollutants(Koelbener et al., 2008). A plant community-based approach provides the opportunity to enhancethe removal of both single pollutants, but also target multiple contaminants.Studies that have looked specifically at phytoremediation using plant communities have shownencouraging results(Fraser et al., 2004; Zhang et al., 2007; Liang et al., 2011; Türker et al., 2016). For example, an experiment testing the removal of N and P from four different emergent macrophytes in parallel (*Carex lacustris*, *Scirpus validus*, *Phalaris arundinacea* and *Typha latifolia*) found that microcosms planted with all four macrophytes in equal proportion, either matched or outperformed microcosms planted with a single species(Picardet al.2005). Earlier studies also suggest thatplant polycultures have a greater removal potential for heavy metals and can reduce biochemical oxygen demand (BOD)(Karpiscaket al., 1996; Scholes et al., 1999). However,Türker et al. (2016) reported that boron removal from mine effluent was more effective in native emergent monocultures compared to polycultures, although the opposite was true for NO_2^- removal. These results suggest that there are probably optimal plant combinations for particular pollutants and further experiments designed to identify these combinations would help to optimise the efficiency of phytoremediation.

Toassembleappropriate plant combinations there are several importantfactors to consider including the functional diversity of the community. It has been reported that simply increasing species diversity in a plant assemblage can increasenutrient removal, although polycultures containing more thanthree species showed no further benefit (Ge et al. 2015;Geng et al. 2017). A common theme among these studies is the importance of species identity in explaining variation in nutrient removal, where specific combinationscan more effectively remove pollutants. Therefore, assembling appropriate plant communities based around the complementaryphytoremediation potential of individual species, and the interaction of those plants withothers in the assemblage is potentiallymore important than simply increasingspecies richness per se. However, the effect of competition between plants is important to recognise as this may impact the community composition, and therefore the ability to remove the targeted pollutants from water(Zhang et al. 2007). In a mesocosm experiment, containing the submerged macrophytes *Stuckenia pectinata* (Sago pondweed), *Potamogeton natans* (broad-leaved pondweed), *Potamogeton crispus* (curled pondweed) and *Zannichellia palustris* (horned pondweed), it was found that *S.pectinata* reduced the biomass of the other species (Engelhardt & Ritchie, 2001). Reducing the biomass of certain species willnot necessarily compromise overall removal efficiency as uptake and sequestration potential will vary with species. However, this highlights the need to understand interspecific interactions in order to enhance removal efficiency, especially when considering targeting water bodies in a non-equilibrium state where conditions favour the dominance of one particular species (Engelhardt & Ritchie, 2002).

A field studyemploying plant communities revealed some of the benefits of combining multiple macrophytes (Wang et al., 2009; Zhao et al., 2011). Nine macrophytes species (five floating, one submerged and three emergent) deployed on FTWs and planted on river banks outside Jiaxing City, China, demonstrated removal rates of TN and TP at 16%-37% and 26%-43% respectively (Zhao et al., 2011). Although the removal rates were relatively low,it was also highlighted that the plant community-based approach allows for species within the community to compensate for deficits in uptake of other species(Zhao et al., 2011). For example, the average P content of floating macrophytes was *ca.* 5.9g/m^2, whereas, emergent species including *Canna indica and Pontederiacordata* with higher biomass accumulation, stored P at a level of*ca.* 7.3g/$m^{2.}$.Similarly,a phytoextraction study with emergent species (*Carex flava*, *Centaurea angustifolia* and *Salix caprea*) allowed the impact of facilitation across increasing concentration gradients to be seen(Koelbener*et al*., 2008). Here, the willow*S. caprea* attenuated the toxic effect of Zn on therelative growth rate of *C. flava* by lowering the availability of Zn, thus mitigating the negative effect of Zn on the sedge(Koelbeneret al., 2008). This highlights that competitive effects may not always be negative and may produce positive effects through ‘over yielding’. The consequences of competitive interactions between candidate macrophytes evidently deserve particularattention within the field of plant community-based phytoremediation.

As well as the potential enhanced removal of pollutants from plant communities with macrophytes of different life forms(Koelbener et al., 2008) there may also be the potential for generating ecosystem services from polycultures.A 2-yearstudy by Wang et al. (2009)explored the potential restoration of Lake Taihuand Lake Machou byusing a mosaic of macrophytes in successional stages highlighting the potential for spatial and temporal diversity in macrophyte deployment, and the provision of ecosystem services. Floating and emergent macrophytes were first introduced to reduce light availability for algal growth,facilitating theintroduction of submerged species leading to removal rates of TN and TP of 60% and 72%(Wang et al., 2009). The provision of ecosystem services due to the different plant life forms was highlighted as an advantage by Wang et al.(2009)as increasedpatches of vegetation provided refuge for zooplankton that subsequently grazed phytoplankton.The added value of diverse plant communities is a factor that requires quantificationto espouse the benefits of aquatic phytoremediation over and above water treatment.

Plant community-based approaches provide the opportunity to build temporally more consistent treatment into phytoremediation by exploiting the differing phenology of plant species; polyculture systems canthus offerthe most consistent water treatment option with least susceptibility to seasonal variation(Karathanasis et al., 2003). However, the temporal dynamics of plant communities within the context of phytoremediation are under-researched, and there is a needto explore the assembly of plants, e.g. in terms ofdiffering phenologies,to extend the growing season, especially in temperate regions where water treatment potential declines after senescence.

12.6 Issues in utilising invasive macrophytes

The most effective phytoremediators have fast growth rates and high biomass accumulation; however, outside of their native range macrophyte species with these traits are often considered to be invasive, and given their potential for rapid colonisation they can quickly outcompete native macrophytes (Chambers et al., 2008). Species that are invasive in the UK, such as *Azolla filiculoides* and *Hydrocotyle ranunculoides*, can clog waterways and have serious ecological impacts on native flora and fauna (Schultz and Dibble, 2012). In the UK, the combined cost of controlling invasive plants, together with their economic impact, is estimated to be £1.7 billion per annum(The Great Britain Non-native Species Secretariat, 2015). Therefore, there is a significantjuxtaposition between using species of invasive plants in phytoremediation, and management strategies to control invasive species (Rodríguez et al., 2012). Given that in many cases the complete eradication of invasive aquatic macrophytes such as *Eichhornia crassipes* is unlikely, it may be more appropriate to exploit these macrophytes as part of an integrated management strategy that controls the spread of these species whilst at the same timeeffectively removing nutrients and metals, capturing suspended sediment, and harvesting the biomass for economic gain (Patel, 2012; Yan et al., 2017). A similar parallel can be drawn with non-native and invasive zebra mussels (*Dreissena polymorpha*) which are often considered detrimental(Matsuzaki et al., 2009), but have also widely been reported to stabilise the clear-water state of shallow lakes through filtering phytoplankton and removing harmful cyanobacteria (Gulati et al., 2008).

Water bodies where invasive species are already present may be targeted for active harvesting allowing periodical regrowth for continued phytoremediation(Xu et al., 2014). However, there are important factors to consider including the containment of macrophytes to avoid transferto other water bodies (e.g. via contaminated harvesting equipment or through downstream spread of fragments), including the most appropriate harvesting technique, and the sustainability of exploiting such an ecological engineering systems(Rodríguez et al., 2012; Yan et al., 2017). The site-specific context will likely determine the appropriateness of active harvest of invasive aquatic plants (Yan et al., 2017). In terms of introducing macrophytes into a freshwater system for phytoremediation, it is inappropriate, and indeed possibly illegal, to deploy invasive species given the potential for ecosystem damage and long terms effects. In these circumstances non-invasive or native plants should therefore be employed, unless containment of invasive plants can be ensured, such as in engineered CW systems.

12.7 Macrophyte planting systems

Macrophyte planting systems are effectivelyplanting strategies that are employed to facilitate targeted phytoremediation of waters in different contexts in terms of point source and diffuse source treatment and restoration. The following section details the key aspects of the three main aquatic phytoremediation planting systems that have been developed; CWs, wild macrophyte harvesting and planting, and FTWs.

12.7.1 Constructed wetlands

Phytoremediation has primarily been optimised for point source wastewater treatment in the form of CWs. CWs have been used for the treatment of a variety of effluents including urban storm water, sewage, mine tailing drainage, storm water treatment, landfill leachate treatment systems and for wastewater polishing (Kivaisi, 2001; Nivalaet al., 2007; Tanner, 1996; Vymazal, 2009; Vymazal, 2011).CWs also show potential for treating wastewater containing emerging contaminants of concern including pharmaceuticals and other endocrine disrupters (Vymazal, 2009).

CWs can be categorised as free water surface flow wetlands (FWSF) or sub-surface flow (SSF) wetlands(Dhir, 2013) (Figure 12.3). FWSF wetlands containemergent, floating and submerged macrophytes growing in shallow ponds or lagoon watersover sandy or organic soils, which allows the influent contaminated water to slowly flow through the emergent macrophyte stems for maximum pollutant uptake and UV degradation (Kadlec, 2009). SSF wetlands are the most common type of CW and comprise emergent macrophytes growing over a substrate of stone or gravel matrix enabling water to comein direct contact with plant roots, rhizomes and biofilms,which promoteaerobic conditions(Vymazal, 2011). Several processes including physical filtering of the water, biological processing of water by plants and microbial biofilms, and chemical changes due to redox state can assist in pollutant removal in SSF systems (Faulwetter et al., 2009). The average SSF CW system is 100 times smaller than the FWSF CW system (Kadlec, 2009), therefore, FWSF are more common in North America and Australia where a larger surface is available, whilst SSF wetlands are more common in Europe where land availability is more limited(Vymazal, 2011). SSF wetlands are frequently used to ameliorate the concentration of biologically derived organic material as indicated by the lowering of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) from waste waters (Vymazal & Kröpfelová, 2009).

CWs are the most advanced form of macrophyte deployment within the umbrella of aquatic phytoremediation (Kennen and Kirkwood, 2015). However, these systems can require high investment costs and they are restricted primarily to pollutant point sources where there is wastewater treatment such as tertiary sewage treatment and wastewater polishing before water enters a natural waterway (Patiño Gómez and Lara-Borrero, 2012). This restricts the application of

CWs for the treatment of water containing pollutants from diffuse sources. Although CWs have the potential to be utilised for treatment of a wide range of contaminants, their most widespread application has been for sewage wastewater-related contaminants, including BOD, COD, N and P, and often they are set up with crop monoculture to maximise plant uptake (Kadlec & Wallace, 2009; Sundaravadivel & Vigneswaran, 2001; Vymazal, 2009).

CWs vary in level of design and engineering required for their development; FWSF wetlands are generally low tech gravity-fed systems, whereas, SSF require more construction and management to import the stone/gravel matrixes, and also may include bundsto separate different treatments then requiring the use of electric pumps (Kadlec and Wallace, 2009). In both types of CWs there are high investmentsin construction and operational costs. CW can also become clogged with sediment, which impacts the functioning of the system and imposes additional costs for excavation and removal of contaminated sediments, and the subsequent reinstatement of macrophytes (Machado et al., 2016). According to design guidance for the treatment of urban waste water and sewage, SSF CWs may require an area of around 5m^2 to 10 m^2 of CW per person equivalent for adequate water purification(Tilley *et al.*, 2014). Therefore, given the potentially large area required, CW-based phytoremediation may be unable to compete for limited land availability with other more profitable land uses. Furthermore, in countries where vector-borne diseases, such as malaria or dengue, are a public health issue the creation of open shallow wetland environments may be undesirable as it has the potential to provide ideal conditions for the propagation of mosquitoes and other disease vectors(Mwendera et al., 2017).

From both industry-based observations and from the available literature, the primary purpose of CWs is water treatment and wastewater polishing. This however, ignores their potential to offer ecosystem services such as sequestering and harvesting nutrients for reuse, provisioning for biodiversity, pollination and carbon sequestration, and thus underplays the overall value of CWs. There is great potential to develop different post-remediation ‘streams’ which have been relatively unexplored, and which emphasise support for different ecosystem services (see section 12.10.2). Aquatic phytoremediation is a promising technology for the treatment and remediation of polluted water with the operational point-source based CW systems in place, but given the limitations of these systems, including the lack of application for diffuse pollutants, investment costs and lack of ecosystem focus there is an opportunity to further develop context-specific, sustainable phytoremediation that provides ecosystem services within wider environmental systems.

12.7.2 Wild macrophyte harvesting

Most aquatic phytoremediation planting systems involve the deliberate deployment (FTW) or engineering of planted systems (CWs). Harvesting of existing wild macrophytes from water bodies such as shallow lakes can also be a phytoremediation strategy,and relies upon the opportunistic and timely removal of macrophyte biomass in order to manage waterborne pollutants suchas N and P(Huser et al., 2016). A study of an urban shallow lake, showed that harvesting an annual amount of 3,600 kg dry weight of *Elodea canadensis* led to 16.4 kg P being removed from the system, equating to around 53% of the TP load removed (Bartodziej et al., 2017). Although the estimated cost of removal was $670 per kg of TP, which was more expensive than chemical flocculating treatment,this wasstill considerably less expensive than many catchment best management practices (Bartodziej et al., 2017). Macrophyte harvesting is often carried out in lakes and waterways ostensibly to relieve navigation, drainage, aesthetic or recreational problems, rather than for phytoremediation purposes, but is notable that nutrient export may be a collateral benefit of such harvesting. Other case studies have shown that macrophyte harvesting for nutrient removal does not reduce nutrient loading quite as favourably (Carpenter and Adams, 1977; Morency and Belnick, 1987), withPeterson et al. (1974) estimating that plant harvesting only removed 1.4% of TP loading.

The variation between these case studies is possibly a result of the levels of nutrient loading, with waters that receive extremely high inputs of nutrients leading to a poor offset by removal from plant harvesting(Bartodziej et al., 2017). Another source of variability for nutrient removal is the coverage of macrophytes across the particular water body; the reported optimal coverage of macrophytes ranges from 5% to 40% (Portielje and Van der Molen, 1999; Dai *et al.*, 2012; Xu et al., 2014). For environmental managers considering macrophyte harvesting as a mechanism for in-water nutrient management, it is crucial that a scoping study is carried out to determine the base balance of nutrient input/output and plant removal capacity, and to identify the need for upstream best practices as part of an integrated management strategy.

The harvestingmethod itselfis also an important element of harvesting wild macrophytes, e.g. removal by hand, or mechanically via specialised boats equipped with cutting or raking apparatus (Quilliam et al., 2015). Hand removal is labour and time intensive, although it allows targeted macrophyte removal and minimises disturbance (Quilliam et al., 2015). Conversely, mechanical removal allowsmore rapid and extensive removal but is non-selective and can lead tohigh levels of turbidity due to the re-suspension of sediments. This can impact invertebrates and fish by removing structural habitat and may ultimately drive the system from a desirable clear water macrophyte-dominated state to a potentially unfavourable phytoplankton-dominated state(Dawson et al., 1991; Sayer et al., 2010; Habib and AR, 2016).

In some circumstances it may be necessary to establish macrophytes in waterbodies by direct planting through seeding or transplanting propagules (e.g. tubers/root crowns) if there are noexisting macrophytes, or if a particular species is required to target certain pollutants (Smart et al., 1998; Hilt et al., 2006). In addition to plant establishment there is also scope to enhancemacrophytegrowth and biomass by engineering interventions such as the assembly of polytunnels over vegetation, or enclosures to reduce grazing losses.

12.7.3 Floating treatment wetlands

Within aquatic phytoremediation one such novel ecological engineering solution that has been developed is the FTW. The premise of this system is that highly productive emergent macrophytes such as *Typha latifolia* are planted within a growth medium, which is supported by a buoyant frame allowing the roots of the emergent macrophytes to be submerged in the water, thus enabling rhizofiltration, phytoextraction and phytodegradation to take place hydroponically(Nichols et al., 2016; Kiiskila et al., 2017) (Figure 12.4). Root uptake associated with FTWs is primarily applicable to water-soluble contaminants within the water column only, although sediment-bound pollutants canbe physically filteredfrom the water column by plant roots (Tanner and Headley, 2011b). FTWs have recently gained increased attention and may also be referred to in the literature as artificial floating islands, integrated ecological floating beds, floating plant bed system and hydroponic root mats (Yeh et al., 2015).

FTWs can accommodate fluctuations in water levels, andthe stability of materials used to construct the buoyant frame may include items such as polyvinyl chloride (PVC) pipes, foam sheets, bottles and bamboo (Ladislas et al. 2013; Wang et al. 2015;Pavlineri et al. , 2017). However, it would be useful within the literature if qualitative information and design challenges were alsoreported to provide an idea of performance and usability of FTWs in practice, and although there are no reported incidences of FTWs capsizing or other failures during pilot tests, this may simply reflect publication bias.

Netting material or foam is generally used to support the growth medium in which the macrophytes are grown (Yeh et al., 2015). Material previously used as substrate includes peat, soil, cotton and coir fibre (Pavlineri et al., 2017). Furthermore, FTWs comprising foam with gaps to support pots have also been designed (Lynch et al., 2015). Growth media physically supports the planted macrophytes and provide nutrition, but the substrate can also enhance pollutant removal through the stimulation of microbial activity (Tanner & Headley, 2011a). Macrophytes may be established by transplanting of seedlings, cuttings or whole plants (Yang et al., 2008; Ning et al., 2014). An advantage of using FTWs rather thandirect plantingof macrophytes is the ease in which the biomass can be harvested from the frame, instead of having to remove plants from the sediment. The quick and simple method of harvesting afforded by growing plants in FTW facilitates recovering pollutants from plant biomass (Bartodziej et al., 2017). There is potential for quick re-planting of the FTW for continued remediation and biomass removal (Wang et al., 2015; Ge et al., 2016).

FTWs have been studied principally for their capacity to remove nutrients, but there have also been attempts to assess heavy metal, pathogen and phytoplankton removal (Borne, 2014; Yeh et al., 2015; Jones et al., 2017; Kiiskila et al., 2017). FTWs have been deployed at a variety of different scales including microcosms, mesocosms, and as pilot trials within lagoons (Headley and Tanner, 2008; Ladislas et al., 2013; Chang et al., 2014; McAndrew et al., 2016; Nichols et al., 2016; Kiiskila et al., 2017). Here the experimental polluted water used has included storm water, lake water, river water, sewage effluents, domestic wastewaters, refinery wastewater, acid mine drainage, and livestock effluents (Zhu et al., 2011; Li et al., 2012; Borne, 2014; Wang and Sample, 2014a; Abed, Almuktar and Scholz, 2017; Kiiskila et al., 2017). Mesocosm-scale studies are the most prominent form of exploration into the effectiveness of FTW thus far (Chen et al., 2016), although there have been a few examples of deployment at field-scale, such as Zhao et al. (2012)who demonstrated thatTN and TP concentrations could be reduced in a polluted Chinese river. Mesocosm studies withsynthetically produced experimental water allows full control of all input parameters. However,they may not be representative of the real remediation performance given that polluted waters contain a multitude of chemicals and microbes which may influence remediation (Javadi et al., 2005). Therefore, further studies would benefit from testing the remediation of water sourced from the environment.

Only a small handful of field-scale experiments have been carried out that assess the usefulness of FTWs in successfully remediating pollutant-impacted waters (Zhu et al., 2012; McAndrew et al., 2016; Nichols et al., 2016; Olguín et al., 2017). Of the available studies that assessFTW performance within water bodies, including streams, urban and rural ponds, results focus on plant tissue element accumulation rather than the arguably more pertinent issue of water quality improvement (Zhu et al., 2012; Olguín et al., 2017; McAndrew et al., 2016; Nichols et al., 2016). Although plant tissue sequestration is extremely important for assessing the bioaccumulation potential of macrophyte species it does not explicitly demonstrate water quality improvement; this can only be proven through monitoring water chemistry. Scaling up mesocosm scale experiments to assess actual field-scale water quality improvement is challenging given the ideal of a control site with comparable water chemistry and abiotic and biotic conditions, or high-temporal resolution baseline water quality data forthe experimental water body, both of which may be unavailable. Where there is a clear opportunity for upstream and downstream water quality sampling near the experimental FTWs, such as a stream, water quality changes are more likely to be attributed to the FTW intervention between these points (Olguín et al., 2017). Similarly, more field studies longer than 2 years, ideally up to 5 to 10 years, would lead to a better understanding of the longer-term performance of FTWs and, crucially, reveal the actual remediation time(Yang et al., 2006).Furthermore, the influence of inter-annual hydrological variability on FTW performance in terms of precipitation and evaporation could also be evaluated. Despite the paucity of scientific studies at the field scale, commercial companies now commonlyoffer FTWs as a water treatment solution, and as part of the aesthetic enhancement of urban rivers. The phytoremediation research community must aim to keep pace with the private sector to corroborate industry-advocatedbenefits of FTWs and avoid any potential reputational damage to aquatic phytoremediation where expectations of these systems from stakeholders are not met (Keenen and Kirkwood, 2015).

The remediation performance of FTWs is highly variable with reported minimum and maximum removal efficiencies for TN values being 0.71 mg/l (4 %) and 51 mg/l (91 %) and 0.06 mg/l (1 %) and 18.85 mg/l (90 %) for TP (Figure 12.5). This high variability may be due to differences in FTW design, macrophyte species employed, and the chemical composition of the experimental water. A further example of variation in removal efficiency comes from Lynch et al. (2015)who compared two commercial FTWs (Beemat and BioHaven®) planted with the rush *Juncus effusus* that had been designed to treat storm water. It was found that Beemat FTW outperformed BioHaven® in both TN and TP removal (Lynch et al. 2015). The difference in removal may have been due to the difference in substrate (coir matting vs. sphagnum peat) or the physical design of FTW(Lynch et al. 2015).The growth medium is indeed an important source of variability within FTW design. Rice straw used as growth medium was found to enhance removal of TN, NH_4^+ and NO_3^-compared to plastic filling(Cao and Zhang, 2014). Similarly, the FTW with straw filling had a greater total densityof nitrifying and denitrifying bacteria which suggests thatthisorganic material was providing both a habitat and a source of C for the growth of microorganisms, which were able contribute to pollutant metabolism (Cao and Zhang, 2014).Commercial FTWs are still an expensive management option, and there is currently a demand for more low-cost growth media that both provides a suitable substrate for macrophytes and enhances pollutant removal; such examples includebiochar, activated carbons, coffee waste and green compost (Tran et al., 2015). To date there has been no research incorporating these materials into FTWs to assess the potential for enhanced remediation and the potential value post-remediation.

HybridFTW planting systems are being developed in an attempted to enhance pollutant removal and ecosystem restoration (Guo et al., 2014; Li et al., 2010; Lu et al. 2015). Such systems integrate a new layer beneath the floating platform containing submerged macrophytes such as *Potamogeton crispus*, and/or bivalves such as freshwater clams (*Corbicula fluminea*) (Guo et al., 2014; Li et al., 2010) (Figure 12.6). Photovoltaic solar panels have also been attached to the frames of FTW to power a submerged aerator to enhance oxygenation in the vicinity of the plant roots and associated microorganisms, thus increasing the nutrient degradation process (Lu et al., 2015) (Figure 12.6).While these hybrid systems appear to enhance pollutant removal from the water column compared to their macrophyte-only counterparts (Guo et al., 2014; Li et al., 2010), the added complexity may impact on the utility of FTW as a phytoremediation system. With increasing complexity of FTW design there is an increase in pollutant removal efficiency, cost and maintenance, but a decrease in user uptake given the added management of submerged plants or solar PV systems. A focus on maximising removal efficiency over the simplicity of the system may create barriers for uptake by stakeholders such as farmers, land managers and government organisations looking for low-cost low maintenance treatment options, especially within developing countries. A useful exercise might be to compare the economics, maintenance requirements and user experience of hybrid versus conventional FTWs to determine when increasing FTW complexity is appropriate.

The coverage of FTW over the target water body is also important, as indicated by a meta-analysis showing that vegetation cover is significantly correlated with the removal of NH_4^-(Pavlineri et al., 2017). Although increasing FTW coverage reduces atmospheric diffusion, oxygen is supplied to water by emergent plants via root oxygenation (Xiao et al., 2016; Yeh et al., 2015). Furthermore, in eutrophic waters this coverage may inhibit algal primary productivity, which may be beneficial for mitigating the potential for occurrences of large algal blooms(Jones et al., 2017). The optimal coverage of FTWs has been reported as 10-25% (Marimon et al., 2013), although generally there is wide variation in the literature with values of between 100 %, 50 % and 5-8 % being reported as acceptable for water treatment (Pavlineri et al., 2017). McAndrew & Ahn (2017) also note that hydraulic retention time and plant productivity are important for determining removal efficiency. Surface cover therefore needs to be considered in tandem with hydrology and macrophyte selection. As the focus within the literature is on coverage, there has been no clear attempt to look at the different surface arrangements of FTW on the water surface. For example, targeting of an area, such as water inlet or outlet to a lake may be more beneficial than increased FTW coverage over the target water body. Clearly, the coverage and area of FTW treatment is context-specific but there is likely to be significant potential in investigating spatially targeted phytoremediation.

Finally, the poor design and management of FTWs is a topic that is rarely discussed within the literature. FTWs have the potential to be pollutant sources should the biomass not be continually harvested and removed, or if water birds attracted to the FTWs defecate into the water inputting nutrients and microbial contaminants (guanotrophication). Nutrient-rich growth media such as peat may also leach nutrients into the target water body compared to more inert coir fibre(Lynch et al., 2015). The placement of FTWs in watercourses must also be givenfull consideration aswater birds and recreational users may also use the target waterbody. FTWs potentially slow the velocity of water in small water bodies such as ditches, which may conflict with farming interests where good drainage is required. As with any good catchment management practice, appropriate consultation with stakeholders is important for success.

12.8 Translocation and element storage in macrophytes

Understanding how and where nutrients and other pollutants are distributed within macrophyte tissues is important to inform plant harvestingfor removalof pollutants. The recovery of nutrients is crucial for the value of post-harvest plant biomass, whilst ensuring correct plant parts are harvested for effective removalof heavy metal and organic pollutants from the planting system. Allometry of pollutants within plants varies according to species, but is also influenced by the environmental conditions in terms of nutrient availability (Barrat-Segretain, 2001; Demars and Edwards, 2007).

Typha domingensis, Eichhornia crassipes, Pistia stratiotes and *Myriophyllum aquaticum*preferentially storeN and P in the shoot compared to therootsorrhizome(Table 12.6), although nutrients can be translocated through the plants leading to temporal dynamismin element distribution driven byplant phenology and diurnal metabolism(Masclaux-Daubresse *et al.*, 2010; Hawkesford *et al.*, 2011; Eid *et al.*, 2012).More than 50% of N can be storedinbelow-groundplant parts by the end of a growing season(Vymazal, 2007).*Phragmites australis*grownin either natural waters or a waste water infiltration pond demonstrated a clear seasonal pattern in the translocation of nutrients from above-groundto below-ground parts as the end of the growing season approached(Meuleman et al., 2002). Early in the growing season N and P concentrations are higher due to sink demand during active growth before concentrations decrease gradually through the season as plants begin to senesce.

Coinciding with the decrease in nutrient concentrations in above-ground biomass, below-ground concentrations of N and P increase, representing the preparation for plant senescence with nutrient storage in the roots and rhizomes for the following season's growth(Garver et al., 1988). Meuleman et al. (2002) suggested that harvesting during the winter meant that only 9% of N and 6% of P associated with nutrient loading was removed, whereas, harvesting above-ground parts during peak nutrient storage in summer enhanced removal to 40-50% of N and P. Seasonality is important,although seasonal effects will differ between temperate, subtropical and tropical zones with macrophytes in the latter two zones showing less element translocation and therefore enabling multiple annual harvests(Vymazal, 2007).Macrophytes may perform poorly if nutrient translocation to the rhizome is inhibited by harvesting during the active growing period (Tanaka et al., 2017), although the issue of nutrient allocation is less problematic for floating macrophytes and emergent macrophytes deployed in FTWs as the full plant can then be harvested(Wang et al. 2014).

Studies on element allocation tend to reportabsolute concentrationsto determine if a species is a betterabove-ground or below-ground accumulator. The potential for pollutant uptake and removal by harvesting the areal parts is a function of both concentration and the biomass produced (Polomski et al., 2009). For example, although shoot concentration of N in *Pistia stratiotes*(13.93mg/g) was greater than in*Eichhornia crassipes*(10.16mg/g) in a study of nutrient recovery, the total areal shoot storage of N for *Eichhornia crassipes* was over four times higher due to its greater biomass(Polomski *et al.*, 2009). This demonstrates that it is more effective to harvest plants with greater above-ground biomass andmoderate tissue concentrations of the pollutant of interest, rather target plants with lower biomass but higher tissue concentrations (Duman *et al.*, 2007; Vymazal, 2016).

In eutrophic waters light is commonly the limiting factor for growth and plants therefore tend to allocate nutrients to above-ground growth to maintain efficient light capture, while excessive nutrient availability negates the requirement for belowground storage (Polomski *et al.*, 2009; Lynch *et al.*, 2015); this also maintain intra-specific competitive advantages in these environments and can be exploited as part of a phytoremediation management strategy . Where non-hyperaccumulator plants are grown in a substrate where high concentrations of heavy metals and organic pollutants are present, physiological mechanisms within these plants often limit the transport of these compounds to above-ground tissue to mitigate damage to important cells, such as those responsible for photosynthesis (Zhu et al., 1999;Verkleij et al. 2009).

Thepreference for below-ground storage by emergent macrophytes has been demonstrated in multiple studies, as listed in Table 12.6. However, there are some occasions where metals are found at greater concentration in aerial parts, such as Pb in *Cyperus esculentus*, Zn in *Glyceria maxima*, Mn in *Phragmites australis* and Cu in *Phragmites australis* (Table 12.6), which suggests that specifically classing species as above-ground or below-ground accumulators of specific pollutants may be inappropriate. Furthermore, not all studies capture the full seasonal dynamics of nutrient or pollutant translocation and allometry under different concentration regimes, and therefore, to enable sound recommendations on harvesting during phytoremediation projects, further studies to characterise chemical allocation over time of key species should be carried out to ensure pollutant removal is appropriatelytargeted.

12.9The role of microbial activity in aquatic phytoremediation

There is debate within the phytoremediation literature as to the relative importance of macrophytes in removing pollutants compared to the independent microbial degradation. This perspective primarily comes from observations showing that unplanted CWs can match or outperform planted CWs in terms of pollutant removal (Cardinal et al., 2014). In addition to microbial activity, processes such as sedimentation in P stabilisation and removal, and the photodegradation of PPCPshave also been noted as important (Cardinal et al., 2014; Tanner & Headley, 2011; Zhang et al., 2014). Microbial activity is also an important factor for enablingphytodegradation of pollutants, however, the independent role of microbial communitiesis now receiving much more attention(Houda *et al.*, 2014). Improved understanding of how microbial activity contributes to pollutant degradationis essential because it not only influences removal rates but may have implications for the value of harvesting plant biomass and post-remediation resource recovery if the actual plant uptake and sequestration (phytoextraction) of target pollutants is low.

There is an abundance of microorganisms associated with macrophyte roots that influence the removal and degradation of pollutants (Stottmeister *et al.*, 2003; Faulwetter *et al.*, 2009). These include bacteria that assist in nitrification and denitrification for the transformation and removal of excess N, and biological mineralization of organic P(Valipour and Ahn, 2016). These processes are integral to the efficient functioning of CWs but the role of macrophytes in facilitating and enhancing the metabolic processes of these microorganisms is still not well understood, although it is likely thatthe rhizosphere provides an energy source for microorganisms(Thijs et al., 2016). Redox state, dissolved oxygen content and temperature are common limiting factors for different microorganisms (Truu et al., 2009), and the potential for macrophytes to oxygenate the substrate surrounding their below-ground organs can alsofacilitate the growth of microbes in the rhizosphere (Pavlineri et al., 2017).

CWs are highly engineered, with multiple design elements that may influence the abundance and diversity of microorganisms.Consequently carefully designed experiments are required to explore the potential role of theplant microbiome in phytoremediation. Applying this knowledge is particularly important for developing novel environmental engineering solutions such as FTWs. The formation of microbial biofilms on the underside of FTWs and plant roots has been suggested as a key removal pathway for nutrients and heavy metals(Tanner et al., 2011). Wang & Sample (2014) found that unplanted FTWs had similar removal efficiencies compared to those planted with monocultures of *Pontederia cordata*and *Schoenoplectus tabernaemontani*(Figure 12.7). In this study, and elsewhere, temperature was a key factor in the performance of FTW which has beenrelated to changes in microbial activity (Van de Moortel, 2011; Wang & Sample, 2014b). In contrast, Zhang et al.(2014) were unable to link microbial community traits associated with FTWs biofilm such as ribotype number and diversity index to the removal efficiency of pollutants.

Given the conflicting evidence on the relative importance of plants and biofilms in phytoremediation,a 'meta-organism' approach to phytoremediation is now required to appreciate the multitude of factors and process at work (Thijs *et al.*, 2016; Feng *et al.*, 2017). Further studies are required in these areas that employ suitable control treatments, along with adequate spatial and temporal characterisation of microbial communities for different macrophytes in monoculture and polyculture, and growth media. Furthermore, within these studies the mass balance of pollutant allocation should be investigated to fully assess where and how pollutants are being stored and translocated. Radio-labelled isotopes have been successfully employed to quantify cycling of nutrients within CWs (Truu et al., 2009). However, such techniques have not been employed during FTW studies, where the application of radio-labelled isotopes would provide an opportunity to understand the biochemical cycling with these novel systems. Finally, after adequate characterisation of microbial communities and their relation to the plant and associated abiotic environment, there may be new opportunities to enhance the microbial community to promote pollutant removal (Glick, 2003; Thijs *et al.*, 2016).

12.10Added value of aquatic phytoremediation

12.10.1 Ecosystem services

The process of phytoremediation has primarily been concerned with maximising the efficiency of water treatment,whilst the benefits of phytoremediation over and above remediation have essentially been overlooked. Clearly, water treatment is the primary ecosystem service in the provision of safe and clean water; however, the planting of vegetation within the environment creates new habitats fororganisms(Zhu et al., 2011). For example, the presence of artificial floating islands improved chickproductivity ofBlack-throated Divers (*Gavia arctica*) by 44 % in waterbodies with these structures (Hancock, 2000), indicating a potential combined role for FTWs in water treatment and improved habitat connectivity. Similarly, a 15year project investigating the environmental benefits of creating treatment wetlands to ameliorate mine tailing effluentsfound that there was a high abundance and diversity of protozoa, higher plants, terrestrial animals, and birds (Yang *et al.*, 2006).

In addition to habitat provisioning there is also the potential for facilitating pollination and carbon sequestration(Nesshöver *et al.*, 2017). The capacity for the latter may depend on the post-remediation stage and the reuse of the biomass. Cultural services can also be provided by an improvement in the aesthetic appeal of an area with increased vegetation(Masi et al., 2017). This is most likely in urban waterways where FTW might provide attractive green infrastructure (Olguín *et al.*, 2017). There is a need to quantify and assess ecosystem services associated with phytoremediation projects in order tobetter appreciate the multiple benefits generated from this form of water treatment.

12.10.2 Resource recovery

The potential to generate large volumes of biomass through phytoremediation means that there are opportunities for resource recovery within the process (Gomes, 2012). Post-remediation biomass re-use streams (PBRSs) are the disposal process and utilisationof the harvested plant tissues of macrophytes used for phytoremediation(Gomes, 2012).As macrophytes are able to remove and assimilate metals there is certainly potential for the recovery of metals such as gold, Cu and Ni (phytomining)(Anderson et al. 2005). To date, most research in this area has focused on terrestrial plants and soils contaminated through industrial mining(Rosenkranz et al., 2017). However, there may be potential to explore metal-contaminated waters and sediments of wetlands used to treat mine-tailing effluents. The usefulness of this process depends on the current market value of target metals and the economic benefits associated with this form of phytoremediation(Sheoran et al., 2009).

The use of macrophytesas biofuels is another possibility and is a feasible option to increase the value of phytoremediation if there is a market for biomass. An economic assessment by Jiang et al. (2015) found that high biomass production plants are required to make this a profitable venture. However, different options need to be considered in pre-treatment, such as de-wetting and briquetting,since fresh plant biomass comprises up to 90% water(Newete and Byrne, 2016).Macrophyte biomass may also be used for animal feed, or to make compost or biochar(Quilliam et al., 2015; Tanaka et al. 2017). Quilliam et al. (2015) discussed in detail the issues with these PBRSs in terms of the transfer of pathogens, bio-magnification of heavy metals and propagation of invasive species. A phytoremediation decision-making system that couples the target pollutants and the PBRS would allow the resource recovery options to be established early in the process (Song and Park, 2017). For example, the remediation of a eutrophic lake would seemto link well with composting or animal feed PBRS given the potential for high nutritional content.However, if heavy metal or pesticide contamination also is identified, then a biofuel or phytomining PBRS may be more appropriate. Larger scale pilot tests of aquatic phytoremediation are required, and these should explore the feasibility of using produced biomass in PBRSs.

12.11 Summary and future perspectives

This chapter has outlined the potential of aquatic phytoremediation to provide efficient, multi-targeted and sustainable remediation solutions for polluted waters. A summary of a proposed research agenda required to fulfil the potential of these systems is presented in Table 12.7. Given the wide range of organic, inorganic and biological pollutants that can impact surface waters there is a need to steer phytoremediation towards a context-specific approach that allows the remediation of multiple water body types, and waters affected by a range of pollutants.

With the development of novel ways to deploy macrophytes, such as by FTWs, there are emerging options for spatial flexibility of applying phytoremediation, which are relatively inexpensive. Larger scale pilot studies are required in this respect to assess the realistic opportunities for use. At present there are a wide range of macrophytes of different growth forms that have been established as efficient accumulators of pollutants. A further focus is required to investigate the remediation potential of submerged species and to establish new accumulators that may be used. Importantly, some of the key hyperaccumulators are considered invasive and would be unsuitable to be deployed in natural surface waters. A proposed advancement for phytoremediation systems is to consider the benefits of a plant community based-approach that assembles polycultures of macrophyteswith good accumulation capacity for different pollutants, enabling multi-targeted remediation. Here, the need for a logical system of macrophyte selection based on plant removal efficiencies and environmental tolerances, and target pollutant specifications, requires development.

The process of macrophyte phytoremediation still requires a deeper understanding of how to enhance removal efficiency and ensure sustainable harvesting of macrophytes. Understanding the spatial and temporal dynamics of pollutant translocation within macrophytes is crucial for permanent pollutant removal from water and for maintaining the economic value of different PBRSs. Furthermore, a ‘meta-organism’ approach needs to be considered in future phytoremediation studies to establish the role of plant-associated microbial communities. There may be untapped potential in manipulating these microbial communities for enhanced performance.

Finally, the focus of phytoremediation has been on the water treatment aspect, whilst there is growing recognition of the capacity of these ecological engineering strategies to provide ecosystem services such as carbon sequestration and biodiversity support. Thesebenefits need to be better quantified to determine the added-value of phytoremediation. With the waste management sector shifting towards a life-cycle approach, there are clear opportunities for resource recovery through identifying PBRSs such as composting, biofuel production and animal feed. These PBRSs require further exploration in terms of their safety, value and ability to link directly with the target pollutants removed (Figure 12.8). A life-cycle approach needs to embedded in prospective aquatic phytoremediation projects,to ensure that target pollutant(s) are being considered in tandem with the PBRS, whilst the frequency of harvest and replacement/regrowth of macrophytes is properly linked into the remediation of the target pollutant (Figure 12.8).

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Table 12.1: Key pollutants impacting the aquatic environment, organised by pollutant category, type and providing examples of the pollutants, their sources and impacts

Pollutant category	Pollutant Type	Example pollutant	Sources	Potential impacts
Organic	Persistent organic pollutants (POPs)/Xenobiotics	Dioxins, organochlorides, Polycyclic aromatic hydrocarbons (PAH), Polychlorinated biphenyls	Industry Agriculture	Toxicity Endocrine disrupting effects
	Pesticides	Glyphosate Hexachlorocyclohexane Fenhexamid Deltamethrin	Agriculture Aquaculture	Toxicity Endocrine disrupting effects
	Pharmaceutical and personal care products (PPCPs)	Antibiotics Hormones Pain relief medication	Domestic Agriculture Aquaculture	Endocrine disrupting effects Antibiotic resistance Destabilising microbial communities
	Algal toxins	Microcystin-LR	Cyanobacterial algal blooms	Acute/chronic toxicity
Inorganic	Nutrients	Nitrogen (N) Phosphorus (P) Potassium (K)	Agriculture Aquaculture Septic tank inputs	Nutrient enrichment/eutrophication
	Metalloid elements	Iron (Fe) Aluminium (Al) Lead (Pb) Nickle (Ni) Cadmium (Cd)	Agriculture Industry (mining and combustion of fossil fuels) Al mobilisation	Toxicity Endocrine disrupting effects

		Copper (Cu) Uranium (U)	through acid rain	
Microbial	Pathogens and parasites	*E.coli*O157 *Cryptosporidium parvum*	Agriculture Aquaculture Domestic	Human illness (intestinal infection)

Figure 12.1: Photo examples of floating, submerged and emergent macrophyte life forms. From left to right: *Persicaria amphibia* (floating), *Ceratophyllum demersum* (Submerged) and *Sparganium erectum* (emergent)

Table 12.2: Phytoremediationmechanisms, adapted fromDhir(2013) and Rezania et al. (2016).

Mechanism	Medium	Contaminant category	Description	Accumulation Part	Example genera
Rhizofiltration/phytofiltration	Water	Organics/inorganics /heavy metals	Extraction from contaminated water by adsorption/absorption	Shoots/roots	*Lemna, Hydrocharis, Eichhornia*
Phytoextraction/phytoaccumulation	Soil/water	Inorganics/heavy metals	Uptake by roots and translocation to upper parts	Shoots	*Juncus, Schoenoplectus*
Phytostablisation	Soil/sediment	Inorganics/heavy metals	Rendering contaminants immobile within soil matrix due to plant root action	Reduction in rhizosphere	*Chenopodium*
Phytovolatilization	Soil/sediment/ water (less common)	Organics	Conversation of containments to volatile form	Atmospheric release	*Phragmites*
Phytodegradation	Soil/sediment/ Water	Organics/inorganics /microbiological	Degradation in Rhizosphere through microbial degradation or by metabolism within plant	Degradation in rhizosphere/pollutant degraded in plant to less harmful metabolite	*Typha, Phragmites, Myriophyllum*

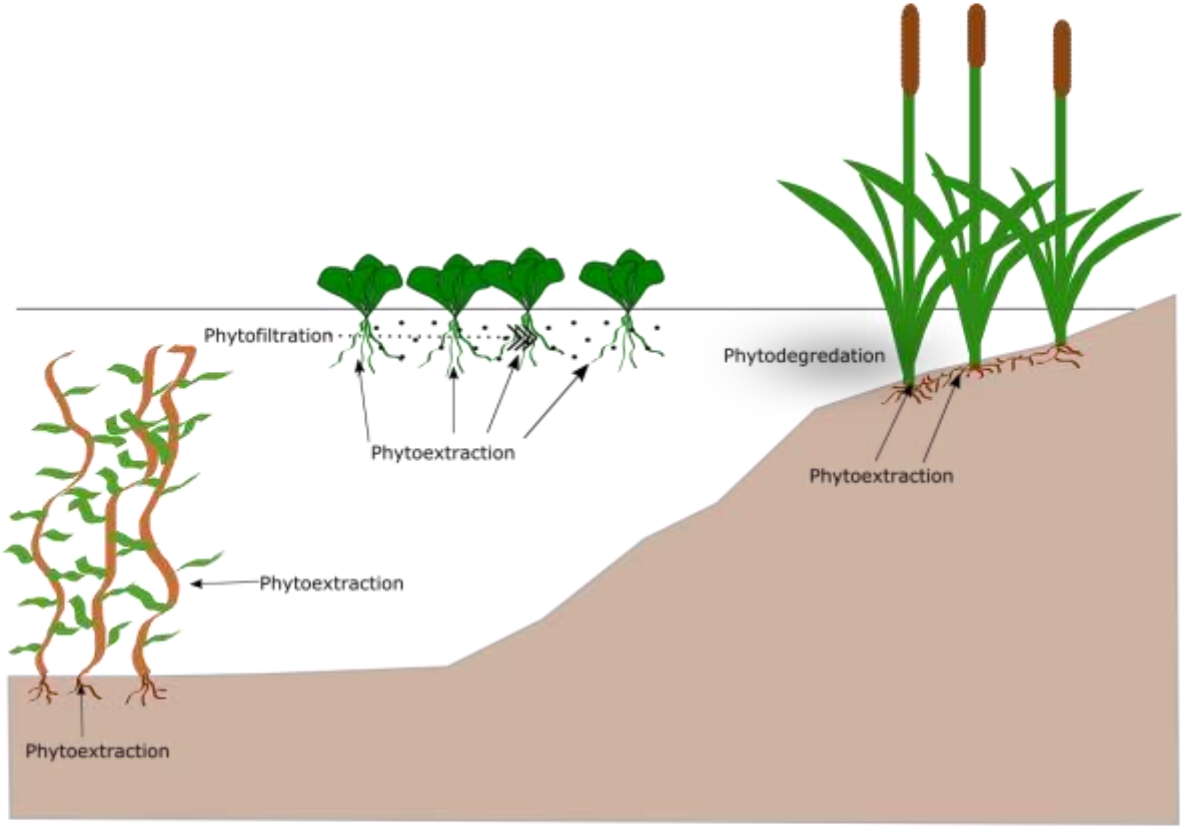


Figure 12.2 Phytoremediation mechanisms used to degrade/remove waterborne pollutants, by growth form.

Table 12.3: Removal efficiencies (%) of macrophyte species investigated in this review of nutrients phytoremediation

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO_3)	Ammonia (NH_3)	Ammonium (NH_4)	Total Phosphorus	Phosphate			
Canna sp.	Emergent	50			100			FTW	Mesocosm	Sun et al (2009)

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO_3)	Ammonia (NH_3)	Ammonium (NH_4)	Total Phosphorus	Phosphate			
					42			FTW	Mesocosm	Ayaz & Saygin (1996)
Cyperus sp.	Emergent				33			FTW	Mesocosm	Ayaz & Saygin (1996)
		72			75			Constructed wetland	Constructed wetland	Kyambadde et al. (2004)
		57			63	54.09		FTW	Microcosm	Kansiime et al. (2005)
Polygonum hydropiperoides	Emergent	74				81		Direct planting	Mesocosm	Lang Martins et al. (2010)
Echinodorus cordifolius	Emergent		45		49.9	10.85		Direct planting	Mesocosm	Moore et al. (2016)
Ipomoea aquatica	Emergent	76						FTW	Mesocosm	Karnchanawong (1995)
		36-46				36-47		FTW	Mesocosms	Li et al. (2010)
		61.94			48	62		FTW	Mesocosm	Li et al. (2010)
Juncus effusus	Emergent	48		50		63		Constructed wetland	Constructed wetland	Coleman et al. (2001)
Leersia oryzoides	Emergent					51		Direct planting	Mesocosm	Tyler et al.(2012)
Limnocharis flava	Emergent			92			96	Constructed wetland	Constructed wetland	Kamarudzaman & Ismail (2011)
Lolium multiflorum	Emergent	81				90		FTW	Mesocosm	Xian et al. (2010)
Miscanthidium violaceum	Emergent	57			47	41		Constructed wetland	Constructed wetland	Kyambadde et al. (2004)
Oenanthe javanica	Emergent	91		97		76		FTW	Mesocosm	Zhou & Wang (2010)
Panicum hemitomon	Emergent		60		54	28		Direct planting	Mesocosm	Moore et al. (2016)

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO_3)	Ammonia (NH_3)	Ammonium (NH_4)	Total Phosphorus	Phosphate			
Phragmites	Emergent				98			FTW	Mesocosm	Kintu Sekiranda & Kiwanuka, (1997)
Saururus cernuus	Emergent		35		-3	-13		Direct planting	Mesocosm	Moore et al. (2016)
Scirpus atrovirens	Emergent			91			82	Constructed wetland	Constructed wetland	Kamarudzaman & Ismail (2011)
Scirpus validus	Emergent	25		25		48		Constructed wetland	Constructed wetland	Coleman et al. (2001)
Sparganium americanum	Emergent					14		Direct planting	Mesocosm	Tyler et al. (2012)
Thalia dealbata	Emergent		46		31	4		Direct planting	Mesocosm	Moore et al. (2016)
Typha angustifolia	Emergent	57				23		FTW	Mesocosm pots	Keizer-Vlek et al. (2014)
Typha latifolia	Emergent	62		62		81		Constructed wetland	Constructed wetland	Coleman et al. (2001)
						53		Direct planting	Mesocosm	Tyler et al. (2012)
			32		17	12		Direct planting	Mesocosm	Moore et al. (2016)
Vetiveria zizanoides	Emergent	49		50		21		FTW	Mesocosm	Boonsong & Chansiri (2008)
Eichhornia crassipes	Floating		61-83					Direct planting	Mesocosm	Ayyasamy et al. (2009)
			92	81		67		Direct planting	Mesocosm	Kutty et al. (2009)
Pistia stratiotes	Floating	50				14-31		Direct planting	Ponds (storm water detention)	Lu et al. (2010)
			31-51					Direct planting	Mesocosm	Ayyasamy et al. (2009)

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO_3)	Ammonia (NH_3)	Ammonium (NH_4)	Total Phosphorus	Phosphate			
Salvinia molesta	Floating		18-36					Direct planting	Mesocosm	Ayyasamy et al. (2009)
Lemna gibba	Floating	97				99		Direct planting	mesocosm-wastwater	Körner & Vermaat (1998)
			100	82			64	Sewage water system	Sewage water system	El-Kheir et al. (2007)
Ceratophyllum demersum	Submerged	42			65	73		Direct planting	Mesocosms	Dai et al. (2012)
Myriophyllum aquaticum	Submerged	88				94		Direct planting	Mesocosm	Souza et al. (2013)
			45		35	7		Direct planting	Mesocosm	Moore et al. (2016)
Species	**Life Form**	**Removal Efficiency (%)**						**Macrophyte Deployment**	**Experiment**	**Reference**
		Total Nitrogen	**Nitrate (NO_3)**	**Ammonia (NH_3)**	**Ammonium (NH_4)**	**Total Phosphorus**	**Phosphate**			
Canna sp.	Emergent	50		100				FTW	Mesocosm	Sun et al (2009)
				42				FTW	Mesocosm	Ayaz & Saygin(1996)
Cyperus sp.	Emergent			33				FTW	Mesocosm	Ayaz & Saygin(1996)
		72		75				Constructed wetland	Constructed wetland	Kyambadde et al.(2004)
		57		63		54.09		FTW	Microcosm	Kansiime et al.(2005)
Polygonum hydropiperoides	Emergent	74				81		Direct planting	Mesocosm	Lang Martins et al.(2010)
Echinodorus cordifolius	Emergent		45		49.9	10.85		Direct planting	Mesocosm	Moore et al.(2016)

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO_3)	Ammonia (NH_3)	Ammonium (NH_4)	Total Phosphorus	Phosphate			
Ipomoea aquatica	Emergent	76						FTW	Mesocosm	Karnchanawong(1995)
		36-46				36-47		FTW	Mesocosms	Li et al. (2010)
		61.94		48		62		FTW	Mesocosm	Li et al. (2010)
Juncus effusus	Emergent	48		50		63		Constructed wetland	Constructed wetland	Coleman et al.(2001)
Leersia oryzoides	Emergent					51		Direct planting	Mesocosm	Tyler et al.(2012)
Limnocharis flava	Emergent			92			96	Constructed wetland	Constructed wetland	Kamarudzaman & Ismail(2011)
Lolium multiflorum	Emergent	81				90		FTW	Mesocosm	Xian et al.(2010)
Miscanthidium violaceum	Emergent	57		47		41		Constructed wetland	Constructed wetland	Kyambadde et al.(2004)
Oenanthe javanica	Emergent	91		97		76		FTW	Mesocosm	Zhou & Wang (2010)
Panicum hemitomon	Emergent		60		54	28		Direct planting	Mesocosm	Moore et al.(2016)
Phragmites	Emergent			98				FTW	Mesocosm	Kintu Sekiranda & Kiwanuka, (1997)
Saururus cernuus	Emergent		35		-3	-13		Direct planting	Mesocosm	Moore et al.(2016)
Scirpus atrovirens	Emergent			91			82	Constructed wetland	Constructed wetland	Kamarudzaman & Ismail(2011)
Scirpus validus	Emergent	25		25		48		Constructed wetland	Constructed wetland	Coleman et al.(2001)
Sparganium americanum	Emergent					14		Direct planting	Mesocosm	Tyler et al. (2012)

Species	Life Form	Removal Efficiency (%)						Macrophyte Deployment	Experiment	Reference
		Total Nitrogen	Nitrate (NO$_3$)	Ammonia (NH$_3$)	Ammonium (NH$_4$)	Total Phosphorus	Phosphate			
Thalia dealbata	Emergent		46		31	4		Direct planting	Mesocosm	Moore et al.(2016)
Typha angustifolia	Emergent	57				23		FTW	Mesocosm pots	Keizer-Vlek et al.(2014)
Typha latifolia	Emergent	62		62		81		Constructed wetland	Constructed wetland	Coleman et al.(2001)
						53		Direct planting	Mesocosm	Tyler et al. (2012)
			32		17	12		Direct planting	Mesocosm	Moore et al.(2016)
Vetiveria zizanoides	Emergent	49		50		21		FTW	Mesocosm	Boonsong & Chansiri (2008)
Eichhornia crassipes	Floating		61-83					Direct planting	Mesocosm	Ayyasamy et al.(2009)
			92	81		67		Direct planting	Mesocosm	Kutty et al. (2009)
Pistia stratiotes	Floating	50				14-31		Direct planting	Ponds (storm water detention)	Lu et al.(2010)
			31-51					Direct planting	Mesocosm	Ayyasamy et al.(2009)
Salvinia molesta	Floating		18-36					Direct planting	Mesocosm	Ayyasamy et al.(2009)
Lemna gibba	Floating	97				99		Direct planting	mesocosm-wastwater	Körner & Vermaat (1998)
			100	82			64	Sewage water system	Sewage water system	El-Kheir et al. (2007)
Ceratophyllum demersum	Submerged	42			65	73		Direct planting	Mesocosms	Dai et al. (2012)
Myriophyllum	Submerge	88				94		Direct planting	Mesocosm	Souzaet al.(2013)

Species	**Life Form**	**Removal Efficiency (%)**						**Macrophyte Deployment**	**Experiment**	**Reference**
		Total Nitrogen	**Nitrate (NO_3)**	**Ammonia (NH_3)**	**Ammonium (NH_4)**	**Total Phosphorus**	**Phosphate**			
aquaticum	d		45		35	7		Direct planting	Mesocosm	Moore et al.(2016)

Table 12.4: Key macrophyte metal accumulators reported in the literature

Species	Life Form	Metals	Reference
Ceratophyllum submersum	Submerged	Ni	Kara (2010)
Ceratophyllum demersum	Submerged	Cr, Pb	Osmolovskaya and Kurilenko (2005)
Potamogeton natans	Submerged	U	Pratas et al. (2014)
Myriophyllum spicatum	Submerged	Co,Cu, Mn, Pb, Zn	Wang et al. (1996);Sivaci et al., (2004); Lesage et al. (2008)
Potamogeton pectinatus	Submerged	Cd, Cu, Mn, Pb, Zn	Rai et al. (2003);Singh et al. (2005)
Hydrilla verticillata	Submerged	As, Cu	Srivastava et al. (2011)
Lemnocharis flava	Emergent	Cu, Fe, Hg, Pb, Zn	Anninget al.(2013)
Glyceria maxima	Emergent	Cu, Zn	Parzych et al.(2016)
Typha latifolia	Emergent	As, Cu, Ni, Zn	Ye et al. (1997);Ha et al.(2009);Manios et al.(2003); Qian et al. (1999)
Typha angustifolia	Emergent	Pb	Panich-pat (2005)
Elodea densa	Emergent	Hg	Molisani and Lacerda(2006)
Phalaris arundinacea	Emergent	Fe, Mn, Ni	Parzych et al. (2016)
Phargmites australis	Emergent	As, Hg	Windham et al.(2003); Afrous et al. (2011)
Scirpus maritimus	Emergent	As,	Afrous et al. (2011)
Spartina alterniflora	Emergent	As,	Carbonell et al. (1998)
Spartina patens	Emergent	Cd	Zayed et al. (2000)
Azolla filiculoides	Floating	Cd, Cr, Ni, Pb, Zn	Oren Benaroya et al. (2004);Aroraet al.(2006):Taghi et al.(2005); Zayed et al.(1998)
Azolla caroliniana	Floating	As, Cr, Cu, Hg	Rahman and Hasegawa(2011); Bennicelli et al. (2004)
Pista stratiotes	Floating	Cr,Cu, Hg	Miretzky et al.(2004);Molisani et al. (2006); Maine et al.(2004)
Salvinia cucullata	Floating	Cd, Pb	Phetsombat et al. (2006)
Salvinia natans	Floating	Cr, Zn	Dhir et al.(2008)
Spirodela polyrhiza	Floating	As	Zhang et al. (2011)
Eichhornia crassipes	Floating	Cd, Cr, Cu, Hg, Ni, Zn	Zhu et al. (1999):Hu et al. (2007); Molisani et al. (2006); Low et al. (1994)
Lemna gibba	Floating	As, Cd, Ni	Mkandawire and Dudel(2005); Mkandawire et al. (2004); Mkandawire et al.(2004)

Table 12.5: Removal efficiencies of macrophyte species investigated in phytoremediation studies of organic pollutants

Organic Pollutant	Species	Life Form	Target pollutant	Experimental situation	Removal (%)	Reference
Pesticides	*Cannaxgeneralise*	Emergent	Isoxaben, oryzalin	Mesocosm	n/a	Fernandez et al. (1999)
	Pontaaderia cordata	Emergent	Isoxaben, oryzalin	Mesocosm	n/a	Fernandez et al. (1999)
	Iris L.x'Charjoys Jan'	Emergent	Isoxaben, oryzalin	Mesocosm	n/a	Fernandez et al. (1999)
	Eichhornia crassipes	Floating	Ethion	Mesocosm	81	Xia & Ma(2006)
	Juncus effusus	Emergent	Atrazine, Lambda-cyhalothrin	Mesocosm	n/a	Bouldin et al.(2006)
	Ludwigia peploides	Emergent	Atrazine, Lambda-cyhalothrin	Mesocosm	n/a	Bouldin et al.(2006)
	Lemna minor	Floating	2,4,5-trichlorophenol	Mesocosm	95	Tront & Saunders(2006)
			Isoproturon, Glyphosate	Mesocosm	25, 8	Dosnon-Olette et al. (2011)
	Spirodela oligorrhiza	Floating	DDT (OP,PP-DDT)	Mesocosm	66, 50	Gao et al. (2000)
	Elodea canadensis	Submerged	DDT (OP,PP-DDT)	Mesocosm	31, 48	Gao et al. (2000)
	Mariophyllum aquaticum	Submerged	DDT (OP,PP-DDT)	Mesocosm	76, 82	Gao et al. (2000)
			Trifluralin, cycloxidim, Atrazine, Terbutryn	Mesocosm	n/a	Turgut (2005)
	Elodea canadensis	Submerged	DDT (OP,PP-DDT)	Mesocosm	89	Garrison et al. (2000)
POP	*Lemna gibba*	Floating	Phenol	Mesocosm	90	Barber et al. (1995)
	Lemna minuta	Floating	Phenol	Mesocosm	100	Paisio et al. (2018)
	Potamogeton crispus	Submerged	Phenol	Mesocosm	70-100	Hafez et al.(1998)
			PAHs (phenanthrene and pyrene)	Mesocosm (sediment pots	18–34 , 14.-24	Meng et al (2015)

				included)		
PPCP	*Phragmites australis*	Emergent	Estrone, 17 beta-estradiol, 17 alpha-ethynylestradiol	Constructed wetland	68-84	Song et al.(2009)
	Scirpus validus	Emergent	Diclofenac	Mesocosm	1-7%	Zhang et al. (2012)
			Naproxen, Carbamazepine,	Constructed wetland	97-99,53-60	Zhang et al. (2013a)
			Caffeine	Mesocosm	>99.7	Zhang et al.(2013b)
	Typha angustifolia	Emergent	Carbamazepine, Naproxen, Diclofenac, Ibuprofen	Constructed wetland	27, 91, 55,80	Zhang et al. (2011)
	Pontederia cordata	Emergent	Troclosan, methyl-triclosan & Triclocarbon	Constructed wetland	n/a	Zarate et al.(2012)
	Sagittaria graminea	Emergent	Troclosan, methyl-triclosan & Triclocarbon	Constructed wetland	n/a	Zarate et al.(2012)
	Typha latifolia	Emergent	Troclosan, methyl-triclosan & Triclocarbon	Constructed wetland	n/a	Zarate et al. (2012)

Note

1. n/a refers to studies where the removal efficiencies are not reported

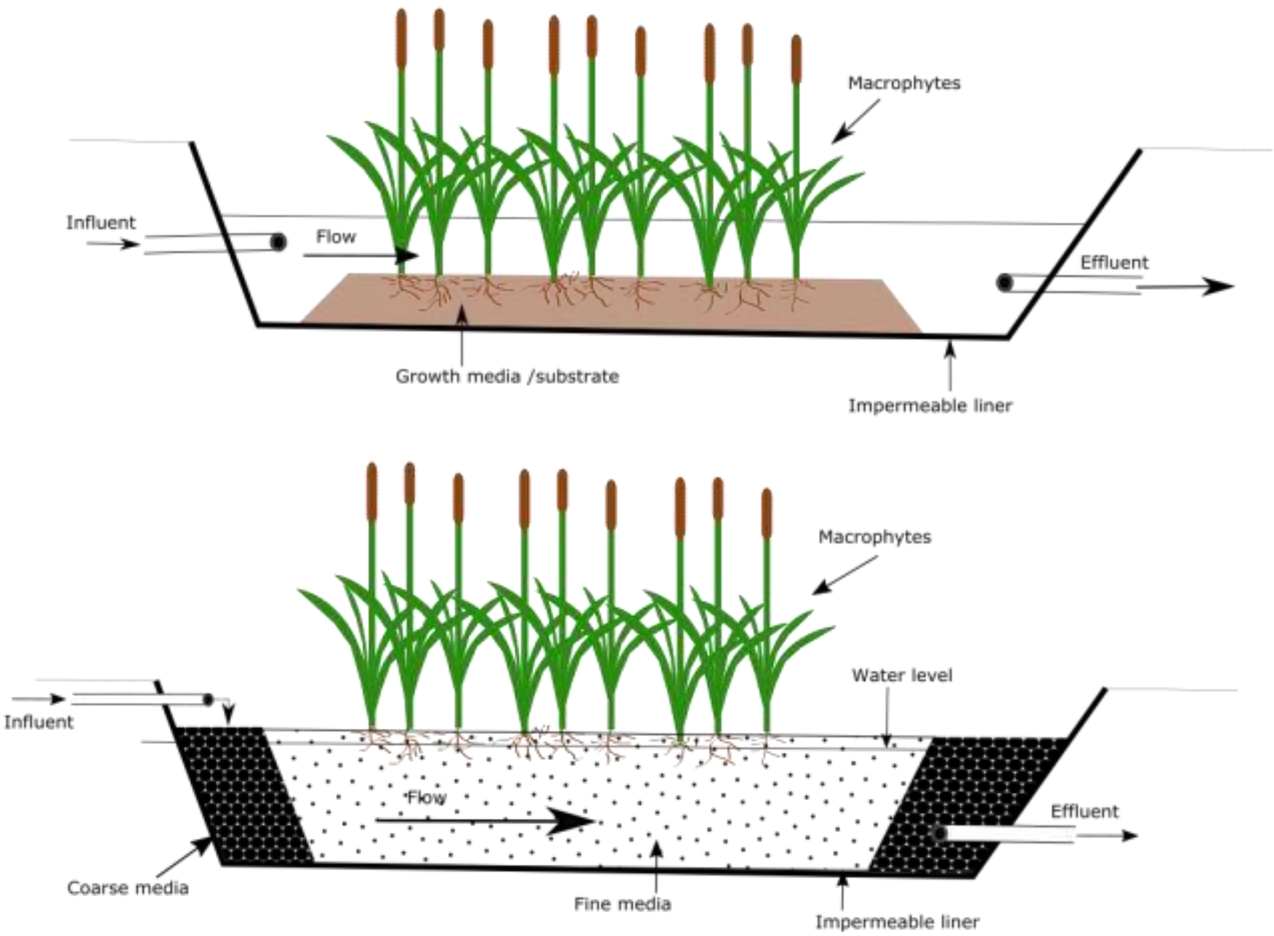


Figure 12.3: Top: Key elements of a free water surface flow wetlands (FWSF) constructed wetland. Bottom: Key elements of a or sub-surface flow (SSF) constructed wetland.

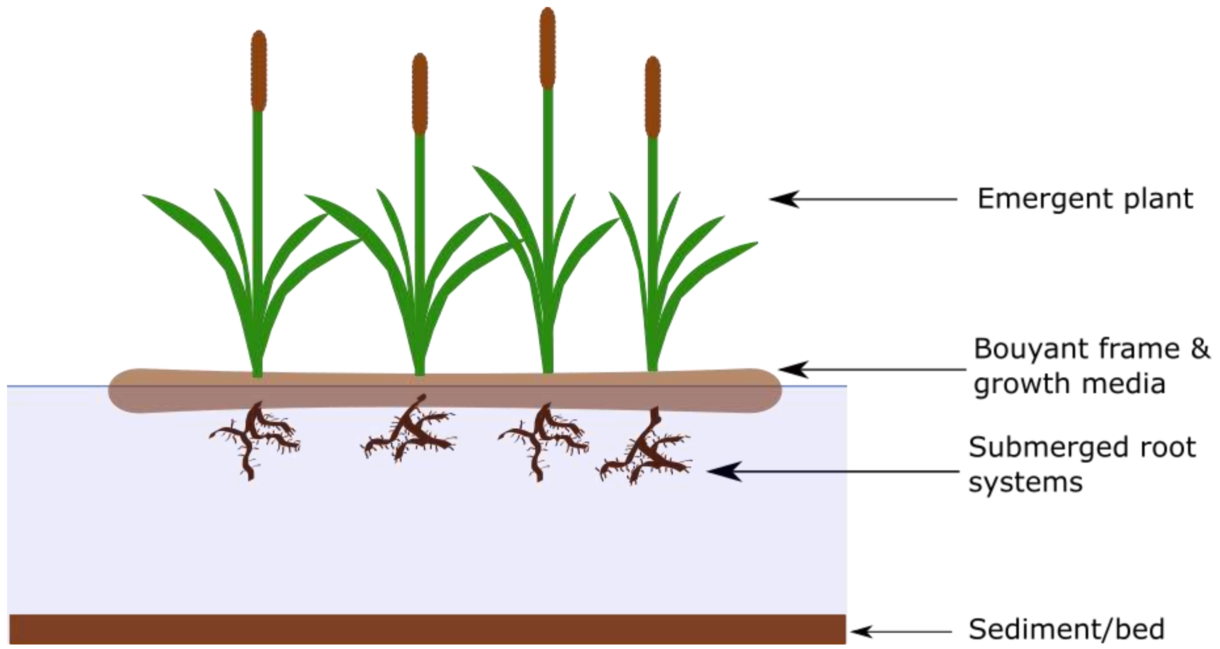


Figure 12.4: Schematic view of a FTW.

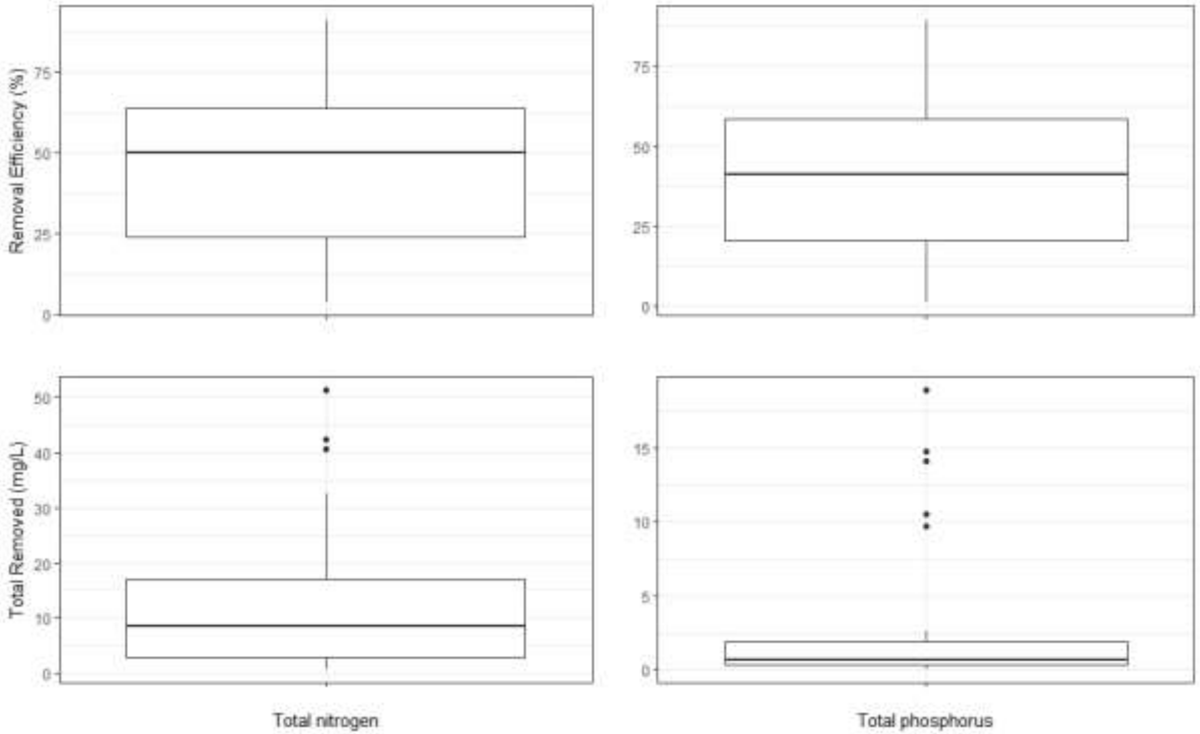
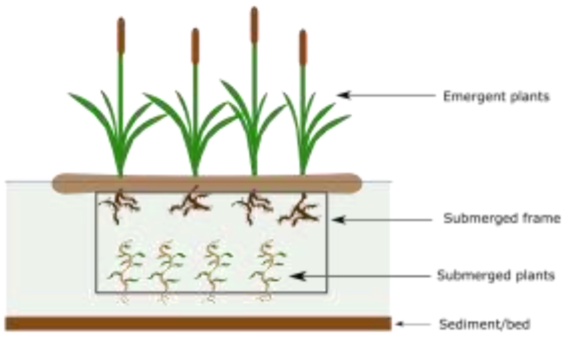


Figure 12.5: Boxplots of removal efficiencies (%) and total removed (mg/l) of Total Nitrogen (TN) (*n*=44) and Total phosphorus (TP) (*n*=28), raw data taken from literature reviewed by Pavlineri et al. (2017).



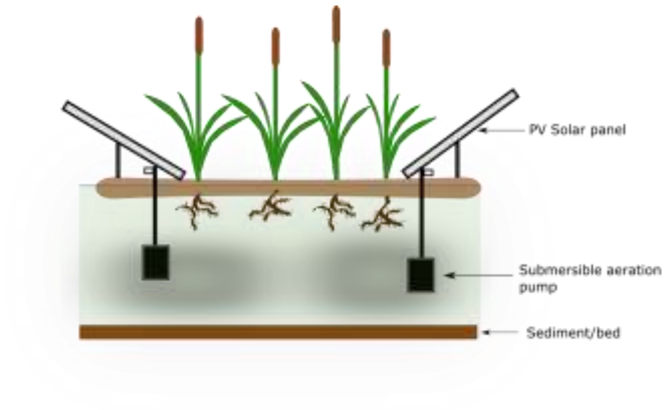


Figure 12.6: Top, a schematic reprentation of a hybrid FTW including submerged vegetatation.

Bottomschematic reprentation of a FTW incorporating solar technolgy to power an areation device.

Table 12.6: Plant allocations of pollutants in selected emergent, floating and submerged macrophytes

Species	**Growth form**	**Plant allocation of pollutant**		**Reference**
		Above-ground	**Below-ground**	
Cyperus riparia	Emergent	Cd, Ni,Zn		Ladislas et al. (2013)
Cyperys esculentus	Emergent	Cd, Cr, Cu, Fe, Mn, Ni	Pb	Chandra & Yadav(2011)
Glyceria maxima	Emergent	Cu, Fe, Mn, Ni, Zn		Parzych et al. (2016)
Juncus effusus	Emergent	Cd, Ni	Zn	Ladislas et al. (2013)
Phalaris arundinacea	Emergent	Cu, Fe, Mn, Ni, Zn		Parzych et al. (2016)
Phargmites australis	Emergent	Cu, Fe, Ni, Zn	Mn	Parzych et al. (2016)
		Cr, Cu, Mn, Ni, Zn		Duman et al.(2007)
Phragmites australis	Emergent	Cd, Cu, Zn	Cr, Fe, Mn, Pb	Chandra & Yadav(2011)
Schoenoplectus lacustris	Emergent	Cu, Ni, Pb, Zn		Duman et al.(2007)
Typha angustifolia	Emergent	Cd, Cr, Cu, Fe, Mn, Ni, Pb	Zn	Chandra & Yadav(2011)
Typha domingensis	Emergent	Ca, Cu, Fe, P, Zn	N	Eid et al. (2012)
Typha latifolia	Emergent	Cu, Fe, Ni, Zn	Mn	Parzych et al. (2016)
Eichhornia crassipes	Floating		N, P	Polomski et al. (2009)
Pistia stratiotes	Floating		N, P	Polomski et al. (2009)
	Floating	Al, Cd, Co, Cr, Cu, Fe, K, Mg, Na	Ca	Lu et al.(2011)
Micranthemum umbrosum	Submerged	Cd	As	Islam et al.(2013)
Myriophyllum aquaticum	Submerged		N, P	Polomski et al. (2009)

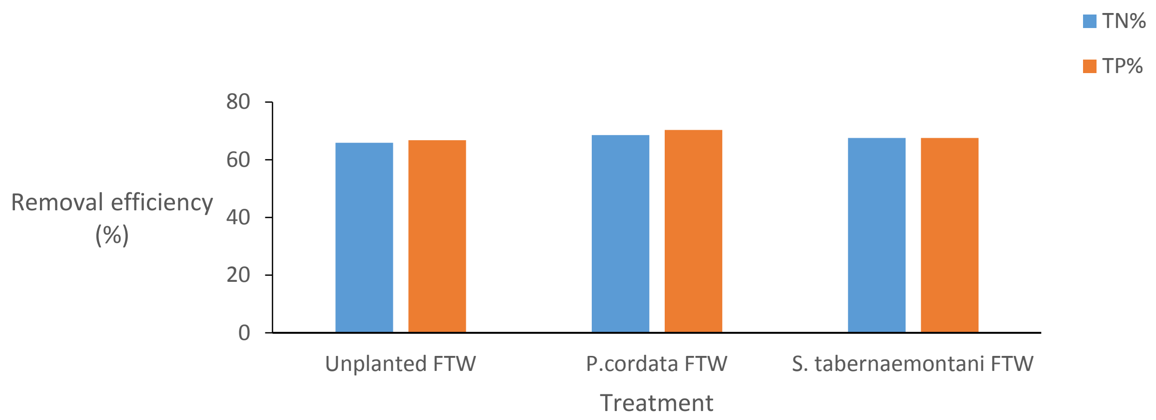


Figure 12.7: Removal efficiencies of TN and TP for an unplanted FTW, a *P. cordata* planted FTW and an *S. tabernaemontani* FTW.Raw data taken from Wang & Sample (2014)

Table 12.7: Summary of the aquatic phytoremediation research agenda required to deliver efficient, multi-targeted and suitable phytoremediation. Research areas, specific lines of investigation and their priority are highlighted.

Research area	Lines of investigation	High priority (0-2 years)	Medium priority (2-5 years)	Low priority (5-10 years)
Identify new macrophyte accumulators for emerging pollutants	To what extent can macrophytes assimilate and degrade PPCPs and pathogens?			
Plant community-based remediation	Evaluate potential for multi-targeted remediation in plant polyculture incorporating temporal/phonological differences and asses plant competitive effects			

Research area	Lines of investigation	High priority (0-2 years)	Medium priority (2-5 years)	Low priority (5-10 years)
Investigate the role of microbial communities on pollutant uptake/ removal	Adopt a 'Metaorganism' approach to address the role of microorganisms and biofilms in phytoremediation by ensuring studies have suitable control treatments, assess spatial and temporal variation in microbial communities in order to fully characterise the bacteria by their functions. Investigate how microbes can maximise the phytoremediation process by different plant associations and FTW growth media. Mas balance studies required, potentially incorporating radiolabelled tracers.			
Assess provision of phytoremediation to provide ecosystem services	Identify and quantify ecosystem services associated with phytoremediation to appreciate the value of method over and above water treatment.			
Develop a system for macrophyte selection	Develop a suitable system for macrophyte selection to provide context-specific phytoremediation as a tool for environmental agencies and stakeholders.			
Identify accumulation zones of pollutants within macrophytes	Further studies into the allocation and translocation of pollutants within plants with temporal assessments of the optimum time to harvest biomass.			
Explore novel ways of deploying macrophytes in the environment for phytoremediation	Explore new ways to deploy macrophytes into aquatic environment, especially by developing aquatic-aquatic attenuation and inducing growth in native flora. Undertake large scale studies of FTWs that assess remediation and FTW surface spatial arrangement. Assess stakeholder usability of novel phytoremediation methods.			
Determine the effect of different growth media on pollutant removal	Assess influence of different FTW growth media e.g. biochar.			
Determine post-remediation re-use streams for resource recovery	Investigate feasible options for resource recovery and identity context-specific post-remediation biomass re-use streams that link with target pollutants e.g. biomass as fertilizers.			

Research area	Lines of investigation	High priority (0-2 years)	Medium priority (2-5 years)	Low priority (5-10 years)
Testing macrophytes for individual accumulators	Continue testing new macrophytes for phytoremediation for inorganic, organic and biological pollutants. Focus on finding non-invasive plants.			

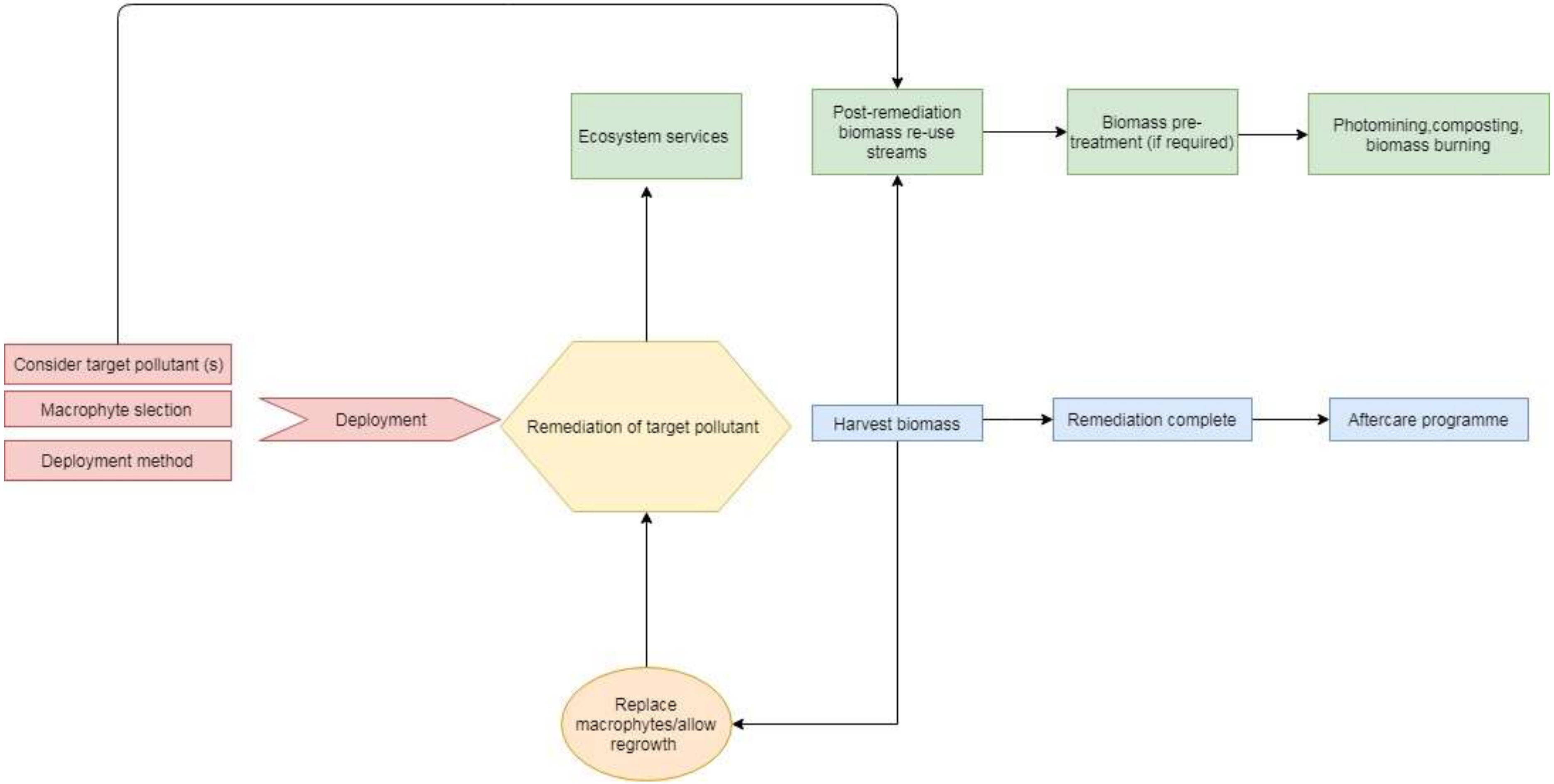


Figure 12.8: Process diagram illustrating the proposed phytoremediation process in its entirety