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Review

Giving waterbodies the treatment they need: A critical review of the application of constructed floating wetlands

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ABSTRACT

Water quality is declining worldwide and an increasing number of waterbodies lose their ecological function due to human population growth and climate change. Constructed floating wetlands (CFWs) are a promising ecological engineering tool for restoring waterbodies. The functionality of CFWs has been studied in-situ, in mesocosms and in the laboratory, but a systematic review of the success of in situ applications to improve ecosystem health is missing to date.

This review summarises the pollutant dynamics in the presence of CFWs and quantifies removal efficiencies for major pollutants with a focus on in situ applications, including studies that have only been published in the Chinese scientific literature. We find that well designed CFWs successfully decrease pollutant concentrations and improve the health of the ecosystem, shown by lower algae biomass and more diverse fish, algae and invertebrate communities. However, simply extrapolating pollutant removal efficiencies from small-scale experiments will lead to overestimating the removal capacity of nitrogen, phosphorus and organic matter of in situ applications. We show that predicted climate change and eutrophication scenarios will likely increase the efficiency rate of CFWs, mainly due to increased growth and pollutant uptake rates at higher temperatures. However, an increase in rainfall intensity could lead to a lower efficiency of CFWs due to shorter hydraulic retention times and more pollutants being present in the particulate, not the dissolved form. Finally, we develop a framework that will assist water resource managers to design CFWs for specific management purposes. Our review clearly highlights the need of more detailed in situ studies, particularly in terms of understanding the short- and long-term ecosystem response to CFWs under different climate change scenarios.

1. Introduction

Waterbodies face unprecedented pressures today through changes in land-use and climate. Natural landscapes are continuously transformed by humans to support the world's growing population and this leads to extensive input of pollutants into waterbodies. In urban areas, heavy metals and polycyclic aromatic hydrocarbons from roads, and herbicides, pesticides and nutrients from agriculture are washed into waterbodies (Aryal et al., 2010; Stagge et al., 2012). In developing countries, 80% of domestic sewage is discharged into rivers, lakes and the ocean without previous treatment (World Water Assessment Programme, 2009) leading to high levels of nutrients, organic matter and pharmaceutical and personal care products (PPCPs) in receiving waterbodies.

Many contaminated waterbodies lose their ecosystem services, such as water supply, nutrient cycling, waste treatment, and recreation (Brauman et al., 2007; Costanza et al., 1997). Low water quality is a major global contributor to diseases (World Water Assessment Programme, 2009) and it was estimated that over 800,000 people die each year from gastrointestinal illnesses as a result of unsafe drinking

Abbreviations: BOD, Biochemical oxygen demand; CFW, Constructed floating wetland; CH_4, Methane; COD, Chemical oxygen demand; DO, Dissolved oxygen; H_2S, Hydrogen sulfide; log K_{ow}, Octanol-water partition coefficients; N, Nitrogen; N_2, Dinitrogen; N_2O, Nitrous oxide; NH_4, Ammonium; NO_2, Nitrite; NO_3, Nitrate; P, Phosphorus; PO_4^{3-}, Phosphate; PPCPs, Pharmaceutical and personal care products; SS, Suspended solids; TN, Total nitrogen; TS, Total solid; TSS, Total suspended solid

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water alone (WHO, 2016). An earlier report by the World Health Organization (WHO, 2002) has estimated that 3.1% of all deaths worldwide are caused by unsafe or inadequate water, sanitation and hygiene.

Improving the health of water resources through sustainable management faces two challenges: to prevent additional pollutants entering the waterbody and to remove existing pollutants. Integrated catchment management is now adopted by an increasing number of water management authorities worldwide and has led to large water quality improvements by reducing input of nutrients. To remove pollutants from waterbodies a number of strategies have been proposed including biomanipulation (Søndergaard et al., 2007), removal of sediments to prevent the release of phosphorus and heavy metals from anoxic sediments (Søndergaard et al., 2003), re-oxygenation (Bormans et al., 2016), and the use of constructed wetlands or constructed floating wetlands. Such strategies also benefit biodiversity protection which is an important political goal in many countries (Brüll et al., 2011).

Constructed floating wetlands (CFWs) are a promising and cost effective ecological engineering tool to restore waterbodies. One of the first reports on the use of a CFW stems from Germany (Hoeger, 1988). This was followed by applications in ponds and reservoirs in the 1980s in other European countries, the US and Japan (Deng and Ni, 2013). While often used by its own, CFWs are now also integral parts within large-scale eco-engineering projects (Fang et al., 2016; Ning et al., 2014). They are relatively low-cost water reclamation schemes based on nature's self-cleaning capacity (Jana, 2011) and are generally are cheaper than other treatment options (Rezania et al., 2016).

CFWs are artificial floating islands made from buoyant carriers that support the growth of macrophytes, whereby the roots extend into the water to take up dissolved pollutants (Headley and Tanner, 2012) (Fig. 1). Regular harvesting of the above surface plant biomass and replanting ensures efficient removal of pollutants from the ecosystem by interrupting the nutrient cycle and energy flow. In addition to the pollutant uptake by plants, the rhizosphere's microbial biofilm incorporates pollutants into their biomass or transforms pollutants through external enzymatic processes (exudates) into compounds that can be taken up by the plants (Kadlec and Wallace, 2009). This symbiotic relationship between the microbes and the roots is considered to be one the major removal pathways for some pollutants, such as organic pollutants, pesticides, and PPCPs (Kadlec and Wallace, 2009; Srivastava et al., 2017). Suspended solids are effectively removed by sedimentation and filtering within the rhizosphere. CFWs provide habitat encouraging biodiversity (Nakamura et al., 1998) and shade the water, which helps regulating water temperature and limits the amount of sunlight for extensive algal growth (Borne, 2013).

Constructed floating wetlands are known by at least 12 different names (Pan et al., 2016; Pavlineri et al., 2017), including hydroponic root mats (Chen et al., 2016), artificial floating islands (Yeh et al., 2015), floating treatment wetlands (Chang et al., 2012; Faulwetter et al., 2011), natural floating wetlands (Pavlineri et al., 2017), ecological floating beds (Bao, 2015; Cao and Zhang, 2014), and constructed floating islands (Bai and Wang, 2009). A number of excellent reviews and studies on CFWs have been published in the last 12 years: Chen et al. (2016) summarized performance data and compared hydroponic root mats with free-floating plants and soil-based constructed wetlands; comprehensive reviews on the use of CFW for stormwater quality improvement were published by Headley and Tanner (2006, 2012); Yeh et al. (2015) reviewed the application of artificial floating islands for stormwater and wastewater treatment; Zhang et al. (2014a) assessed the performance of CFWs to remove PPCPs and reviewed their removal mechanisms; and Pavlineri et al. (2017) provided a meta-analysis of

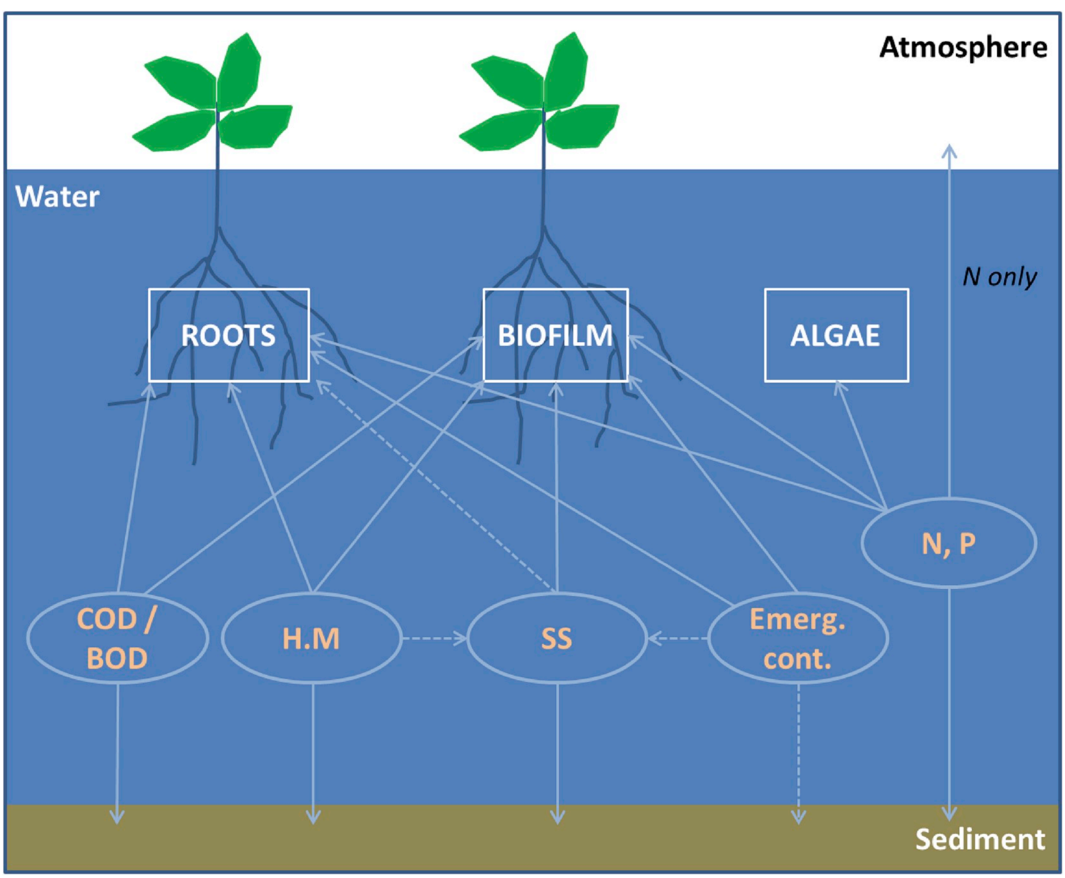

Fig. 1. Framework indicating the main removal pathways for key contaminant groups in the presence of CFWs. White squares indicate main compartments: ROOTS include uptake by the roots and the adsorption within the rhizosphere; BIOFILM indicates the microbial degradation within the rhizosphere; ALGAE describes the uptake by phytoplankton. Dashed line indicates adsorption only; Emerg. cont. = emerging contaminants (i.e. herbicides, pesticides, PPCPs), H.M. = heavy metals.

mesocosm studies to identify relationships between nutrient removal rates and design parameters.

Installing CFWs has profound and long-lasting bottom-up effects on the aquatic ecosystem. Up to date a systematic review of in situ applications, their success rates and their effects on the aquatic ecosystem is missing. This review aims to close this gap by identifying how CFW design affects the dynamics and removal of common pollutants and by comparing removal rates reported from in situ applications with those predicted from mesocosm and laboratory experiments. We include in situ applications described in Chinese scientific journals, because this valuable source of information is unavailable to the non-Chinese speaking science community. We assess how CFWs affect the ecology of the waterbody and discuss how the predicted changes in climate might impact their efficiency. Finally, we present a framework that will assist water resource managers to design CFWs for specific management purposes.

2. Constructed floating wetland components and design

The main components responsible for pollutant removal efficiency in conventional CFWs are macrophytes and the biofilm attached to the roots. The size and placement of the CFW within the waterbody are further important aspects because of their impact on the removal capacity. Aeration, submerged plants and artificial biofilm carriers have also been trialled to increase CFW efficiencies. In the following, we call any CFW that contains addition components 'hybrid CFWs'.

2.1. Macrophytes

Macrophytes are the main players in CFWs. Uptake by the roots and translocation and accumulation of pollutants in the above surface plant biomass is the main removal process for dissolved species of nitrogen, phosphorus, heavy metals and dissolved organic matter. Higher transpiration rates of plants during warmer periods support a higher mass flux of pollutants to the above ground biomass (Chaudhry et al., 2005; Pilon-Smits, 2005).

The roots release oxygen and organic compounds that support the degradation of organic pollutants (Rehman et al., 2017). They provide a living surface for biofilm development, which is important for nutrient removal (Haberl et al., 2003; Stottmeister et al., 2003). Roots of fibrous-root plants (e.g. *Cyperus flabelliformis*) provide a larger surface for biofilm development, display higher photosynthesis rates and radial oxygen loss and thus can remove nutrients more efficiently than thick-root plants (e.g. *Aglaonema commutatum*) (Lai et al., 2011, 2012). The thick network of roots and associated biofilms are also effective for trapping and settling of particulate matters (Borne et al., 2013a). As root surface area often increases with plant age, suspended solid (SS) removal rates are often higher in mature CFWs (Smith and Kalin, 2001).

2.2. Biofilm

Biofilms are complex matrices of bacteria and algae held together by extracellular polymeric substance. Biofilms have a higher biodiversity than open water microbial communities, making them more resilient towards disturbances (Chen et al., 2016; Zhang and Bishop, 2003). The biofilm entraps suspended solids, is critical for the removal of phosphorus and nitrogen and has been linked to allelopathic effects in the waterbody (Nakai et al., 2010; Srivastava et al., 2017).

Artificial biofilm carriers are used to increase the underwater surface area and biofilm biomass, in order to increase the efficiency of CFWs. Recent studies have shown that artificial fibrous biofilm carriers have a higher specific area (3000–7000 m^2/m^3) (Felföldi et al., 2015; Xiao and Chu, 2015) compared to plant roots (7–114 m^2/m^3) (Smith and Kalin, 2001; Tanner and Headley, 2011). Due to the much larger reacting surface, the presence of artificial biofilm carrier can efficiently buffer fluctuations of flow, temperature and pollutant input during storms. However, the structure of bacterial biofilms attached to biological surfaces show a higher biodiversity than those on artificial biofilm carriers (Münch et al., 2007; Zhang et al., 2016), indicating that they are more efficient per area.

2.3. Hybrid CFWs

The use of hybrid CFWs has strongly increased within the last 10 years. Hybrid CFWs include additional components, such as aeration (Gao et al., 2009; Sheng et al., 2013), artificial biofilm carriers (Li et al., 2010b; Song et al., 2014), different substrates (Guo et al., 2014; Zhang et al., 2012), aquatic animals (Li et al., 2010b) or submerged plants (Guo et al., 2014; Luo et al., 2011). They have been shown to have higher removal efficiencies than conventional CFWs (Li et al., 2010b; Wang et al., 2012a).

Aeration stimulates biofilm development and supports biological pollutant removal even at low temperatures. In addition, aeration can reduce CH_4 emission and H_2S production by increasing the dissolved oxygen concentration in the water (Wang and Hua, 2012).

The **substrate** has numerous functions in CFWs. First, it supports plant growth and provides nutrients for the plants during their establishment phase. Second, substrates that have large specific surface areas (e.g., bamboo fibre, wood, coconut coir) (Headley and Tanner, 2006; Xiao and Chu, 2015) support a large biofilm biomass – even larger than the roots. Third, substrates like pumice, perlite, coarse peat and zeolite directly adsorb nutrients from the water (Headley and Tanner, 2006). Although the substrates play an important role in the function of CFWs, it is essential to choose them carefully to avoid additional nutrient release into the water (Chang et al., 2013).

Aquatic animals, such as filter-feeding bivalves can ingest large amounts of phytoplankton and particulate matters. This accelerates nutrient and other pollutant removal from the waterbody (Li et al., 2010b; Waajen et al., 2016). Filter feeding fish, such as silver and bighead carp can effectively control the phytoplankton biomass and harmful algal blooms in eutrophic waterbodies (Ke et al., 2009; Ma et al., 2012).

Submerged plants can improve nutrient removal from the water and sediment by direct uptake. They provide additional surface for biofilm establishment. Oxygen production by submerged plants increases DO concentration in the water which counteracts the release of phosphate from sediments (Guo et al., 2014; Luo et al., 2011). Submerged macrophytes can also effectively prevent sediment resuspension, thus reducing turbidity (Dai et al., 2012). They further provide habitat for zooplankton which increases the ecological stability (Horppila and Nurminen, 2003; Vermaat et al., 2000).

3. Pollutant dynamics in constructed floating wetlands

The main purpose of constructed floating wetlands (CFWs) is to remove nutrients, organic pollutants and suspended solids from often shallow waterbodies (Fig. 1). Some success has been shown for the removal of heavy metals and emerging pollutants (e.g., pesticide, herbicides, PPCPs).

Analysing a wide range of publications on water pollution we found that the type of pollutants present in a waterbody depends on the pollution source (Table 1). Understanding the dynamics of specific pollutants within a system is essential to assess the potential of CFWs to successfully improve the water quality of a given waterbody. The fundamental mechanisms for pollutant uptake and assimilation by the plants are known from phytoremediation studies. The processes responsible for the success of CFWs have been described in laboratory-scale and mesocosm experiments reviewed in Chen et al. (2016) and Deng and Ni (2013).

Table 1
Indicative presence of major pollutant groups in water from different sources. WW = wastewater.

Pollutant	Domestic WW	Industrial WW	Livestock WW	Aqua- culture	Urban runoff	Agricultural runoff
Nutrients (N, P)	+ - ++	++	++	++	++	++
Organics	++	++	++	++	+ - ++	++
Suspended solids	+	+	++	+	++	++
Heavy metals	0	++	0	0	++	0
Pesticides	0	0	+	0	+ - ++	++
PPCPs	++	0	++	+	0	+

++ = pollutant is likely to be present at high concentration.
+ = pollutant is likely to be present at low concentration.
0 = pollutant does not present a major concern.

3.1. Nutrients (nitrogen and phosphorus)

Nitrogen (N) and phosphorus (P) are essential elements for the growth and functioning of any organism. However, too much of these nutrients in waterbodies results in eutrophication and leads to the deterioration of aquatic ecosystems (Bai and Wang, 2009). The main forms of P and N in the water are organic phosphorus, orthophosphate (PO_4^{3-}), organic nitrogen, ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) (Fig. 2). Organic phosphorus is degraded by bacteria to its dissolved form (PO_4^{3-}), which in turn is taken up by plants, algae and bacteria and assimilated into organic phosphorus (Fig. 2). Biological uptake is therefore the main process of P removal. Organic nitrogen is degraded by bacteria into ammonium, nitrite and nitrate, all of which can be assimilated by plants, algae and bacteria. This assimilation step closes the nitrogen cycle by transforming dissolved nitrogen forms into organic nitrogen. This cycle can be broken up by denitrifying bacteria, which transform nitrate into nitrous oxide (N_2O) and nitrogen gas (N_2), two potent greenhouse gases that are released into the atmosphere (Fig. 2).

The three main processes to remove nitrogen from the water are i) denitrification, which leads to the permanent removal of nitrogen from the system; ii) sedimentation, which subsequently buries nitrogen in the sediment; and iii) uptake by aquatic plants (Saunders and Kalff, 2001). The primary process in lakes and rivers is denitrification with studies showing that up to 80% of N is removed by denitrification (reviewed in Saunders and Kalff, 2001). Sedimentation and uptake by plants share the remaining 20% in equal parts. Chen et al. (2013) quantified that N uptake by CFWs planted with perennial ryegrass accounted for 18% of the total N removal from wastewater. Sedimentation plays only a minor role for N and P removal, especially in a) waterbodies receiving agricultural runoff, because the main nitrogen input is in form of nitrate, which does not settle out, b) in rivers, where a significant flow can prevent sedimentation, and c) in shallow lakes, where wind events can resuspend sediment leading to increased total N and total P concentration in the water column after storm events (Reynolds and Davies, 2001). Nutrient removal can therefore be increased by strategic

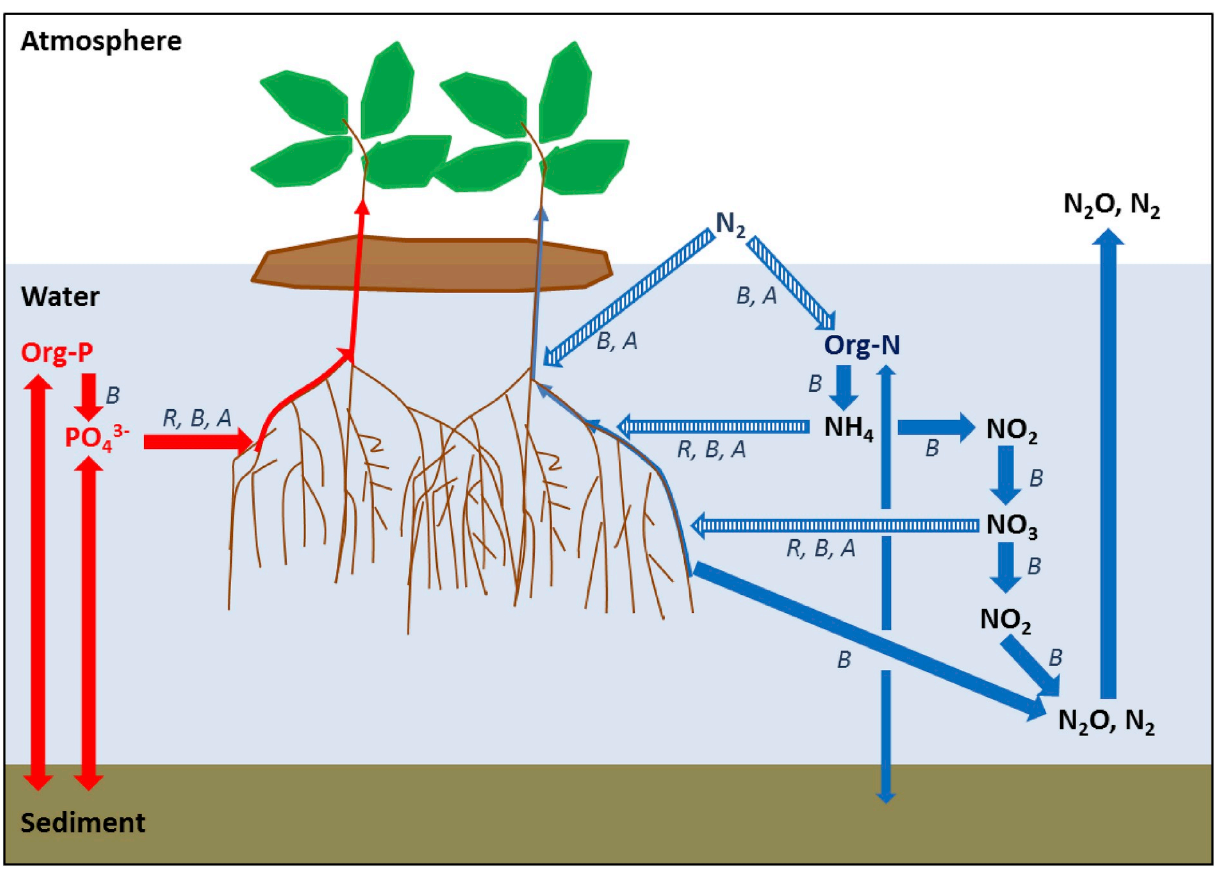

Fig. 2. Major pathways of N and P in a system with a CFW. Thick broken arrows indicate uptake, thick solid arrows indicate transformation, and thin solid lines indicate transport. Italicised letters indicate uptake by R = roots, B = bacteria or A = algae.

harvesting of macrophytes (P, N), and by enhancing areas suitable for denitrification, such as the rhizosphere (N only).

3.2. Organic pollutants

Organic pollutants encompass molecules and compounds of varying size with at least one carbon atom. The carbon can be used as an energy source by organisms, thus fuelling the production of biomass. This can lead to extensive growth of algae. As the bacterial degradation of large organic compounds requires oxygen, organic contamination can lead to oxygen depletion and subsequent fish kills.

CFWs can lower the concentration of organic pollutants by three processes: i) by the direct uptake of dissolved organic pollutants through the cell wall and/or membrane of bacteria, algae and vascular plant roots (Pilon-Smits, 2005); ii) by microbial transformations of large organic compounds into smaller compounds, which can be taken up by plants (Davey and O'Toole, 2000); iii) by adsorption of hydrophobic organic compounds onto particulate matter or directly onto the biofilm with subsequent precipitation to the sediment.

3.3. Suspended solids (SS)

Suspended solids (SS) increase the turbidity of waterbodies and therefore decrease light availability for algae, submerged macrophytes and benthic communities. In addition, SS can smother fish eggs and benthic invertebrate communities and hinder zooplankton feeding (Bilotta and Brazier, 2008).

Suspended solids are mostly inorganic particles that are larger than 2 µm, but can also be of organic nature (i.e. algae, bacteria). As inorganic particles have no nutritional value for organisms, they are not directly taken up by plants or biofilm. However, suspended solids can effectively be removed from the water column by sedimentation in the area below the floating islands, due to laminar flow conditions with reduced turbulence in the open water layer between the roots and the sediment (Chen et al., 2016). As the filtering of suspended solids requires flow, it is likely that removal is higher in stormwater ponds (Tanner and Headley, 2011) and rivers (Billore et al., 2009) than in stagnant lakes. It is important to note that suspended solids are not entirely removed from the waterbody by CFWs, because they precipitate to the sediment layer. Strategic removal of the sediment layer below a CFW might therefore be useful to avoid aggradation (Headley and Tanner, 2006).

3.4. Heavy metals

Heavy metals originate from runoff from roads and commercial areas, and from industrial wastewater (Hwang et al., 2016). Heavy metals are mainly present in the particulate form, with only a small fraction being available in the dissolved form. The dissolved heavy metal fraction can be taken up by plants via interaction with functional groups within the cell wall. The removal efficiency of dissolved heavy metals in CFWs depends on the physical and chemical conditions of the water, including the redox potential, temperature, pH, heavy metal concentration and nutrient availability, and on plant physiology and plant species (Dhir, 2013). High salinity and co-pollution by other heavy metals reduces the removal efficiency due to competition at non-selective cation transporters (e.g. arsenate is taken up by phosphate transporters, selenate by sulfate transporter) (Abedin et al., 2002; Shibagaki et al., 2010).

Only few studies have directly quantified the removal of heavy metals in conventional (Table 2, Table S1) or in hybrid CFWs (Table 3, Table S2). Borne et al. (2013a) showed that the entrapment of the particulate heavy metals within the rhizosphere and its biofilm contributed more to the removal than plant uptake. In stormwater, where heavy metals are normally associated with fine particles (Headley and Tanner, 2006), a fine and abundant root mass enhanced sedimentation of particulate metals (García et al., 2010). It has been shown that more heavy metals accumulate in sediments in the presence of CFWs than in systems without CFWs (Ning et al., 2014).

3.5. Pesticides and herbicides

Pesticides and herbicides occur in waterbodies either in dissolve or particulate form. Some pesticides, such as the widely prohibited DDT, are persistent in the environment, while recently developed pesticides generally have shorter half-lives (Gavrilescu, 2005).

Partially reversible adsorption and microbial degradation have been identified as the main removal processes for this pollutant group (Chen et al., 2017; Passeport et al., 2013). Direct uptake by plants was very low to negligible ($< 0.6\%$) (Chen et al., 2017; Mahabali and Spanoghe, 2014). Pesticides with high octanol-water partition coefficients (log K_{ow}) are likely to adsorb to epidermal lipids in the roots without further uptake into plants (Chen et al., 2017). Although this removes these pesticides from the water, it does not completely eliminate them from the waterbody. Under certain conditions, moderately sorbing pesticides, such as isoproturon or metazachlor, can be released back into the water (Passeport et al., 2011). Even highly sorbent pesticides with a long half-life re-enter the water when roots die off or degrade. Few studies describe the removal efficiency of pesticide or herbicide by CFWs. A recent study by Chen et al. (2017) indicates that more than 90% of three types of chloroacetanilide herbicides was removed within 9 days through root adsorption and plant-assisted microbial degradation.

3.6. Pharmaceutical and personal care products (PPCPs)

Pharmaceutical and personal care products (PPCPs) are a large group of compounds that differ widely in their chemical properties. This group encompasses cosmetics and pharmaceuticals such as antibiotics, painkillers (e.g. ibuprofen) and synthetic hormones (Daughton, 2004). Many of the PPCPs act directly as endocrine disrupting compounds, or contain chemicals, such as plasticizers, that can disrupt the human reproduction pathway (Herreros et al., 2010). PPCPs reach waterbodies mainly through contamination by domestic and livestock wastewater (Table 1). Most PPCPs are hydrophobic and likely to be adsorbed onto particulate matter (García et al., 2010).

In the absence of any in situ studies on the removal of PPCPs in CFWs, we here discuss the removal pathways identified through laboratory experiments and field work in constructed wetlands. Potential removal pathways are microbial degradation (e.g., ibuprofen, salicylic acid, galaxolide) (Onesios et al., 2009; Petrie et al., 2015), uptake by plants (e.g., carbamazepine) (Shenker et al., 2011), adsorption onto particulate matter (e.g., triclosan, tetracycline) with subsequent sedimentation (Bester, 2005; Ruhmland et al., 2015) and photodegradation (e.g., ketoprofen, naproxen, triclosan, diclofenac) (Bi et al., 2018; Reyes-Contreras et al., 2012).

Plant-assisted microbial removal has been identified as the main process for PPCPs removal (Reyes-Contreras et al., 2012; Ruhmland et al., 2015). A longer contact time of chemical compounds with the biofilm on the roots increases the degradation efficiency as long as the redox conditions are not adversely affected by the CFWs' coverage area (Hijosa-Valsero et al., 2011). Although the plant uptake capacity of PPCPs is species dependent, it is generally considered to be of minor importance in the overall removal efficiency (Zhao et al., 2016).

Many PPCPs, such as diclofenac, ketoprofen or naproxen are quickly photodegraded (Reyes-Contreras et al., 2012). CFWs can either enhance or reduce light penetration in the waterbody: while CFWs reduce the open water surface area and as such the amount of light reaching the water, they can also reduce algal biomass which in turn increase the water clarity. Whether photodegradation of PPCPs is ultimately enhanced or reduced by the installation of CFWs will therefore be system specific.

Table 2
Minimum (Min) and maximum (Max) removal efficiencies (%) of water pollutants and changes in physical water characteristics quantified in conventional CFW in situ applications. WW = wastewater; N = number of replicates; Ref. = reference.

Parameter	Stormwater pond				River				Pond/Reservoir				WW treatment				Drain			
	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.
TS					43	43	1	1												
TSS	−5	95	6	2−5	47	47	1	1												
TDS					26	26	1	1	15	15	1	6								
DO	0	0	2	7	−15	−15	1	1	−26	−26	1	6	−136	68	3	8	0	0	2	9
TKN	35	89	2	2−4,10	28	28	1	1												
TN	−94	88	14	2−5,10−13									−9	67	5	8,14	11	29	3	9,15
NH_4^+-N	5	98	5	2−4,7,10	40	40	1	1	−1	−1	1	6	−20	20	3	8	60	60	1	15
NO_3-N	−1	51	4	7,11	11	11	1		34	34	1	6	−6	95	3	8	0	14	3	9,15
NO_2-N													−100	97	3	8	60	60	1	15
NO_x-N	21	82	5	2−4,10,11																
ON	11	81	3	2−4,10	26	26	1	1												
DIN	44	44	1	2−4																
BOD	0	0	2	7	39	39	1	1	17	17	1	6	0	67	3	8	52	52	1	9
COD	31	31	2	7					15	15	1	6	3	56	3	8	13	66	4	9,15
TP	−120	88	14	2−5,10−13									−10	6	3	8	27	65	2	9,15
PO_4^{3-}-P	20	25	2	7					36	46	2	6−16	−29	2	3	8				
OP	42	92	4	10,11																
PP	29	82	2	10																
PZn	40	40	1	2−4																
PCu	29	29	1	2−4																
DCu	16	16	1	2−4																
Temp.	0	0	4	7,10									0	9	3	8				
pH	0	0	2	7					−11	−11	1	6	−3	0	3	8	0	0	2	9
EC	3	3	1	7									0	13	3	8				
K	20	22	2	7																
Cd	25	25	2	7																
Cr	0	0	2	7																
Cu	20	30	2	7																
Zn	10	20	2	7																
Pb	10	10	2	7																
Chl-a*									−154	62	2	6,16								
*E. coli**													20	95	3	8				
Eh													−1	1	3	8				
SO_4^{2-}									5	5	1	6								

* or cell counts.
Abbreviation: BOD = biochemical oxygen demand; COD = chemical oxygen demand; D_{Cu} = dissolved copper concentration; DIN = dissolved inorganic nitrogen; DO = dissolved oxygen; NH_4^+−N = ammonium; NO_2—N = nitrite; NO_3—N = nitrate; NO_x-N = nitrogen oxides; ON = organic nitrogen; OP = organic phosphorus; P_{Cu} = particulate copper concentration; P_{Zn} = particulate zinc concentration; PP = particulate phosphorus; PO_4^{3-}-P = phosphate; TDS = total dissolved solid; Temp = temperature; TKN = total kjeldahl nitrogen; TN = total nitrogen; TP = total phosphorus; TS = total solid; TSS = total suspended solid.
References: 1,(Billore et al., 2009); 2, (Borne, 2014); 3, (Borne et al., 2013a); 4, (Borne et al., 2013b); 5,(Schwammberger, 2017); 6, (Olguin et al., 2017); 7, (Revitt et al., 1997); 8, (Mietto et al., 2013); 9, (De Stefani et al., 2011); 10, (Winston et al., 2013); 11, (Chang et al., 2013); 12, (Nichols et al., 2016); 13, (Hartshorn et al., 2016); 14, (Vazquez-Burney et al., 2015); 15, (Zhang et al., 2014b); 16, (Garbett, 2005).

3.7. Algal blooms

Algal blooms are a widespread problem in many eutrophic waterbodies and can lead to impoverished ecosystems, odour issues and fish kills. The main trigger for the development of algal blooms are nutrients (Sinang et al., 2015), and in specific N and P. The reduction of nutrients and changes of the N:P ratio by CFWs will directly facilitate the reduction of algal biomass. Reducing the light availability will decrease phytoplankton biomass and influence species composition. Pinto et al. (2007) showed that too much shading can shift the phytoplankton community to colonial cyanobacteria, which are nuisance algae themselves. However, Liu et al. (2010) showed that cyanobacteria presented only 10% of the phytoplankton community in a mesocosm with CFW compared to a control mesocosm without CFW that was dominated by *Microcystis*.

4. In situ applications of constructed floating wetlands

4.1. Targeted systems

CFWs are used to improve the quality of stormwater, rivers, lakes, domestic or industrial wastewater, fish-farm effluent, and combined stormwater-sewer overflow. In comparison with the vast literature on small-scale experiments (reviewed in Chen et al., 2016; Deng and Ni, 2013; Pavlineri et al., 2017), we found only 28 publications within the peer-reviewed literature that investigated the success of pollutant removal by in situ application of CFWs (Web of Science topical key words used: "constructed floating wetlands", "floating treatment wetlands", "hydroponic root mats", "artificial floating islands", "natural floating wetlands", "ecological floating beds"). Of these 28 studies, 17 used conventional CFWs (Table 2, S1), while 11 used hybrid systems that combined CFW with other remediation technologies (e.g. submerged plants, aeration) (Table 3, S2). The main application of conventional CFWs was stormwater quality improvement (Table 2), while it was the remediation of rivers for hybrid CFWs (Table 3). Other applications were the treatment of wastewater (Mietto et al., 2013; Vazquez-Burney et al., 2015), polluted ponds (Garbett, 2005; Olguin et al., 2017), lakes (Wu et al., 2006), reservoirs (Castro-Castellon et al., 2016; Garbett, 2005), and a coastal lagoon (Huang et al., 2013) (Table S1, S2).

4.2. Removal efficiencies reported in in situ studies

Removal efficiencies vary largely between the above mentioned 28 studies, expressed by the large boxes in Fig. 3. This is due to differences

Table 3
Minimum (Min) and maximum (Max) removal efficiencies (%) of water pollutants and changes in physical water characteristics quantified in hybrid CFW in situ applications. N = number of replicates; Ref. = References.

Parameter	River				Lake/Pond/Reservoir				WW treatment			
	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.
TSS	−73	90	4	1−3	76	76	1	4	79	79	1	5
DO	−1170	18	2	2,6				4	68	68	1	7
TN	12	58	6	2,3,6,8,9				4	34	34	1	7
NH_4^+-N	16	83	5	1−3,6	50	50	2	4				
NO_3-N	13	26	3	2,3					49	95	2	5,7
NO_2-N	27	53	3	2,3					97	97	1	
BOD									67	87	2	5,7
COD	8	80	4	1,2,6,9	71	71	1		56	58	2	5,7
TP	0	88	7	1−3,6,8,9	65	72	2		6	6	1	7
PO_4^{3-}-P	11	11	1	2					−3	−3	1	7
Temperature									0	0	1	7
pH	5	5	1	2					0	0	1	7
Conductivity	8	8	1	2								
Turbidity	−35	−35	1	2								
Transparency	−32	17	2	2,6								
Cd	0	30	2	3								
Cr	40	87	3	2,3								
Cu	9	55	3	2,3								
Zn	17	17	1	2								
Pb	−59	54	3	2,3								
Chl-a*	6	65	3	3,6								
*E. coli**	61	71	2	3					89	95	2	5,7
As	41	43	2	3								
Hg	39	44	2	3								
S^{2-}	91	91	1	1								
Eh									0	0	1	7
EC									13	13	1	7
Mn	47	47	1	2								
Fe	22	22	1	2								
Ni	−26	−26	1	2								
Al	21	21	1	2								
F^-	33	33	1	2								
Cl^-	22	22	1	2								
SO_4^{2-}	6	6	1	2								

Abbreviation: As = arsenic; BOD = biochemical oxygen demand; COD = chemical oxygen demand; Cd = cadmium; Cr = chromium; Cu = copper; Chl-a = chlorophyll a; DO = dissolved oxygen; EC = electrical conductivity; *E. coli* = *Escherichia coli;* Eh = oxidation-reduction potential; Hg = mercury; Mn = manganese; NH_4^+−N = ammonium; NO_2−N = nitrite; NO_3−N = nitrate; Pb = lead; PO_4^{3-}-P = phosphate; S^{2-} = sulphur ions; TN = total nitrogen; TP = total phosphorus; TSS = total suspended solid; Zn = zinc.
References: 1, (Sheng et al., 2013); 2, (Ning et al., 2014); 3, (Zhao et al., 2012); 4, (Wu et al., 2006); 5, (Goldoni et al., 2014); 6, (Chen et al., 2012); 7, (Mietto et al., 2013); 8, (Liu et al., 2016a); 9, (Fang et al., 2016).

in the design (mainly the plant species and plant density), but also climate, flow, pollutant concentrations and environmental conditions. It is interesting to note that the concentrations of some pollutants, such as TSS, TN, TP, and chlorophyll *a* increased in some studies (Fig. 3), warranting further investigations into the removal processes. There is a trend that hybrid systems perform slightly better, but it was only

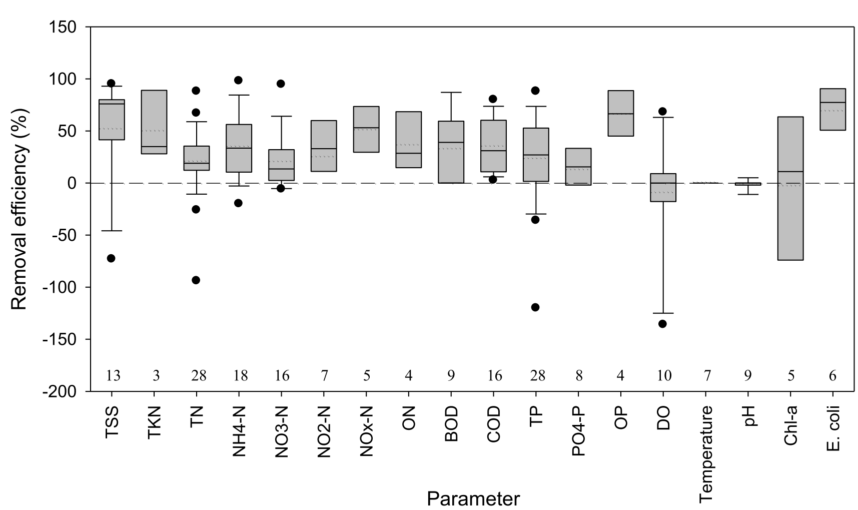

Fig. 3. Pollutant removal rates quantified in-situ from the studies listed in Tables 2 and 3. The boxes are 25th and 75th percentile; the solid line is the median, the broken line the mean. Whiskers present the 10th and 90th percentile and filled circles are outliers. The numbers represent the number of samples for each parameter.

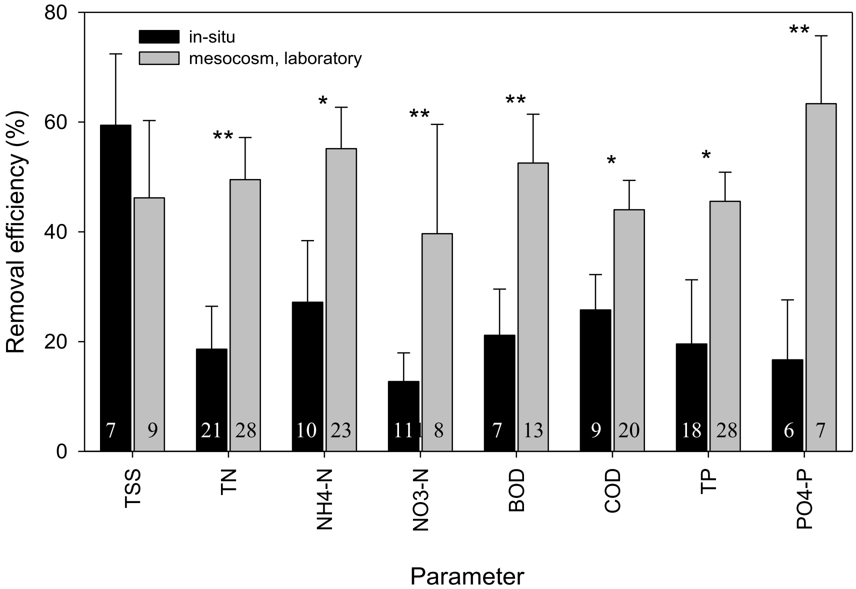

Fig. 4. Average (± 1 SE) removal efficiencies (%) of in-situ and small scale experiments for 10 water quality parameters. Numbers indicate the number of replicates. * indicates statistical differences on the $p < 0.1$ level, ** on the $p < 0.05$ level. The list of the small scale studies used can be found in Table S3, the in situ studies used can be found in Tables 2 and 3.

significant for the removal of nitrate-N with a removal efficiency of 12.7% ± 5.2 (mean ± SE) for conventional CFWs and 39.9% ± 15.0 for hybrid systems (t-test: $t = -2.18$, d.f. = 14; $p < 0.05$) (data not shown).

4.3. Comparison of removal efficiencies between in situ and mesocosm/laboratory studies

Mesocosm and laboratory studies can yield different results to in situ applications (Williams et al., 2002). We compared removal efficiencies for key pollutants quantified in conventional in situ CFW studies (Table 2) with efficiencies from 20 small-scale experiments (mesocosm or laboratory; references and data listed in Table S3). We found that removal efficiencies are often significantly higher in small-scale experiments compared to in situ studies (Fig. 4). The fact that the conditions in the smaller scale experiments are more controlled with less natural fluctuations than the real-world applications experience might contribute to this result. In addition, optimum plant growth conditions are often chosen during laboratory experiments, while the longer duration of in situ experiments averages removal efficiencies over all seasons. In practise this means that removal efficiencies are overestimated when extrapolated to large scale applications.

4.4. Effects of constructed floating wetlands on aquatic ecosystem

If CFWs are successful in removing pollutants, this has profound and potentially long-lasting bottom-up effects on the whole ecosystem. Following the principle of *alternate stable state theory* (Scheffer et al., 2001) which describes the shift between contrasting ecosystem states (phytoplankton versus submerged macrophytes) (Scheffer et al., 1993), the installation of CFWs can be seen as a way to move the system back to the preferred, macrophyte-rich state. It can be hypothesised that waterbodies with CFWs might reach this transition faster than systems in which only nutrient loads are managed (e.g., by sediment capping, removing of point sources), because of the additional provision of habitat for zooplankton, invertebrates and fish. However, the effect of CFWs on aquatic fauna and on long-term ecosystem effects has so far not been studied.

Some understanding may be derived from field and mesocosm studies with free-floating macrophytes, as they also provide shading and refuge. Free-floating macrophytes can significantly decrease phytoplankton biomass (Chen et al., 2012), change the phytoplankton species composition and diversity (Ji et al., 2016; Pinto et al., 2007). This represents a desirable outcome as many waterbodies to be remediated suffer from algal blooms. However, free-floating macrophytes can also encourage the growth of potential nuisance algae, such as cyanobacteria, through increased shading (Pinto et al., 2007). This dominance could further be encouraged by longer-lasting and more stable stratification (Reichwaldt and Ghadouani, 2012) in the presence of macrophytes, because they lessen the wind effect on the water (Headley and Tanner, 2006; Yeh et al., 2015).

CFWs can support a higher diversity of fish, benthic and pelagic invertebrate communities (Nakamura et al., 1998). This results in a shift from communities indicative of polluted water (e.g. *Culicidae, Chironomidae, Hirudo nipponica*) to those indicative of moderately polluted water (Chang et al., 2014). The presence of floating plants increased zooplankton biodiversity and total biomass, although total zooplankton abundance was lower (Fontanarrosa et al., 2010; Kurbatova and Ershov, 2012). Anoxia within the rhizosphere can decrease zooplankton density (Fontanarrosa et al., 2010). A well oxygenated rhizosphere however allows a more stable zooplankton community compared to the open water (Castro-Castellon et al., 2016). This suggests that CFWs change zooplankton communities. If these changes are significant, this will impact the phytoplankton community (food source) and the invertebrate and fish community (predators).

4.5. In situ applications described in Chinese scientific journals

Constructed floating wetlands were first adopted in China in 1989 with the purpose of growing rice on a floating system (Song, 1991; Song et al., 1996). Since then the application has gained tremendous momentum, mainly for the purpose of water remediation, supported by China's national policy for medium- and long-term scientific development. The Chinese government has established major science and technology projects for water pollution control under the 11th Five-Year Plan. Consequently, many environmental engineering companies, research institutes and universities have since installed large scale in situ CFWs with some positive outcomes (e.g., Danhe river, Taihu Meiliang Bay). However, the results of these trials are often reported in Chinese only. To give access to this vast source of information we here summarise the results of relevant in situ applications.

We chose CNKI (www.cnki.net) as the search engine and used six different Chinese terms for “floating treatment wetland” (“ren gong fu dao”, “sheng tai fu dao”, “ren gong fu chuang”, “sheng tai fu chuang”, “zhi wu fu dao”, “sheng wu fu chuang” in Chinese characters). Approximately 400 documents were found. Nine of those were

Table 4
Minimum (Min) and maximum (Max) removal efficiencies (%) of water pollutants and changes in physical water characteristics quantified in conventional CFW in situ applications summarized from research paper published in Chinese. N = number of replicates; Ref. = References.

Parameter	River (connecting to reservoir)				Reservoir				Lake				Aquaculture			
	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.
TSS									22	22	1	5				
SD									19	19	1	5	0	170	1	9
DO	12.5	12.5	1	1					42	76	2	5,8				
TKN																
TN			1	1	14	15	2	2,3	7.2	93	5	4−8	33	33	1	9
NH_4^+-N													29	29	1	9
NO_3-N																
BOD					25	25	1	2	36	36	1	8				
COD	15.6	15.6	1	1					10	80	3	5,6,8	15	15	1	9
TP			1	1	14	50	2	2,3	16	64	5	4−8	50	50	1	9
PO_4^{3-}-P	0	63	1	1					65	73	1	6				
Temp.																
pH	0	6	1	1												
Chl-a	30.4	30.4	1	1	34	34	1	3	0	0	1	5				
Org. C													−28	−28	1	9

Abbreviation: BOD = biochemical oxygen demand; COD = chemical oxygen demand; Chl-a = chlorophyll a; DO = dissolved oxygen; NH_4^+−N = ammonium; NO_3−N = nitrate; Org.C = organic carbon; PO_4^{3-}-P = phosphate; SD = Secchi depth; Temp = temperature; TKN = total kjeldahl nitrogen; TN = total nitrogen; TP = total phosphorus; TSS = total suspended solid.
References: 1, (Zheng et al., 2013); 2, (Chen and Lin, 2014); 3, (Wang et al., 2012b); 4, (Wen et al., 2015); 5, (Gao et al., 2011); 6, (Song et al., 2011); 7, (Zhang, 2011); 8, (Wei et al., 2009); 9, (Zeng et al., 2016).

Table 5
Minimum (Min) and maximum (Max) removal efficiencies (%) of water pollutants and changes in physical water characteristics quantified in hybrid CFW in situ applications summarized from research paper published in Chinese N = number of replicates; Ref. = References.

Parameter	River inflow to lake				River				Drain				Catchment				Aquaculture				Lake			
	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.	Min	Max	N	Ref.
Turbidity	70	70	1	3																				
TSS	86	86	1	2					60	60	1	10												
SD	150	300	1	3					150	150	1	11												
DO									80	236	2	10,11									11	76	1	14
TKN																								
TN	32	77	3	1−3	6	86	4	4−6	9	56	3	8−10	60	60	1	12	21	23	1	13	29	93	1	14
NH_4^+-N	49	85	3	1−3	6	83	5	4−6,7	25	70	4	8−11									21	89		14
NO_3-N	−102	−83	2	1,3													27	62	1	13	12	43		14
NO_2-N	−60	–	2	1,3													38	69	1	13				
COD	60	72.5	2	1−2	17	56	3	4,5,									13	36	1	13				
TP	41	75	3	1−3	6	96	5	4,6,	11	81	4	8−11	55	55	1	12	20	22	1	13	11	37		
PO_4^{3-}-P	68	68	1	1					0	64	3	8,9,11												
Temp.																	0	22	1	13				
pH																								
Chl-a																	17	75	1	13				

Abbreviation: COD = chemical oxygen demand; Chl-a = chlorophyll a; DO = dissolved oxygen; NH_4^+−N = ammonium; NO_2−N = nitrite; NO_3−N = nitrate; PO_4^{3-}-P = phosphate; SD = Secchi depth; Temp = temperature; TKN = total kjeldahl nitrogen; TN = total nitrogen; TP = total phosphorus; TSS = total suspended solid.
References: 1, (Gao et al., 2009); 2, (Li et al., 2009); 3, (Li et al., 2007); 4, (Liu et al., 2016b); 5, (Fu and Xie, 2014); 6, (Duan et al., 2013); 7, (Chen et al., 2011); 8, (Jiang et al., 2013); 9, (Li et al., 2011); 10, (Huang et al., 2010); 11, (Liu et al., 2009); 12, (Li et al., 2010a); 13, (Luo et al., 2011); 14, (Wei et al., 2009).

conventional CFW in situ installations (Table 4, Table S4) and 14 were hybrid CFW in situ installations (Table 5, Table S5).

Removal efficiencies found in the Chinese publications are similar to what has been described in section 4.2. In most studies removal efficiencies were quantified during the plants' growth phase in summer and autumn when high removal efficiencies of COD, TN, TP were found (Li et al., 2007; Liu et al., 2009). The oxygen released by the rhizosphere stimulated bacterial nitrification, with higher NO_3−N concentrations found closer to the CFWs (Gao et al., 2009; Li et al., 2009), especially at higher temperatures (Wang and Hua, 2012). Elevated ammonium concentrations were found in the water during the colder season due to the lower biological activity (Zheng et al., 2013). Entrapment of suspended particles was identified as an important pathway for eliminating pollutants from rivers and drains (Liu et al., 2016b).

Both conventional and hybrid CFWs remove TN, TP and COD from eutrophic systems. The removal was slightly higher in hybrid than conventional CFWs (Liu et al., 2016b), especially in the presence of biofilm carriers or floating plants (Li et al., 2010b; Liu et al., 2016b). Conventional CFWs were mainly applied in stagnant waterbodies, such as reservoir and artificial lakes, whereas hybrid CFWs were applied in rivers and drains (Tables 4 and 5). Interestingly, while the main application of conventional CFWs found in the English literature was stormwater quality improvement, no such application was found in the Chinese literature. This is likely due to the lack of a Chinese stormwater management policy.

Some studies found higher phytoplankton (Liu et al., 2016b; Zheng et al., 2013) and zooplankton biodiversity and increased densities (Zeng et al., 2016) in the presence of CFWs. However, the seasonal effect on phytoplankton and zooplankton community variations was stronger than the effect of CFWs (Liu et al., 2016b; Zheng et al., 2013). None of

Table 6
Potential consequences of climate change and future increased pollutant input on pollutant removal rates.

Trend	Effect on	Consequence	Removal rates	Pollutant affected
Temperature ↑	Air temperature ↑	Changes in plant growth, depending on their optimum growth range[1,2]	↑ or ↓ [2–5]	Pollutants that are directly taken up
		Longer period of plant growth	↑[2]	Pollutants that are directly taken up
	Water temperature ↑	Rates of abiotic and biotic (microbial) processes increase[6,7]	↑	All pollutants
		Higher evaporation rates increase salinity	↓[8]	Heavy metals
	Oxygen ↓	Anaerobic areas support denitrification	↑[9]	Nitrate
		Lower degradation rates of some pollutants[10,11]	↓	PPCPs, BOD/COD
		Increased mobilisation from sediment leads to a larger dissolved fraction that can be directly taken up by plants[12]	↑	Phosphorus, heavy metals
		Very low concentrations can limit nitrate uptake by some plants[4]	↓	Nitrate
Dry periods ↑	Water temperature ↑	Rates of abiotic and biotic (microbial) processes increase[6,7]	↑	All pollutants
	Amount of sunlight ↑	Increased plant growth and longer growth period[1,2]	↑	Pollutants that are directly taken up
	Water level ↓	Development of anaerobic zone below the CFW as roots reach bottom	↑	Nitrate
		Roots reach the bottom and act like a filter[13]	↑	Fine particles; dissolved pollutants
	HRT ↑	Increase in uptake rates[3]	↑	TP, TN, NH_4^+
	Salinity ↑	Heavy metals form chloride complex	↓[14]	Heavy metals
	pH↑	Changes speciation and thus availability to plants	↑↓[8]	Heavy metals, pesticides
	UV-B ↑	Reduced nitrate uptake by plants[15]	↓	Nitrate
	Stratification ↑	Development of a nutrients-rich lower layer that is disconnected from the upper layer hosting the rhizosphere[16]	↓[2,3,17]	Pollutants that are directly taken up
Rainfall intensity ↑	HRT ↓	More particles captured by higher flow within the rhizosphere[3]	↑	SS, particle bound pollutants
		Reduced treatment time[3]	↓	Pollutants that are directly taken up
	Water level ↑	Area with reduced turbulence between roots and sediment[13,18]	↑	Coarse SS
	Nutrients ↑ (input)	Higher concentrations can lead to higher removal rates[2,3,17]	↑	Nutrients
	Nutrients ↓ (flushing)	Lower concentrations can lead to lower removal rates[2,3,17]	↓	Nutrients
	Water temperature ↓	Rates of abiotic and biotic (microbial) processes decrease[6,7]	↓	All pollutants
		Nitrogen uptake decreases[15]	↓	Nitrate
	Stratification ↓	Turbulence transports dissolved nutrients from the lower layer to the layer hosting the rhizosphere[19,20]	↑	Pollutants that are directly taken up
	Pollutant ratio (particulate to dissolved)↑[21,22]	More particulate than soluble nutrient forms in water	↑	SS, particle bound pollutants
			↓	Pollutants that are directly taken up
Pollutant input ↑	Pollutant concentrations ↑	Higher pollutant concentrations lead to higher removal rates[2,3,17]	↑	All pollutants
		Toxic effects on plants and microbial community[13]	↓	All pollutants

References: 1, (Hu et al., 2010); 2, (Deng and Ni, 2013); 3, (Pavlineri et al., 2017); 4, (Bose and Srivastava, 2001); 5, (Van de Moortel et al., 2010); 6, (Price and Sowers, 2004); 7, (Bouletreau et al., 2012); 8, (Dhir et al., 2009); 9. (Uhrig, 2017); 10, (Ruhmland et al., 2015); 11, (Vymazal, 2011); 12,(Chorus and Bartram, 2000); 13, (Chen et al., 2016); 14, (De Lacerda et al., 2015); 15, (Tischner, 2000); 16, (Wilhelm and Adrian, 2010); 17, (Fox et al., 2008); 18, (Headley and Tanner, 2012); 19, (Fabbro and Duivenvoorden, 1996); 20, (Prepas and Charette, 2005); 21, (Budai and Clement, 2007); 22, (Gentry et al., 2007).

the publications studied the long-term effects of CFWs on the ecosystem.

5. Effects of climate change on constructed floating wetland efficiencies

Waterbody health will decline in the future due to climate change, population growth and land-use changes, leading to eutrophication and accelerated pollutant input. To secure the continuing delivery of ecosystem services by waterbodies it is important to develop sustainable remediation approaches (Costanza et al., 1997). In this space, CFWs are a promising tool to manage a number of pollutants successfully. However, the question remains how the success rate of CFWs will be affected by the coming changes.

The main changes in the future are an increase in temperature, changes in rainfall patterns, including longer dry periods, and higher pollutant input though land-use changes. The predicted increase in temperature and the linked changes in rainfall patterns (IPCC, 2007b) are expected to greatly impact physical and chemical processes within aquatic systems (Table 6) and their catchments (IPCC, 2007a; Reichwaldt and Ghadouani, 2012). These changes will affect ecosystem functioning (Reichwaldt et al., 2015; Wrona et al., 2006), aquatic biodiversity (Balint et al., 2011), microbial community composition (Daufresne et al., 2009) and will favour invasive species (Rahel and Olden, 2008) and the development of cyanobacterial blooms (Paerl and Huisman, 2009; Reichwaldt and Ghadouani, 2012). All of the above will affect removal efficiencies (Table 6).

With global warming, prolonged dry periods and extreme rainfall events are predicted to occur more often (Brunetti et al., 2004; Groisman et al., 2005; IPCC, 2007b). This will impact the waterbody and CFWs directly and indirectly. Higher air temperature will lead to longer plant growth periods and an increased water temperature, which in turn results in lower oxygen solubility in the water (Table 6). Extensive dry periods can further increase water temperature due to more sunshine and by decreasing the water level which increases the hydraulic residence time of flowing waterbodies. Longer dry periods can also lead to higher salinity due to evaporation, changes in the pH due to higher phytoplankton productivity and a more stable stratification due to calmer weather patterns (Table 6). In contrast, high-intensity rainfall events will lead to opposite effects, such as higher water levels, lower hydraulic residence time as water is rushed through the system, lower water temperature and a decrease in water column stability. Strong rainfall events will increase nutrients concentrations through transport from the catchment (Chorus and Bartram, 2000), but in the short term these events might be responsible for lower dissolved pollutant concentrations due to dilution and flushing (Reichwaldt and Ghadouani, 2012) (Table 6).

Pollutant removal efficiencies by CFWs are a function of the complex interactions between the organisms and the physical and chemical conditions. Therefore, it is hard to quantitatively evaluate how future

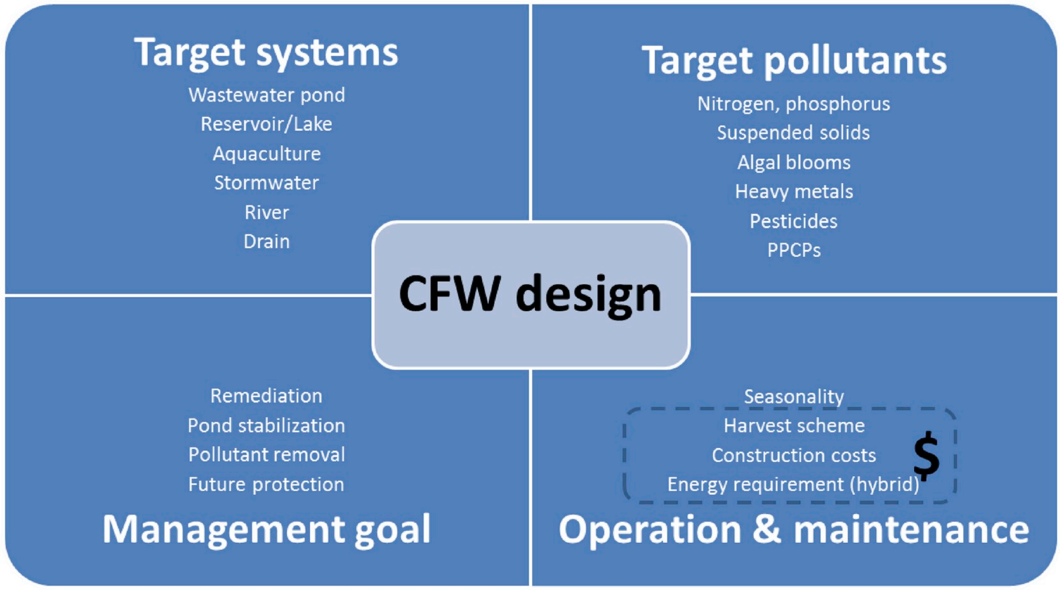

Fig. 5. Framework for CFW design.

changes will affect the removal efficiencies. In the following, we therefore limit ourselves to identifying trends on how future changes in the climate and pollutant level might affect removal efficiencies.

Many of the conditions prevalent under future climate scenarios seem to have a positive effect on the removal efficiencies achieved by CFWs (Table 6). Probably the most important change that will positively affect the removal efficiency is a higher temperature. This will increase pollutant uptake by macrophytes fuelled by their faster growth, and pollutant break-down due to higher microbial metabolism rates (Bouletreau et al., 2012; Price and Sowers, 2004). While lower oxygen concentrations can lead to lower degradation rates of PPCPs, BOD and COD, and in extreme cases limit nitrate uptake by plants, it might stimulate denitrification (Table 6) which will break up the nitrogen cycle in the system. Turbulence and de-stratification caused by wind during rainfall events will resuspend dissolved and particulate pollutants from the sediment into the water column. The subsequent uptake of the dissolved forms (e.g., nutrients, heavy metals) through the roots will eventually increase the complete removal of these nutrients from the waterbody once the plants are removed.

Many waterbodies to be remediated by CFWs are shallow and well mixed. With higher air temperatures and higher incident solar radiation levels such waterbodies are prone to develop stable stratification so that wind-induced turbulence might be essential to avoid accumulation of pollutants within the sediment.

Heavy rainfall events can lead to massive erosion resulting in very high TSS input, especially into artificial waterbodies (Chorus and Bartram, 2000), which are often the target of remediation by CFWs. The nutrients added during high intensity events will be biased towards particulate rather than soluble nutrient forms (Budai and Clement, 2007; Gentry et al., 2007). Compared to soluble nutrients, particulate nutrients cannot be directly used by the plants, but settle out and accumulate in the sediment. The requirement to remove such pollutants from the sediment highlights again the importance of regular resuspension of the sediment, especially under future scenarios of increased particle input.

Due to changes in the rainfall pattern, CFWs will have to be able to cope with fluctuations of pollutant pulses more than today. Their floating design makes CFWs very suitable to cope with water level fluctuations (Tanner and Headley, 2008). In addition, their biological complexity may also make them resilient to large physical and chemical fluctuations (McCann, 2000); however, the extent of this has yet to be investigated.

6. Framework for the design of constructed floating wetlands

We here develop a framework for CFW design with the aim to support successful water resource management plans for polluted waterbodies (Fig. 5). The framework is based on the facts presented in previous sections of this review.

The design of a CFW will depend on the target system, the pollutants and on the management goal. Considering local climate and seasonality will help to choose suitable plants and will allow fine-tuning the design. In practice, the budget for land purchase, construction, operation and maintenance is often limiting the design.

Large stagnant waterbodies with relatively low concentrations of pollutants, such as reservoirs, can suffer from sudden input of pollutant loads during storms. Here, CFWs can be used to stabilise the waterbody against these fluctuations and choosing a conventional design with local, perennial plant species is often sufficient (Garbett, 2005). In contrasts, stagnant waterbodies that have constant high pollution levels, such as lakes or wastewater ponds, require a more complex design, such as hybrid CFWs, as they have higher removal efficiencies (Sheng et al., 2013). In this case, mixing of the water column and oxygenation through aeration is advantageous to support pollutant removal. The addition of artificial biofilm carriers will further increase removal rates. In rivers and drains, where contact times with pollutants are shorter and particles float longer than in stagnant waterbodies, a large contact surface can counteract the shorter contact time (Tanner and Headley, 2011). Therefore, choosing plants with a large rhizosphere and fine roots or adding artificial biofilm carriers will improve removal rates.

Native plants generally perform better than non-natives and, in addition, they do not pose a risk of becoming invasive if escaping from the CFWs. Many floating plants have a high capacity for phosphorus uptake and can therefore be considered in addition to CFWs under high phosphorus loading (e.g. *Lemna minor/gibba, Azolla filiculoides*) (Alnozaily et al., 2000; Peeters et al., 2016). A bonus here is that floating plants can be harvested more easily than the macrophytes.

Good management practise strives to achieve multiple aims, such as maintaining good water quality, encouraging biodiversity, producing food and improving aesthetics. CFWs can be used to achieve all of them. While the main purpose of CFWs is to remove pollutants, they also provide habitat for aquatic and terrestrial fauna (Nakamura et al., 1998; Strosnider et al., 2017) and increase the recreational value by improved aesthetics. Using CFWs for production of vegetables for human production (e.g., pumpkins, eggplants, tomatoes) (Irfanullah et al., 2011; Zhang et al., 2008) might be one solution to lessen the food crisis in developing countries. In this case, it is important to ensure that the food meets the food safety requirements (Zhao et al., 2012). If the plant material is contaminated with heavy metals or organic pollutants, it should be disposed properly (e.g., ashing) (Ernst, 2005; Pilon-Smits, 2005).

Lastly, developing an effective operation and maintenance plan is critical for the wetland's long-lasting success. Macrophytes must be harvested regularly to avoid pollutant return into the waterbody when plants die-off. If safe, the plants can be used as animal fodder, otherwise ashing or disposing them is advised (Ernst, 2005; Pilon-Smits, 2005). In addition, CFWs are biological systems and their performance varies significantly with changes in temperature and seasonality. In climates with distinct seasons, hybrid systems using aeration and artificial biofilm carriers are superior, because they maintain some biological activity even during low temperature when macrophytes are dormant.

7. Conclusion

Embracing their capability to self-design, constructed floating wetlands have successfully been used to restore disturbed waterbodies. To achieve the best outcome, their design has to be adapted to local conditions, including the degree of disturbance and the nature of the waterbody. While hybrid CFWs tend to be slightly more efficient, their higher costs and maintenance requirements will limit their application, particularly in developing countries, where environmental projects often have limited resources.

This review highlights the critical need to assess in situ studies in terms of their stability and performance reliability under ever changing conditions. This is especially true for information on the reduction of heavy metals, herbicides, pesticides and pharmaceutical and personal care products. In addition, long-term studies that include a holistic assessment of ecosystem changes are rare. There is evidence that CFWs can result in more diverse and healthier ecosystems, mainly through habitat provision and better water quality. Such studies are also critical to enable the estimation of CFW's ecosystem service value.

Finally, while there is evidence that CFWs might be able to cope well and even increase their success rate under future climate change and eutrophication scenarios, there are many unknowns. The large knowledge gaps with respect to their functioning does not allow us to estimate current and even less future success rates reliably. Therefore, we call for more experimental studies to increase our understanding of how this technology will adapt to future changes.

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Appendix A. Supplementary data

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