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REVIEW ARTICLE

The effects of different aeration strategies on the performance of constructed wetlands for phosphorus removal

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Abstract

The effects of different aeration methods such as tidal flow (TF), effluent recirculation (ER), and artificial aeration (AA) on the performance of vertical-flow constructed wetland (VFCW), horizontal-flow constructed wetland (HFCW), and hybrid constructed wetland (HCW) are extensively and critically evaluated in this review paper. Aerated constructed wetlands (CWs) demonstrate superior performance compared with non-aerated systems. The removal of total phosphorus (TP) showed substantial variation among different types of CWs and aeration strategies, with mean and standard deviation of 68 ± 20% estimated from all reviewed studies on aerated systems. The TF-VFCW designated the highest removal efficiency and removal rate of 88 ± 6% and 2.6 ± 2.5 g m^{-2} day^{-1}, respectively, followed by the ER-HCW with values of 79 ± 18% and 1.3 ± 0.7 g m^{-2} day^{-1}, respectively. The superior performance of TF-VFCW could be attributed to a positive effect of TF in rejuvenating the wetland with fresh air, thus enhancing dissolved oxygen (DO) in the system, and augmenting phosphorus precipitation and adsorption to the substrate. A positive correlation of TP and orthophosphate (PO_4^{3-}-P) with DO indicates that the improvement in DO levels due to redox manipulation with aeration strategies facilitates the phosphorous removal processes (e.g., through precipitation and adsorption to the substrate). The conflicting results on the impact of AA and ER reported by many studies need the cautious interpretation of their impact and require further studies. Only few studies have examined the impact of oxidation-reduction potential on phosphorous removal, which requires more attention in future research, as it appears as an important factor in enhancing the phosphorus removal.

Keywords Constructed wetlands · Dissolved oxygen · Orthophosphate · Oxidation-reduction potential · Total phosphorus · Wastewater

Introduction

Eutrophication is a huge problem of surface water such as streams, lakes, and reservoirs. It is generally considered that nitrogen and phosphorus are the main causes of this problem, but the impact of phosphorus is proved more significant (Liu et al. 2010 cited in Wang et al. 2013). Concentration of phosphorus as low as 100 μg L^{-1} is still sufficient to cause eutrophication (Bitton et al. 1974). Therefore, for many years, its removal has been studied by various technologies and/or methods including constructed wetlands (CWs). Two designs of CWs are widely used: free water surface flow constructed wetland (FWSCW) and subsurface flow constructed wetland (SSFCW). Among the SSFCW, two types exist: vertical-flow constructed wetland (VFCW) and horizontal-flow constructed wetland (HFCW). The performance and pollutant removal mechanisms of all types of CWs are different (Kadlec and Wallace 2009). Due to the limitations of FWSCW, HFCW, and VFCW, the idea of hybrid constructed wetland (HCW), the combination of VFCW and HFCW, one next to the other was developed to produce good-quality effluent (Cooper et al. 1999). Although properly designed HCW is capable of removing nitrogen up to a high level, phosphorus removal is yet not sufficient (Babatunde et al. 2010).

The major processes responsible for phosphorus removal in CWs are adsorption on the substrate media, chemical precipitation, and assimilation into microbial and plant biomass

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(Fig. 1) (Howard-Williams 1985; Drizo et al. 1997; Lantzke et al. 1999; Tanner et al. 1999; Arias et al. 2001). A theoretical hierarchy of the processes is as follows: soil adsorption (low to moderate magnitude, moderate rate), chemical precipitation (moderate magnitude, fast rate), plant uptake (low to moderate magnitude, slow rate), and microbial uptake (very low magnitude, very fast rate) (Richardson and Craft 1993; Richardson et al. 1997; Richardson 1999). The previous studies suggest that in all types of CWs, the removal of total phosphorus (TP) varied between 40 and 60% with removed load ranging between 45 and 75 g P m^{-2} $year^{-1}$ depending on CW types and inflow loading (Vymazal 2007).

Several studies reported a significant difference in TP removal between planted and unplanted systems ($P < 0.05$) (e.g., Akratos and Tsihrintzis 2007; Zhang et al. 2010). For instance, Akratos and Tsihrintzis (2007) found that planted beds had 40% higher removal of TP compared with unplanted beds. Tao et al. (2010) found that the removal of TP was higher in plant growth season but lower during plant dormancy, which indicated that plants played an important role in TP removal by ways of plant uptake, promoting microbial assimilation process and substrate absorption. The removal of phosphorus with macrophytes and its associated micro-organisms was also observed (Korner and Vermaat 1998; Mander et al. 2003). According to Korner and Vermaat (1998), the biological floating mat complex (plants and microbes) was responsible for the removal of phosphorus up to 75%. The uptake of phosphorus by the macrophytes was up to 52%, and the associated organisms and micro-organisms removed the rest. However, Mander et al. (2003) found that the removal of phosphorus by plants and micro-organisms was up to 6.1 and 4.4%, respectively. Analogous to that, several other studies indicated that the amount of phosphorus removed when harvesting the plants is very little compared with the amount of phosphorus introduced in the raw wastewater (Brix 1994 and 1997; Arias et al. 2001). The removal of phosphorus via harvesting of aboveground biomass of emergent vegetation is low (10–20 g P m^{-2} $year^{-1}$), but for lightly loaded systems, it could be significant (Vymazal 2007). According to Gerrites (1993), phosphorus may also be bound to the media of CWs because of adsorption and precipitation reactions with calcium (Ca^{2+}), aluminum (Al^{3+}), and ferric iron (Fe^{3+}) in the sand or gravel. As precipitation and/or adsorption of phosphorus by substrate in CWs are limited processes, therefore, after the saturation of the material, it has to be either replaced or washed. Therefore, phosphorus adsorption capacity of a material is considered central parameter while selecting materials for phosphorus removal media in CWs (Kadlec and Knight 1996; Johansson 1999).

The most efficient and cost-effective solution for CWs is the use of a filter media with high adsorption capacity and high content of the cations that are able to precipitate phosphorus, for example, magnesium (Mg^{2+}), Ca^{2+}, Fe^{3+}, ferrous iron (Fe^{2+}), and Al^{3+} (Rittmann et al. 2011). The media texture and grain size distribution should also be considered to increase the surface area and consequently the adsorption sites, which will help to provide adequate hydraulic conductivity and reduce the risk of clogging (Arias et al. 2001; García et al. 2010). A large number of media materials can be classified into natural materials (e.g., apatite, bauxite, dolomite, gravel, zeolite, laterite, limestone, sand, opoka, peat, and shale), industrial by-products (e.g., bauxsol, burnt oil shale, coal fly ash, ochre, red mud, and slag), and man-made products (e.g., alunite, filter P, filtralite, light weight aggregates, norlite, oyster shell, and polonite). Many of them have been tested as substrate in CWs. Among various industrial by-products, the highest phosphorus removal capacities stated for some furnace slags are up to 420 g P kg^{-1}. The natural materials have been reported for maximum removal capacities of about 40 g P kg^{-1} for heated opoka, and man-made media materials have been reported for highest removal capacities of about 12 g P kg^{-1} for filtralite (Vohla et al. 2011).

Although much development has taken place within CWs to enhance the efficiency of the system, phosphorus removal up to the level to avoid eutrophication has not been achieved. An extensive research indicated that substrate of high adsorption capacity enhances the removal of phosphorus in CWs. The profound knowledge published in international journals and books on enhanced treatment performance of CWs with different substrates has increased spectacularly in recent years.

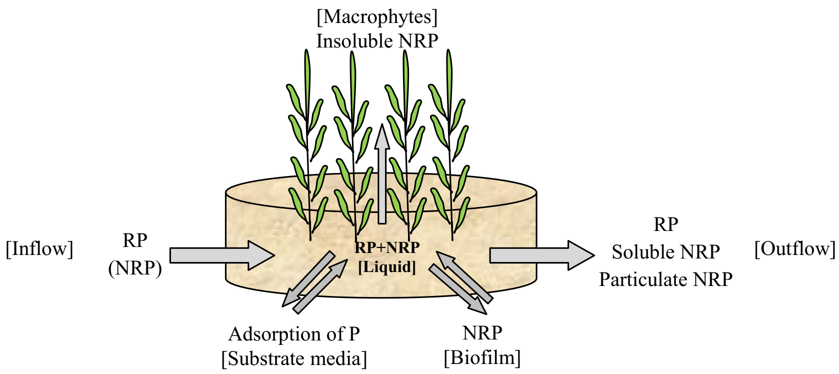


Fig. 1 Active components, phosphorus forms, and removal pathways in planted CWs. P phosphorus, RP reactive phosphorus, NRP non-reactive phosphorus (Adopted from Lantzke et al. 1999)

The enhanced performance of CWs using different substrates for phosphorus removal was reviewed in Vohla et al. (2011). The aim of the paper was to provide and inspire some new ideas in the development of CWs mainly with different substrates for the removal of phosphorus.

Despite the general perception that phosphorus removal is mainly by adsorption on substrate media, chemical precipitation, uptake by the plants, and assimilation into microbial biomass, Vymazal (2011) mentioned that the transformations of phosphorus in CWs are controlled by the interactions of oxidation-reduction potential (ORP). Vohla et al. (2007) reported that TP concentration in water is negatively correlated with ORP. It is revealed that aerobic conditions and ORP are related to each other (Kantawanichkul and Somprasert 2005; Foladori et al. 2013; Wu et al. 2015b; Zhong et al. 2015; Sochacki and Miksch 2016). Thus, redox manipulation with aeration strategies might be responsible for the removal of phosphorus (Zhong et al. 2015) because improvement in dissolved oxygen (DO) level might accelerate phosphorus precipitation and adsorption to the substrate (De-Bashan and Bashan 2004; Zhang et al. 2010). Therefore, ORP is the essential parameter in evaluation of oxic/anoxic conditions in CWs and DO is considered one of the most important factors for phosphorus removal in CWs.

However, the enhanced performance of intensified CWs for phosphorus removal is still not sufficiently synthesized. The optimization of DO in VFCW, HFCW, and HCW with different aeration strategies such as tidal flow (TF), effluent recirculation (ER), and artificial aeration (AA) is summarized in this paper. The effects of these strategies on treatment performance of different types of CWs are extensively and critically evaluated for orthophosphate (PO_4^{3-}-P) and TP removal.

Methodology

The relevant literature, such as journal articles, books, reports, and conference proceedings, was accumulated from various sources, mainly using Scopus, Google Scholar, and individual journal websites. The search resulted in accumulation of over 70 documents, which were further screened and used for the purpose of this research. Considering the objective of this review paper, the treatment performance of all types of CWs such as VFCW, HFCW, and HCW was evaluated. Different parameters such as treatment scale, wastewater type, depth, area, hydraulic loading rate (HLR), hydraulic retention time (HRT), experiment duration, system age, organic loading rate (OLR), filter media, DO, fill and drain time ratio, recirculation flow ratio (RFR), air flow rate (AFR), PO_4^{3-}-P, and TP were considered for the comparison of different aeration strategies. These parameters were accumulated from the reviewed studies or estimated using the given information in those studies. Moreover, statistical analysis (descriptive statistics, correlation, and regression analyses) was conducted for a few indicators for which adequate data were available.

Results and discussion

The comparison of non-aerated and aerated CWs (VFCW, HFCW, and HCW) with different aeration strategies (TF, ER, and AA) for PO_4^{3-}-P and TP removal is made in this section. Additionally, the factors influencing the removal efficiencies of the studied parameters are also discussed.

Performance of non-aerated CWs

Different studies clearly revealed that in non-aerated CWs, the level of DO was very low in VFCW (0.12–1.3 mg L^{-1}) and HFCW (0.17–2.6 mg L^{-1}) (Table 1). In VFCW, the removal of TP was 29–74% (Lian-sheng et al. 2006; Tao et al. 2010; Dong et al. 2012; Foladori et al. 2013; Fan et al. 2013; Wu et al. 2015a; Wang et al. 2015) (Table 1). In HFCW, the removal of TP was 10–85% (Ciria et al. 2005; Ham et al. 2007; Sirianuntapiboon and Jitvimolnimit 2007; Konnerup et al. 2009; Stefanakis and Tsihrintzis 2009; Zhang et al. 2010; El-Khateeb and El-Bahrawy 2013; dos Santos et al. 2013) (Table 1).

In HCW, the removal of TP was 27–76% (Travis et al. 2012; Foladori et al. 2012; Zapater-Pereyra et al. 2015). In HCW, which was the combination of VFCW on top of the horizontal flow filter (HFF) arranged in a stack design for the treatment of low strength wastewater, the contribution of both compartments was different. The total removal of TP was 76% by HCW, HFF contributed to the 48% removal, and the rest of the 28% was removed by VFCW (Zapater-Pereyra et al. 2015) (Table 1).

The removal of PO_4^{3-}-P is not investigated by VFCW in the reported studies. However, based on very limited number of studies, the removal of PO_4^{3-}-P was 53–85% by HFCW (Stefanakis and Tsihrintzis 2009; Zhong et al. 2015) and 59% by HCW (Sochacki and Miksch 2016) (Table 1).

Influence of aeration strategies

Different aeration strategies are applied on all types of CWs to overcome the oxygen transfer limitation including TF (Sun et al. 2006), ER (Lian-sheng et al. 2006), and AA (Zhong et al. 2015). The influence of different aeration methods on PO_4^{3-}-P and TP removal in the reported studies is summarized in this section.

Tidal flow constructed wetland

This operation strategy is expected to enhance the performance of CWs because in TFCW, the filling and draining of

Table 1 The performance of non-aerated VFCW, HFCW, and HCW

Wetland type/scale	WT	Depth (m)	Area (m^2 PE^{-1})	HLR (m^3 m^{-2} day^{-1})	OLR (g COD m^{-2} day^{-1})	HRT (days)/SA/ED (months)	Filter media (mm)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/Rem (%)	TP Rem rate (g m^{-2} day^{-1}) Rem (%)	Author
VFCW												
Pilot	P	1.0	1.0	0.08	133	0.25/13.5/12	30-cm fine zeolite (5–8) 40-cm cinder (12–20)	0.8	30/17.5	NA/NA	0.9/42	Lian-sheng et al. (2006)
Lab	D	0.7	5.7	0.2	48	1.0/15/12	55- and 45-cm sand (< 4) 15-cm gravel (5–8)	0.6	2.3/0.6	NA/NA	0.34/74	Tao et al. (2010)
Lab	R	0.8	9.9	0.19	12	2.0/5.0/1.0	50-cm gravel (7–15) 10-cm gravel (18–32)	1.3	3.9/2.7	NA/NA	0.23/31	Dong et al. (2012)
Pilot	D	0.8	3.6	0.07	32	NA/32/8.0	5-cm gravel (7–15) 50-cm sand (1–3) 5-cm gravel (7–15) 20-cm gravel (15–30)	NA	8.4/6.0	NA/NA	0.17/29	Foladori et al. (2013)
Lab	S	0.65	4.0	0.07	30	3.0/6.0/5.0	15-cm sand (< 2) 15-cm gravel (10–20) 25-cm gravel (10–30) 10-cm gravel (40–50)	0.6	3.9/1.8	NA/NA	0.15/55	Fan et al. (2013)
Lab	S	0.65	9.7	0.01	12	3.0/6.0/4.0	As above	0.12	7.9/3.8	NA/NA	0.05/52	Wu et al. (2015a)
Lab	S	0.5	NA	NA	NA	1.5/6.0/4.5	5-cm sand (1–5) 5-cm gravel (5–10) 25-cm lava (10–35) 10-cm gravel (35–50)	< 0.5	0.7/0.24	NA/NA	NA/66	Wang et al. (2015)
HFCW												
Pilot	RS	1.0	3.5	0.05	27	4.7/20/18	40-cm gravel (5–10)	NA	23/14	NA/NA	0.45/39	Ciria et al. (2005)
Pilot	RS	1.0	2.5	0.05	37	4.7/20/18	40-cm gravel (5–10)	NA	29/26	NA/NA	0.15/11	Ciria et al. (2005)
Pilot	AnE	1.0	8.2	0.063	15	3.5/NA/NA	100-cm sand (1–2)	2.4	13/7.1	NA/NA	0.37/44	Ham et al. (2007)
Lab	RS	0.82	6.6	0.086	7.9	6.0/NA/3.0	70-cm gravel (7.3)	NA	5.0/0.7	NA/NA	0.37/85	Sirianuntapiboon and Jitvimolnimit (2007)
Lab	RS	0.82	3.4	0.17	15	3.0/NA/3.0	70-cm gravel (7.3)	NA	5.0/1.1	NA/NA	0.66/77	Sirianuntapiboon and Jitvimolnimit (2007)
Lab	RS	0.82	1.7	0.34	32	1.5/NA/3.0	70-cm gravel (7.3)	NA	5.0/2.3	NA/NA	0.92/53	Sirianuntapiboon and Jitvimolnimit (2007)
Pilot	D	1.0	16	0.055	7.0	4.0/NA/2.0	40-cm gravel (10–25) 20-cm gravel (2–10)	NA	7.1/NA 9.8/6.4	NA/NA	0.19/35	Konnerup et al. (2009)
Pilot	D	1.0	8.0	0.11	15	2.0/NA/2.0	As above	NA	6.6/NA 9.2/7.1	NA/NA	0.23/23	Konnerup et al. (2009)
Pilot	D	1.0	4.4	0.22	27	1.0/NA/2.0	As above	NA	6.0/NA 8.5/7.5	NA/NA	0.22/12	Konnerup et al. (2009)
Pilot	S	1.0	12	0.01	8.0	6.0/36/24	45-cm fine gravel (0.25–16)	1.47	8.4/1.3 9.2/2.1	0.08/85	0.08/77	Stefanakis and Tsihrintzis (2009)
Pilot	D	1.0	3.4	0.06	35	NA/NA/12	120-cm limestone (8–16)	0.2	8.4/1.3	NA/NA	0.44/85	Zhang et al. (2010)
Lab	AnE	1.0	6.8	0.073	14	3.0/NA/12	60-cm pea gravel (2–4)	NA	4.5/3.0	NA/NA	0.11/33	El-Khateeb and EL-Bahrawy (2013)

Table 1 (continued)

Wetland type/scale	WT	Depth (m)	Area (m^2 PE^{-1})	HLR (m^3 m^{-2} day^{-1})	OLR (g COD m^{-2} day^{-1})	HRT (days)/SA/ED (months)	Filter media (mm)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/Rem (%)	TP Rem rate (g m^{-2} day^{-1}) Rem (%)	Author
Pilot	SPE	0.65	3.0	0.26	69	6.0/NA/5.0	40-cm gravel (15–20) 10-cm sand (1–2)	2.6	14/13	NA/NA	0.36/10	dos Santos et al. (2013)
Lab	D	0.7	11	0.10	11	1.0/20/15	65-cm ceramsite (3–8)	0.17	3.6/1.6	0.2/53	NA/NA	Zhong et al. (2015)
HCW												
Pilot$^{(V+V)}$	O	0.6/0.4	1.8	0.04	110	0.3/NA/12	30-cm sand (0.4) 15-cm gravel (10) 15-cm gravel (30) 40-cm bioballs	NA	91/37	NA/NA	2.2/59	Travis et al. (2012)
Pilot$^{(V+H)}$	D	0.6/0.6	2.6	0.06	43	NA/NA/2.0	[30-cm fine gravel (1–6), 10-cm gravel (7–15), 20-cm gravel (15–30)]^v, [50-cm gravel (15–30), (3–7), and (15–30)]^h	NA	9.6/3.5	NA/NA	0.37/64	Foladori et al. (2012)
Lab $^{(V+H)}$	D	0.8/0.35	7.9	0.046	15	$[0.06]^V$, $[3.0–4.0]^H$/6.9-/1.0	[70-cm sand (1–2), 10-cm gravel (15–30)]^v, [35-cm sand (1–2)]^h	NA	9.0/2.2	NA/NA	0.31/76	Zapater-Pereyra et al. (2015)
Lab $^{(V+H)}$	D	0.8/0.35	3.4	0.046	27	$[0.06]^V$, $[3.0–4.0]^H$/6.9-/1.0	[70-cm sand (1–2), 10-cm gravel (15–30)]^v, [35-cm sand (1–2)]^h	NA	9.0/5.5	NA/NA	0.16/39	Zapater-Pereyra et al. (2015)
Lab $^{(V+H)}$	D	0.8/0.35	2.6	0.046	37	$[0.06]^V$, $[3.0–4.0]^H$/6.9-/1.0	[70-cm sand (1–2), 10-cm gravel (15–30)]^v, [35-cm sand (1–2)]^h	NA	9.0/6.6	NA/NA	0.11/27	Zapater-Pereyra et al. (2015)
Lab$^{(V+FEM)}$	D	0.8/0.45	1.9	0.08	63	7.0/12.6/1.8	65-cm sand (0.5–1), 15-cm gravel (4–8)	NA	21/8.2	1.0/59	NA/NA	Sochacki and Miksch (2016)

The population equivalent (PE) is calculated based on the common relation 1 PE = 60 g BOD day^{-1} . BOD values were approximated using the ratio COD/BOD = 2 in the studies where BOD was not reported (Konnerup et al. 2009; Foladori et al. 2012; Fan et al. 2013; Wu et al. 2015a; Zhong et al. 2015; Zapater-Pereyra et al. 2015; Sochacki and Miksch 2016)

VFCW vertical-flow constructed wetland, *HFCW* horizontal-flow constructed wetland, *HCW* hybrid constructed wetland, *WT* wastewater type, *P* piggery, *D* domestic, *R* river, *S* synthetic, *RS* raw sewage, *AnE* anaerobic effluent, *SPE* stabilization pond effluent, *O* oil-rich, *HLR* hydraulic loading rate, *OLR* organic loading rate, *COD* chemical oxygen demand, *HRT* hydraulic retention time, *SA* system age, *ED* experiment duration, *DO* dissolved oxygen (DO), PO_4^{3-} *-P* orthophosphate, *TP* total phosphorus, *NA* not available, *V+V* VFCW and VFCW connected in series, *V+H* VFCW over horizontal flow filter, *V+FEM* VFCW and floating emergent macrophyte CW connected in series

Table 2 Comparison of studies using TF in VFCW, HFCW, and HCW

Wetland type/scale	WT	Depth (m)	Area (m^2 PE^{-1})	HLR (m^3 m^{-2} day^{-1})	OLR (g COD m^{-2} day^{-1})	HRT (days)/SA/ED (months)	Filter media (mm)	OM
VFCW								
Pilot	P	0.6–1.0	0.25	0.12	330	NA/NA/2.0	Gravel (6–60)/(1.7–60)	IF
Lab	S	0.65	3.3	0.10	36	3.0/6.0/4.0	15-cm sand, 40-cm gravel (10–30), 5-cm gravel (40–50)	IF
Lab	S	0.65	3.3	0.10	36	3.0/6.0/4.0	As above	IF
Lab	S	0.65	3.3	0.10	36	3.0/6.0/4.0	As above	CF
Pilot	AF	1.1	5.0	0.29	118	1.0/NA/10	10-cm gravel (20), 65-cm alum sludge, 10-cm gravel (10)	IF
Pilot	AF	1.1	0.3	0.29	376	1.0/NA/10	As above	IF
Lab $^{(D/U)}$	P	0.7	2.2	0.44	88	1.58/5.4/3.1	60-cm alum sludge, 5-cm gravel (10–30), 5-cm gravel (5–10)	IF
Lab $^{(D/U)}$	P	0.7	0.6	0.44	264	1.58/5.4/2.3	As above	IF
HFCW								
Pilot	S	0.6	14	0.03	8.4	2.0/NA/NA	30-cm gravel (4–10)	IF
Pilot	S	0.6	14	0.03	8.4	2.0/NA/NA	30-cm gravel (4–10)	CF
Pilot	S	0.6	14	0.03	8.4	4.0/NA/NA	30-cm gravel (4–10)	IF
Pilot	S	0.6	14	0.03	8.4	4.0/NA/NA	30-cm gravel (4–10)	CF
HCW								
Lab $^{(V+H)}$	D	0.8/0.35	7.9	0.046	15	$[1.0]^V$, $[3–4]^H$/6.9/1.0	[70-cm sand (1–2), 10-cm gravel (15–30)]^v, [35-cm sand (1–2)]^h	IF
Lab $^{(V+H)}$	D	0.8/0.35	3.4	0.046	27	$[1.0]^V$, $[3–4]^H$/6.9/1.0	As above	IF
Lab $^{(V+H)}$	D	0.8/0.35	2.6	0.046	37	$[1.0]^V$, $[3–4]^H$/6.9/1.0	As above	IF

Wetland type/scale	Fill and drain time ratio (h/h)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/Rem (%)	TP Rem rate (g m^{-2} day^{-1})/Rem (%)	Author
VFCW						
Pilot	NA	NA	73/40	4.0/45	NA/NA	Sun et al. (2006)
Lab	1:2	6.96	4.2/0.34	NA/NA	0.39/92	Jia et al. (2010)
Lab	2:1	6.87	4.2/0.33	NA/NA	0.39/92	Jia et al. (2010)
Lab	3:0	5.28	4.2/0.53	NA/NA	0.37/88	Jia et al. (2010)
Pilot	4:4	NA	8.6/0.3, 11/0.7	2.4/97	3.0/94	Zhao et al. (2011)
Pilot	4:4	NA	33/9.0, 33/8.0	7.0/73	7.3/75	Zhao et al. (2011)
Lab $^{(D/U)}$	1:1	2.0–4.7	7.3/0.7, 8.2/0.9	2.9/90	3.2/88	Hu et al. (2014)
Lab $^{(D/U)}$	1:1	1.0	7.9/0.8, 8.9/0.9	3.1/89	3.5/88	Hu et al. (2014)
HFCW						
Pilot	NA	NA	NA/8.7	NA/NA	NA/61	Zhang et al. (2012)
Pilot	NA	NA	NA/15	NA/NA	NA/31	Zhang et al. (2012)
Pilot	NA	NA	NA/7.2	NA/NA	NA/67	Zhang et al. (2012)
Pilot	NA	NA	NA/12.5	NA/NA	NA/43	Zhang et al. (2012)

Table 2 (continued)

Wetland type/scale	Fill and drain time ratio (h/h)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/Rem (%)	TP Rem rate (g m^{-2} day^{-1})/Rem (%)	Author
HCW						
Lab $^{(V+H)}$	1:2	2.5	9.0/1.8	NA/NA	0.33/80	Zapater-Pereyra et al. (2015)
Lab $^{(V+H)}$	1:2	2.5	9.0/3.5	NA/NA	0.25/61	Zapater-Pereyra et al. (2015)
Lab $^{(V+H)}$	1:2	2.5	9.0/5.0	NA/NA	0.18/44	Zapater-Pereyra et al. (2015)

The population equivalent (PE) is calculated based on the common relation 1 PE = 60 g BOD day^{-1} . BOD values were approximated using the ratio COD/BOD = 2 in the studies where BOD was not reported (Jia et al. 2010; Zhang et al. 2012; Zapater-Pereyra et al. 2015). Fill and drain time ratio is given in days (Jia et al. 2010; Zapater-Pereyra et al. 2015). HLR and OLR are referred for the whole cycle of the tidal flow systems

TF tidal flow, *VFCW* vertical flow constructed wetland, *HFCW* horizontal flow constructed wetland, *HCW* hybrid constructed wetland, *WT* wastewater type, *P* piggery, *S* synthetic, *AF* animal farm, *D* domestic, *HLR* hydraulic loading rate, *OLR* organic loading rate, *COD* chemical oxygen demand, *HRT* hydraulic retention time, *SA* system age, *ED* experiment duration, *OM* operation mode, *IF* intermittent flood, *CF* continuous flood, *h* hour, *DO* dissolved oxygen, PO_4^{3-}*-P* orthophosphate, *TP* total phosphorus, *NA* not available, *D* VFCW downflow, *U* VFCW upflow, *V+H* VFCW over horizontal flow

the wastewater result in increasing the entrance of fresh air into the system (Green et al. 1997). Later, this approach has been verified in several studies (Table 2).

Influence of operation mode in TFCW Different studies revealed that in TFCW, the removal of phosphorus was independent of the operational strategies, intermittent flood (IF) and continuous flood (CF) of the system. In VFCW, the removal of phosphorus was attributed to the adsorption of phosphorus on substrate media, uptake by the reeds, and chemical precipitations (Sun et al. 2006) (Table 2). The removal of phosphorus was also attributed to the adsorption of phosphorus on substrate media, and chemical precipitations in the studies that used alum sludge as a filter media along with TF to enhance the treatment efficiency of the system (Zhao et al. 2011; Hu et al. 2014) (Table 2).

In some studies, the effect of operational mode (IF and CF) on enhancing the performance of TFCW for phosphorus removal was observed. For instance, Jia et al. (2010) in VFCW and Zhang et al. (2012) in HFCW (Table 2) observed the possible saturation of filter media with CF and, thus, decreasing the sorption capacity. The change of physicochemical and oxidation conditions influenced the removal of TP.

In HCW with TF, the enhanced removal of TP was observed even for the treatment of medium-strength wastewater. In HCW (combination of VFCW on top of HFF), the total removal of TP was 61%, the VFCW contributed to the 50% removal of TP, and the rest of the 11% was removed by HFF. The removal of TP was increased from 39% without TF (Table 1) to 61% with TF (Table 2). The additional 22% removal with TF might be due to redox manipulation with TF. The duration of the experiment and age of the system were 1.0 and 6.9 months in both conditions (Zapater-Pereyra et al. 2015) (Tables 1 and 2).

In general, TF-VFCW resulted in the highest performance, whereas TF-HFCW showed the least removal efficiency.

Effluent recirculation

In ER, a fraction of effluent is transferred back to the inflow of the system for the purpose of increasing the aerobic microbial activity through the intense interaction between pollutants and micro-organism without major modifications in the system operation. This approach has been proposed by many researchers as an operational alteration to improve the effluent quality of CWs (Table 3). ER with a ratio of 0.5 to 2.5 was mostly applied in VFCW and HFCW (Wu et al. 2014).

Influence of ER Various studies give contradictory information regarding the removal of phosphorus by CWs with ER. This might be due to the different types of CWs investigated in these studies. In VFCW and HFCW, the flow patterns are different. In HCW, the contribution of more than one stage

Table 3 Comparison of studies using ER in VFCW, HFCW, and HCW

Wetland type/scale	WT	Depth (m)	Area (m^2 PE^{-1})	HLR (m^3 m^{-2} day^{-1})	OLR (g COD m^{-2} day^{-1})	HRT (days)/SA/ED (months)	Filter media (mm)
VFCW							
Pilot	P	1.0	1.6	0.06	86	NA/16/4.0	10-cm fine gravel (1.7–3.4), 40-cm pea gravel (6), 10-cm round gravel (12), 40-cm round stone (30–60)
Pilot	P	1.0	1.0	0.08	133	0.25/13.5/1.5	30-cm fine zeolite (5–8), 40-cm cinder (12–20), 30-cm round gravel (10–40)
Pilot	P	1.0	0.5	0.15	265	0.25/13.5/1.5	As above
Lab	LL	0.9	1.0	0.32	890	8.0/NA/NA	50-cm gravel (5–25), 30-cm round gravel (35–55)
Lab	LL	0.9	1.0	0.32	890	6.0/NA/NA	As above
Lab	LL	0.9	1.0	0.32	890	4.0/NA/NA	As above
Pilot	D	0.6	1.4	0.17	83	NA/32/8.0	30-cm sand (1–6), 10-cm gravel (7–15), 20-cm gravel (15–30)
HFCW							
Pilot	S	1.0	12	0.01	8.0	6.0/36/12	45-cm fine gravel (0.25–16)
Pilot	S	1.0	6.0	0.03	15	8.0/36/12	45-cm fine gravel (0.25–16)
HCW							
Pilot $^{(V+H)}$	P	1.4	4.7	0.03	32	0.17/11.5/4.0	[30-cm coarse sand (1–2), 15-cm gravel (10–12), 15-cm gravel (30–60)]^{v}, [20-cm gravel (30–60), 16-cm coarse sand (1–2), 20-cm gravel (30–60)]^{h}
Pilot $^{(V+H)}$	P	1.4	2.6	0.06	71	0.17/11.5/4.0	As above
Pilot $^{(V+H)}$	P	1.4	1.8	0.12	137	0.17/11.5/3.5	As above
Pilot $^{(H+V)}$	P	0.6/0.6	4.2	0.03	37	0.17/11.5/4.0	As above
Pilot $^{(H+V)}$	P	0.6/0.6	1.9	0.06	70	0.17/11.5/4.0	As above
Pilot $^{(H+V)}$	P	0.6/0.6	1.5	0.12	147	0.17/11.5/3.5	As above
Lab $^{(V+H)}$	P	1.0	14.5	0.02	21	1.0/5.1/NA/8.0	[30-cm coarse sand (3–5), 10-cm gravel (30–60)]^{v}, [12.5-cm gravel (30–60), 75-cm coarse sand (3–5), 12.5-cm gravel (30–60)]^{h}
Lab $^{(V+H)}$	P	1.0	3.6	0.08	83	0.1/0.4/NA/8.0	As above
Pilot $^{(V+V)}$	O	0.6/0.4	1.8	0.04	110	0.3/NA/12	30-cm sand (0.4), 15-cm gravel (10), 15-cm gravel (30), 40-cm bioballs
Full $^{(V+V+V+H+V)}$	P	0.8	1.7	0.007	53	NA/48/40	NA

Wetland type/scale	RFR (*R* vol/*I* vol)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/ Rem (%)	TP Rem rate (g m^{-2} day^{-1})/ Rem (%)	Author
VFCW						
Pilot	NA	10	35/19	1.0/46	NA/NA	Sun et al. (2003)
Pilot	0.5:1	2.3	30/15.4	NA/NA	1.1/49	Lian-sheng et al. (2006)
Pilot	0.5:1	2.3	30/15.4	NA/NA	2.2/49	Lian-sheng et al. (2006)
Lab	1:1	5.2–8.0	5.5/3.2	NA/NA	0.73/42	Lavrova and Koumanova (2010)
Lab	2:1	5.2–8.0	5.5/2.2	NA/NA	1.05/60	Lavrova and Koumanova (2010)
Lab	3:1	5.2–8.0	5.5/1.8	NA/NA	1.18/67	Lavrova and Koumanova (2010)
Pilot	0.6:1	NA	8.4/6.6	NA/NA	0.3/21	Foladori et al. (2013)
HFCW						
Pilot	0.5:1	0.46	8.1/2.1, 11/3.5	0.08/69	0.1/65	Stefanakis and Tsihrintzis (2009)
Pilot	0.5:1	0.46	8.1/2.1, 11/3.5	0.16/69	0.19/65	Stefanakis and Tsihrintzis (2009)
HCW						
Pilot $^{(V+H)}$	1:1	NA	18/0.6	NA/NA	0.52/97	Kantawanichkul et al. (2003)
Pilot $^{(V+H)}$	1:1	NA	19/2.0	NA/NA	1.02/93	Kantawanichkul et al. (2003)

Table 3 (continued)

Wetland type/scale	RFR (*R* vol/*I* vol)	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/ Rem (%)	TP Rem rate (g m^{-2} day^{-1})/ Rem (%)	Author
Pilot $^{(V+H)}$	1:1	NA	26/12	NA/NA	1.68/55	Kantawanichkul et al. (2003)
Pilot $^{(H+V)}$	1:1	NA	21/0.3	NA/NA	0.62/99	Kantawanichkul et al. (2003)
Pilot $^{(H+V)}$	1:1	NA	23/3.0	NA/NA	1.2/90	Kantawanichkul et al. (2003)
Pilot $^{(H+V)}$	1:1	NA	25/10	NA/NA	1.8/63	Kantawanichkul et al. (2003)
Lab $^{(V+H)}$	1:1	2.0/0.4	46/12	NA/NA	0.68/75	Kantawanichkul et al. (2003)
Lab $^{(V+H)}$	1:1	0.5/0.1	46/23	NA/NA	1.84/50	Kantawanichkul and Somprasert (2005)
Pilot $^{(V+V)}$	1:1	NA	91/25	NA/NA	2.7/73	Travis et al. (2012)
Full $^{(V+V+V+H+V)}$	2.6:1	4.9	146/12	NA	0.9/90	Zhang et al. (2016)

The population equivalent (PE) is calculated based on the common relation 1 PE = 60 g BOD day^{-1}. BOD values were approximated using the ratio COD/BOD = 2 in the studies where BOD was not reported (Kantawanichkul and Somprasert 2005). HLR and OLR are referred to the initial loads, and for ER, the RFR is given to estimate the HLR and OLR after ER

ER effluent recirculation, *VFCW* vertical flow constructed wetland, *HFCW* horizontal flow constructed wetland, *HCW* hybrid constructed wetland, *WT* wastewater type, *P* piggery, *LL* landfill leachate, *D* domestic, *S* synthetic, *O* oil-rich, *HLR* hydraulic loading rate, *OLR* organic loading rate, *COD* chemical oxygen demand, *HRT* hydraulic retention time, *SA* system age (SA), *ED* experiment duration, *RFR* recirculation flow ratio, *R vol/I vol* recirculated volume to influent volume, PO_4^{3-}*-P* orthophosphate, *TP* total phosphorus (TP), *NA* not available, *V+H* VFCW over horizontal flow sand bed, *H+V* HFCW and VFCW connected in series, *V+V* VFCW and VFCW connected in series, *V+V+V+H+V* four VFCWs and one HFCW connected in series

for the removal of phosphorus is possible. In VFCW, the application of ER was considered less effective for phosphorus removal (Sun et al. 2003; Lian-sheng et al. 2006; Lavrova and Koumanova 2010) (Table 3). The removal of phosphorus from wastewater was attributed to the chemical reactions between the inorganic phosphorus and metal compounds inside the bed matrices, adsorption on substrate media, and uptake by the plants. Inorganic chemical reactions are normally rapid processes that are not affected by the increase of the wastewater-media contact time; neither are the rates of phosphate uptake by the plants and adsorption onto the surfaces of the media. Thus, ER had less impact on PO_4^{3-}-P and TP removal processes.

In HFCW, the use of ER negatively affected the removal of PO_4^{3-}-P and TP, which were decreased 16 and 12%, respectively, compared with the system without ER. The performance was deteriorated due to the increased HLR that saturated the limited adsorption capacity of the filter media (Stefanakis and Tsihrintzis 2009) (Table 3).

However, in HCW, the enhanced removal of TP was observed (Kantawanichkul et al. 2003; Kantawanichkul and Somprasert 2005; Travis et al. 2012; Zhang et al. 2016) (Table 3). For instance, Travis et al. (2012) observed an additional 14% removal of TP with ER compared with the system without ER. The increase in TP removal from 59% without ER (Table 1) to 73% with ER (Table 3) might be due to redox manipulation with ER. The duration of the experiment was 12 months in both conditions, but with ER, the removal of TP increased even in the case of high influent phosphorus concentration (91 mg L^{-1}) (Tables 1 and 3).

Artificial aeration

The AA is used to create an aerobic condition beneficial to enhance the performance of HFCW, VFCW, and HCW. CWs are aerated with air pump and air blower in two modes, intermittent aeration (IA) and continuous aeration (CA). The effectiveness of the approach has been shown at laboratory scale in VFCW and at laboratory and pilot scales in HFCW (Table 4).

Influence of AA The effect of AA on phosphorus removal is still not clear. Different studies give conflicting information regarding the enhancement of phosphorus removal with AA in VFCW. Tao et al. (2010) found that IA did not have significant influence ($P > 0.05$) on TP removal (Tables 1 and 4). However, Dong et al. (2012) and Wang et al. (2015) observed that CA and aeration position (AP) had little influence on TP removal and found an increase of 6 and 4%, respectively, compared with non-aerated systems (Tables 1 and 4).

In contrast, Fan et al. (2013) and Wu et al. (2015a) found an increase of 37 and 39%, respectively, in TP removal with the application of IA (Tables 1 and 4). Tang et al. (2009) observed that IA increased TP removal up to 50%. Vera et al. (2014)

Table 4 Comparison of studies using AA in VFCW, HFCW, and HCW

Wetland type/scale	WT	Depth (m)	Area (m^2 PE^{-1})	HLR (m^3 m^{-2} day^{-1})	OLR (g COD m^{-2} day^{-1})	HRT (days)/SA/ED (months)	AM	AP
VFCW								
Lab	D	0.7	5.7	0.2	48	1.0/15/12	IA	B
Lab	R	0.8	9.9	0.19	12	2.0/5.0/1.0	CA	M
Lab	R	0.8	9.9	0.19	12	2.0/5.0/1.0	IA	M
Lab	S	0.65	4.0	0.07	30	3.0/6.0/5.0	IA	B
Pilot	D	0.6	1.8	0.16	64	NA/32/8.0	IA	B
Lab	S	0.65	9.7	0.01	12	3.0/6.0/4.0	IA	B
Lab	S	0.5	NA	NA	NA	1.5/6.0/4.5	CA	S
Lab	S	0.5	NA	NA	NA	1.5/6.0/4.5	CA	M
Lab	S	0.5	NA	NA	NA	1.5/6.0/4.5	CA	B
HFCW								
Pilot	D	1.0	3.4	0.06	35	NA/NA/12	IA	F
Lab	D	0.7	11	0.10	11	1.0/20/15	NA	F
HCW								
Pilot $^{(H+F+H)}$	D	1.0	2.3	1.6	51	5.4/NA/4.0	NA	S
Pilot $^{(H+F+H)}$	D	1.0	1.2	3.2	102	2.7/NA/8.0	NA	S
Lab$^{(V+H)}$	D	0.8/0.35	2.6	0.046	37	$[0.06]^{V}$, $[3.0–4.0]^{H}$/6.9/1.0	IA	B
Lab $^{(V+H)}$	D	0.8/0.35	2.6	0.046	37	$[0.25–4]^{V}$, $[3.0–4.0]^{H}$/6.9/1.0	IA	B
Lab $^{(V+H)}$	D	0.8/0.35	2.6	0.046	37	$[1.0]^{V}$, $[3.0–4.0]^{H}$/6.9/1.0	IA	B
Lab $^{(V+FEM)}$	D	0.8/0.5	0.6	0.2	198	7.0/12.6/1.0	IA	B

Wetland type/scale	Filter media (mm)	AFR (m^3 h^{-1})	Effluent DO (mg L^{-1})	Influent/effluent PO_4^{3-}-P/TP (mg L^{-1})	PO_4^{3-}-P Rem rate (g m^{-2} day^{-1})/Rem (%)	TP Rem rate (g m^{-2} day^{-1})/Rem (%)	Author
VFCW							
Lab	55- and 45-cm sand (< 4), 15-cm gravel (5–8)	0.25	1.0	2.3/0.6	NA/NA	0.34/74	Tao et al. (2010)
Lab	50-cm gravel (7–15), 10-cm gravel (18–32)	NA	4.4	3.9/2.5	NA/NA	0.27/37	Dong et al. (2012)
Lab	As above	NA	3.0	3.9/2.6	NA/NA	0.25/35	Dong et al. (2012)
Lab	15-cm sand (< 2), 15-cm gravel (10–20), 25-cm gravel (10–30), 10-cm gravel (40–50)	0.09	8.01	3.9/0.3	NA/NA	0.25/92	Fan et al. (2013)
Pilot	30-cm sand (1–6), 10-cm gravel (7–15), 20-cm gravel (15–30)	3.5	NA	8.4/6.4	NA/NA	0.32/24	Foladori et al. (2013)
Lab	As above	1.86	4.06	7.9/0.7	NA/NA	0.09/91	Wu et al. (2015a,)
Lab	5-cm sand (1–5), 5-cm gravel (5–10), 25-cm lava (10–35), 10-cm gravel (35–50)	0.0004	0.41–2.82	0.7/0.21	NA/NA	NA/70	Wang et al. (2015)
Lab	As above	0.0004	1.23–2.32	0.7/0.21	NA/NA	NA/70	Wang et al. (2015)
Lab	As above	0.0004	0.42–1.85	0.7/0.22	NA/NA	NA/69	Wang et al. (2015)
HFCW							
Pilot	120-cm limestone (8–16)	60	0.2–0.6	8.4/1.3	NA/NA	0.44/85	Zhang et al. (2010)
Lab	65-cm ceramsite (3–8)	0.24	0.27	3.6/1.0	0.26/70	NA/NA	Zhong et al. (2015)
HCW							
Pilot $^{(H+F+H)}$	15-cm soil (1–2), 65-cm gravel (5–20), 20-cm gravel (20–60)	NA	2.04	6.2/2.1	NA/NA	0.7/67	Ye and Li (2009)
Pilot $^{(H+F+H)}$	As above	NA	2.22	6.2/2.2	NA/NA	1.3/64	Ye and Li (2009)
Lab$^{(V+H)}$		0.12	6.0	9.0/3.3	NA/NA	0.26/63	Zapater-Pereyra et al. (2015)

Table 4 (continued)

Wetland type/scale	Filter media (mm)	AFR ($m^3 h^{-1}$)	Effluent DO ($mg L^{-1}$)	Influent/effluent PO_4^{3-}-P/TP ($mg L^{-1}$)	PO_4^{3-}-P Rem rate ($g m^{-2} day^{-1}$)/Rem (%)	TP Rem rate ($g m^{-2} day^{-1}$)/Rem (%)	Author
	[70-cm sand (1–2), 10-cm gravel (15–30)]^v, [35-cm sand (1–2)]^h						
Lab $^{(V+H)}$	As above	0.12	3.2	9.0/2.3	NA/NA	0.31/74	Zapater-Pereyra et al. (2015)
Lab $^{(V+H)}$	As above	0.12	2.5	9.0/3.1	NA/NA	0.27/66	Zapater-Pereyra et al. (2015)
Lab $^{(V+FEM)}$	65-cm sand (0.5–1), 15-cm gravel (4–8)	3.6	NA	24/5.6	3.9/74	NA/NA	Sochacki and Miksch (2016)

The population equivalent (PE) is calculated based on the common relation 1 PE = 60 g BOD day^{-1} . BOD values were approximated using the ratio COD/BOD = 2 in the studies where BOD was not reported (Fan et al. 2013; Wu et al. 2015a, b; Zhong et al. 2015; Zapater-Pereyra et al. 2015; Sochacki and Miksch 2016)

AA artificial aeration, *VFCW* vertical flow constructed wetland, *HFCW* horizontal flow constructed wetland, *HCW* hybrid constructed wetland, *WT* wastewater type, *D* domestic, *R* river, *S* synthetic, *HLR* hydraulic loading rate, *OLR* organic loading rate, *COD* chemical oxygen demand, *HRT* hydraulic retention time, *SA* system age, *ED* experiment duration, *AM* aeration mode, *CA* continuous aeration, *IA* intermittent aeration, *AP* aeration position, *B* bottom, *M* middle, *S* surface, *F* front, *AFR* air flow rate, *DO* dissolved oxygen, *PO_4^{3-}-P* orthophosphate, *TP* total phosphorus, *NA* not available, *H+F+H* HFCW, free water surface flow CW, and HFCW in a stack design, *V+H* VFCW over horizontal flow filter, *V+FEM* VFCW and floating emergent macrophyte CW in series

found a significant effect of AA with an increase in up to 30% for PO_4^{3-}-P removal. The significant increase in TP removal could be due to low HLR in Fan et al. (2013) and Wu et al. (2015a) compared with that in Tao et al. (2010) and Dong et al. (2012). The higher HLR increases the influent load of TP resulting in the higher effluent concentration, indicating the decrease in TP removal even with IA.

In HFCW, Zhang et al. (2010) found no effect of IA on TP removal, although it was more stable with aeration as the better mixing with aeration promoted the formation of precipitates (Tables 1 and 4). On the other hand, Zhong et al. (2015) observed an increase of 17% in PO_4^{3-}-P removal (from 53% in non-aerated HFCW to 70% in aerated HFCW) due to redox manipulation with front aeration (Tables 1 and 4). The duration of the experiment (15 months) was the same in both conditions, which indicated that increase in ORP (Table 5) established the suitable conditions for phosphorus precipitation and adsorption to the substrate and increased the removal of PO_4^{3-}-P.

In HCW with the application of IA, the TP removal was increased up to 36%, from 27% without aeration (Table 1) to 63% with aeration (Table 4) for the treatment of high-strength wastewater. The overall TP removal efficiency of the HCW with IA was 63%, and the VFCW contributed more for the removal up to 37%, whereas the rest of the 26% was removed by HFF (Zapater-Pereyra et al. 2015) (Table 4). Similarly, the removal of PO_4^{3-}-P was increased up to 15%, from 59% without aeration (Table 1) to 74% with aeration (Table 4) in HCW, which was the combination of VFCW and floating emergent macrophyte CW (FEM-CW) connected in series (Sochacki and Miksch 2016). The total removal of PO_4^{3-}-P by HCW with IA was 74%, and VFCW contributed more (66%) compared with the FEM-CW (8%). However, Ye and Li (2009) found that passive aeration did not affect the TP removal in HCW, which was the combination of three CWs: HFCW, FWSCW, and HFCW (Table 4).

The role of redox manipulation in the performance of CWs

The improvement in DO level due to redox manipulation with aeration strategies (TF, ER, and AA) might be responsible for the removal of phosphorus (Zhong et al. 2015), as increased DO level might expedite phosphorus precipitation and adsorption to the substrate (De-Bashan and Bashan 2004; Zhang et al. 2010). However, ORP is measured by few of the reviewed studies such as by Lian-sheng et al. (2006), Foladori et al. (2012, 2013), Zhong et al. (2015), Zhang et al. (2016), and Sochacki and Miksch (2016). Moreover, the interaction of ORP with phosphorus removal is discussed by limited studies. Foladori et al. (2013) with ER and AA and Zhong et al. (2015) and Sochacki and Miksch (2016) with AA verified the positive effect of aeration strategies by indicating the high values of ORP (Table 5).

Table 5 Oxidation-reduction potential (ORP) with different aeration strategies

Aeration strategy	Wetland type/scale	Influent ORP (mV)	Effluent ORP (mV)	Author
Without aeration	VFCW/lab	+ 312	+ 23.5	Lian-sheng et al. (2006)
	HCW$^{(V+H)}$/pilot	− 190	+ 115	Foladori et al. (2012)
	VFCW/pilot	− 227	+ 83	Foladori et al. (2013)
	HFCW/lab	− 34	− 67	Zhong et al. (2015)
	HCW$^{(V+FEM)}$/lab	NA	− 162	Sochacki and Miksch (2016)
Effluent recirculation	VFCW/lab	− 185	+ 150	Lian-sheng et al. (2006)
	VFCW/pilot	− 227	+ 105	Foladori et al. (2013)
	HCW$^{(V+V+V+H+V)}$/full	+ 123	+ 311	Zhang et al. (2016)
Artificial aeration	VFCW/pilot	− 227	+ 77	Foladori et al. (2013)
	HFCW/lab	− 34	+ 127	Zhong et al. (2015)
	HCW$^{(V+FEM)}$/lab	NA	+ 75	Sochacki and Miksch (2016)

VFCW vertical flow constructed wetland, *HFCW* horizontal flow constructed wetland, *HCW* hybrid constructed wetland, *V+H* VFCW over horizontal flow filter, *V+FEM* VFCW and floating emergent macrophyte CW in series, *V+V+V+H+V* four VFCWs and one HFCW connected in series

For instance, Zhong et al. (2015) estimated the increase in ORP from − 34 mV in influent wastewater to + 127 mV in effluent wastewater with the application of AA. However, the ORP in effluent wastewater of non-aerated HFCW was − 67 mV (Table 5). The progressive increase in ORP demonstrated the formation of suitable conditions for phosphorus precipitation and adsorption to the substrate, which aids to increase the removal of PO_4^{3-}-P from 53% in non-aerated HFCW (Table 1) to 70% in aerated HFCW (Table 4).

In HCW (combination of VFCW and FEM-CW connected in series), the removal of PO_4^{3-}-P was increased up to 15%, from 59% without aeration (Table 1) to 74% with aeration (Table 4) (Sochacki and Miksch 2016). The increase in PO_4^{3-}-P removal might be due to redox manipulation with IA, which increased the ORP from − 162 mV in non-aerated HCW to + 75 mV in aerated HCW (Table 5). The durations of the experiment were 1.8 and 1.0 month without and with aeration, respectively (Tables 1 and 4), and the ages of the system were 9.8 and 11.7 months, respectively. Considering the fact that with time, due to adsorption and precipitation reactions of phosphorus with Ca^{2+}, Al^{3+}, and Fe^{3+} in the sand or gravel, the substrate reached to its saturation. The redox manipulation with IA might accelerate the phosphorus precipitation and adsorption to the substrate leading to enhanced removal of PO_4^{3-}-P even when the age of the system was more than that of the experiment without aeration that was performed. Thus, ORP which is the vital parameter in evaluation of oxic conditions in CWs needs consideration in the future studies.

The role of microbes in the performance of CWs

It is also expected that the aeration strategies would significantly modify the aerobic/anaerobic conditions of the substrate media, consequently affecting the microbial habitats of phosphate-accumulating organisms. Phosphates are immobilized and stored as polyphosphates at the aerobic stage and released after the decomposition at the anaerobic stage (Vohla et al. 2007). Polyphosphate synthesis by bacterial community can be very active under aerobic conditions but is reversible by nature (phosphate release) under anaerobic conditions (Faulkner and Richardson 1989; Gopal 1999; Merlin et al. 2002). In CWs with TF operation, the establishment of anoxic, anaerobic, and aerobic environments is achieved, which results in the removal of phosphorus by microorganisms (Behrends et al. 2001; Jia et al. 2010). In aerated CWs, the additional removal of phosphorus (4.5%) compared with non-aerated CWs was also attributed to microbial assimilation under aerobic conditions and adsorption to the substrate (Wang et al. 2015). However, among the studies on the effects of aeration strategies for the removal of phosphorus reviewed in this paper, only Wang et al. (2015) reported the effect of aeration method on microbial habitats of phosphate-accumulating organisms and quantified their contribution in TP removal. Currently, very limited scientific knowledge is available on the effect of aeration methods on phosphate-accumulating micro-organisms and their consequent contribution in phosphorous removal, which needs further research.

Comparison of phosphorus removal by aeration method and wetland type

In non-aerated VFCW, the removal of TP was 29–74% and the removal of PO_4^{3-}-P is not investigated in the reported studies. In non-aerated HFCW, the removal of PO_4^{3-}-P and TP was 53–85 and 10–85%, respectively. In non-aerated HCW, the removal of PO_4^{3-}-P and TP was 59 and 27–76%, respectively (Table 1).

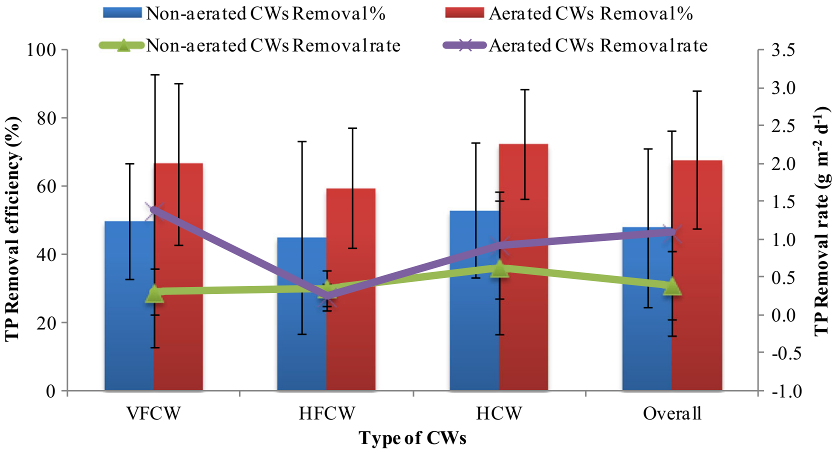


Fig. 2 Overall statistics (mean and standard deviation) of TP removal with and without aeration methods in CWs

In VFCW, the removal of PO_4^{3-}-P and TP was 45–97 and 75–94%, with TF (Table 2). The removal with ER was 46 and 21–67%, respectively (Table 3). With AA, the removal of TP was 24–92% and the removal of PO_4^{3-}-P was not investigated in the reported studies using AA to improve the treatment efficiency (Table 4).

In HFCW, the removal of TP was 31–67% with TF and the removal of PO_4^{3-}-P was not calculated in the reported studies using TF (Table 2). The removal of PO_4^{3-}-P and TP with ER was 69 and 65%, respectively (Table 3). With AA, the removal of PO_4^{3-}-P and TP was 70 and 85%, respectively (Table 4).

In HCW, the removal of TP was 39–61% with TF (Table 2), 50–99% with ER (Table 3), and 63–74% with AA (Table 4). The removal of PO_4^{3-}-P was not considered in the reported studies using TF and ER (Tables 2 and 3), but with AA, it was 74% (Table 4).

As expected, aerated CWs performed much better compared with non-aerated CWs, as indicated by Fig. 2. The overall TP removal efficiencies of aerated and non-aerated CWs were estimated as 68 ± 20 and 48 ± 23%, respectively, and the removal rates were 1.1 ± 1.4 and 0.4 ± 0.4 g m^{-2} day^{-1}, respectively. Comparing the performance by wetland types revealed the lowest TP removal by HFCW (aerated 60 ± 18%, 0.2 ± 0.2 g m^{-2} day^{-1}; non-aerated 45 ± 28%, 0.4 ± 0.2 g m^{-2} day^{-1}). The VFCW and HCW perform somewhat similar, though HCW gives the highest TP removal (aerated 72 ± 16%; non-aerated 53 ± 20%) compared with VFCW (aerated 67 ± 24%; non-aerated 50 ± 17%). These observations are valid for both aerated and non-aerated CWs. Although the TP removal rate of non-aerated HCW (0.6 ± 0.9 g m^{-2} day^{-1}) was higher compared with non-aerated VFCW (0.3 ± 0.3 g m^{-2} day^{-1}), the removal rate of aerated VFCW was increased more (1.4 ± 1.8 g m^{-2} day^{-1}) compared with aerated HCW (0.9 ± 0.7 g m^{-2} day^{-1}).

When compared by aeration method, TF showed the highest TP removal efficiency followed by ER and AA (Fig. 3), with means and standard deviation of 72 ± 21, 67 ± 21, and 65 ± 20%, respectively. The corresponding TP removal rates were 1.9 ± 2.3, 1.1 ± 0.7, and 0.4 ± 0.3 g m^{-2} day^{-1}, respectively.

Consistent with the above mentioned observations, TF-VFCW indicated the highest removal efficiency and removal rate with mean and standard deviation of 88 ± 6% and 2.6 ± 2.5 g m^{-2} day^{-1}, respectively. The ER-HCW stood next with values of 79 ± 18% and 1.3 ± 0.7 g m^{-2} day^{-1}, respectively (Fig. 4). The variation in reported efficiencies was higher in ER-HCW compared with TF-VFCW, as could be seen in the standard deviation results. The lower removal efficiencies were observed in the cases of TF-HFCW and ER-VFCW with mean and standard deviation of 51 ± 17 and 48 ± 16%, respectively, though the TP removal rate of ER-VFCW (1.1 ± 0.6 g m^{-2} d^{-1}) was comparable with ER-HCW. It was also revealed by the contribution of the compartments in TF-HCW for TP removal that VFCW played a major role in the treatment compared with HFF (Zapater-Pereyra et al. 2015).

The enhanced removal of phosphorus with TF-VFCW and ER-HCW clearly demonstrates high potential for practical application of these systems for phosphorus removal. However, in the case of organic matter and nitrogen removal, ER-HCW, TF-HCW, and AA-VFCW are the promising systems (Ilyas and Masih 2017a). Furthermore, while considering

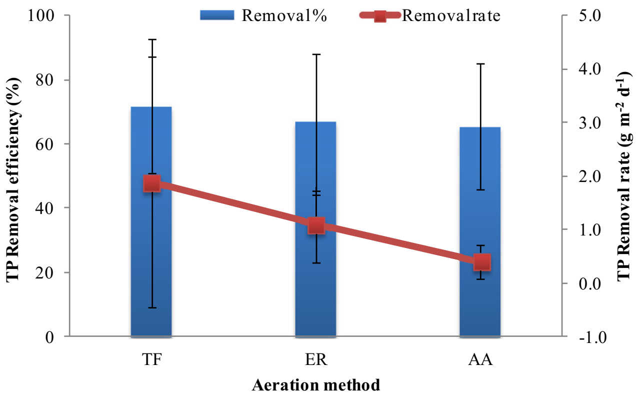


Fig. 3 Overall statistics (mean and standard deviation) of TP removal by different aeration methods

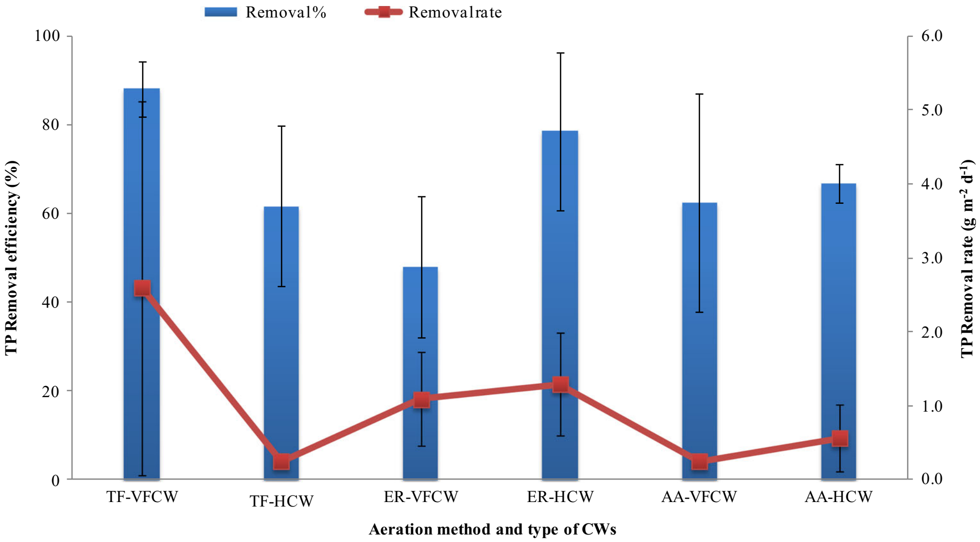


Fig. 4 Comparison of TP removal among different types of CWs and aeration methods

the area requirement of these system, the average area requirements stood at 2.1, 4.0, 4.6, and 4.6 m^2 PE^{-1} in the case of TF-VFCW, ER-HCW, TF-HCW, and AA-VFCW, respectively (Ilyas and Masih 2017b). Therefore, for the overall performance of the CW system, i.e., for the removal of phosphorus, nitrogen, and organic matter as well as area requirement, ER-HCW can be the best option for practical application followed by TF-VFCW, TF-HCW, and AA-VFCW.

Factors influencing removal of phosphorus

The results of the Pearson correlation statistics shown in Fig. 5 indicate that the TP removal does not show significant correlation with any of the studied parameters. However, the causality of the negative correlation between TP and area (though not significant) was contrary to the expectation, as the wetland systems with more area requirement should potentially lead to more TP removal. The negative correlation could be due to the influence of high-performing systems with comparatively less area requirement (VFCW and HCW) against the low-performing HFCW with large area requirement. However, the relationship between TP and area is also not a strong one showing large scatter and low coefficient of determination ($R^2 = 0.05$) (Fig. 6a).

Removal of TP and PO_4^{3-}-P seems to increase with increasing DO, as indicated by a positive correlation among them, though significant only between DO and PO_4^{3-}-P (Fig. 5 and 6b). The positive correlation of TP and PO_4^{3-}-P with DO is consistent with studies indicating that the improvement in DO might accelerate the precipitation and adsorption of phosphorus to the substrate (De-Bashan and Bashan 2004; Zhang et al. 2010; Vymazal 2011; Zhong et al. 2015). Furthermore, a significant positive correlation of PO_4^{3-}-P with HLR was observed (Fig. 5 and 6c). A negative correlation of TP with HLR, though not significant, is consistent with some studies, which demonstrated that the increase in HLR decreased the removal of TP and PO_4^{3-}-P that was attributed to the limited adsorption capacity of the filter media (Kantawanichkul and Somprasert 2005; Stefanakis and Tsihrintzis 2009; Dong et al. 2012). Kantawanichkul and Somprasert (2005) reported high

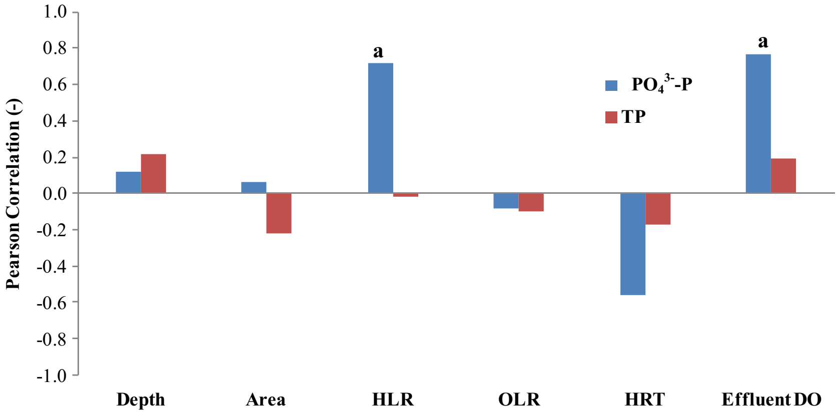


Fig. 5 Correlation statistics among the studied factors and water quality parameters. ‘a’ shows a significant correlation between the parameters at 90% confidence level

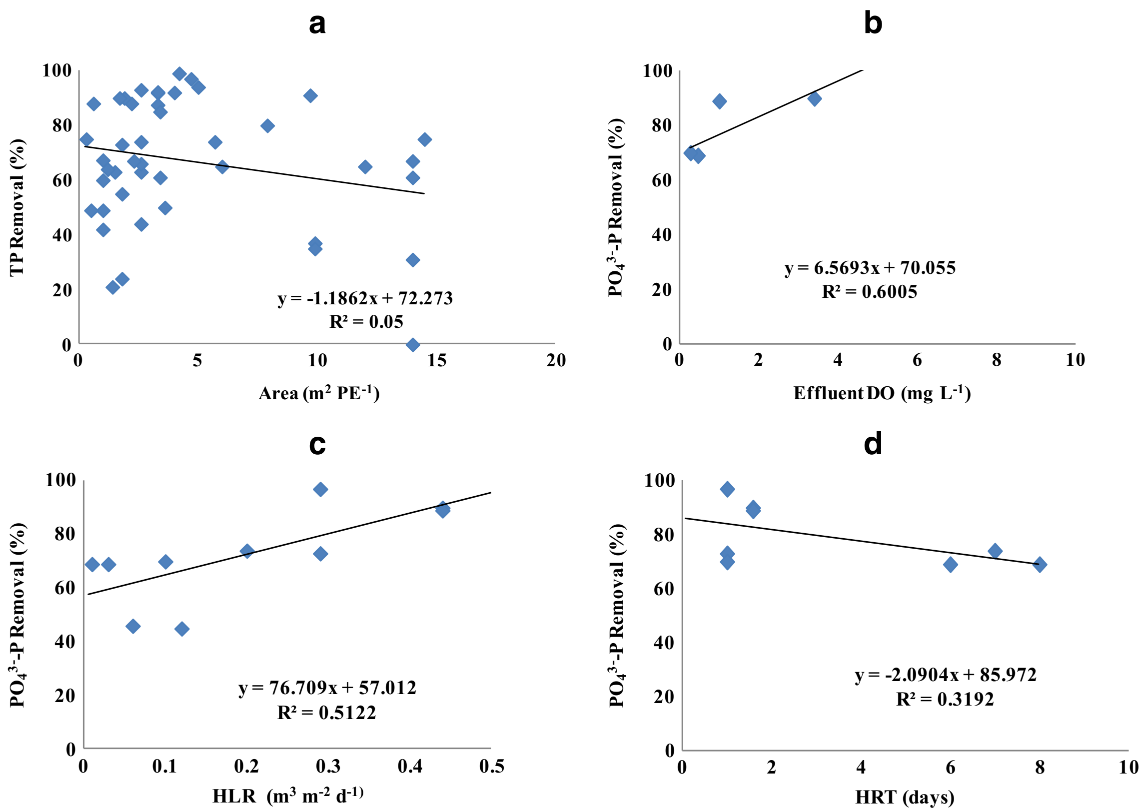
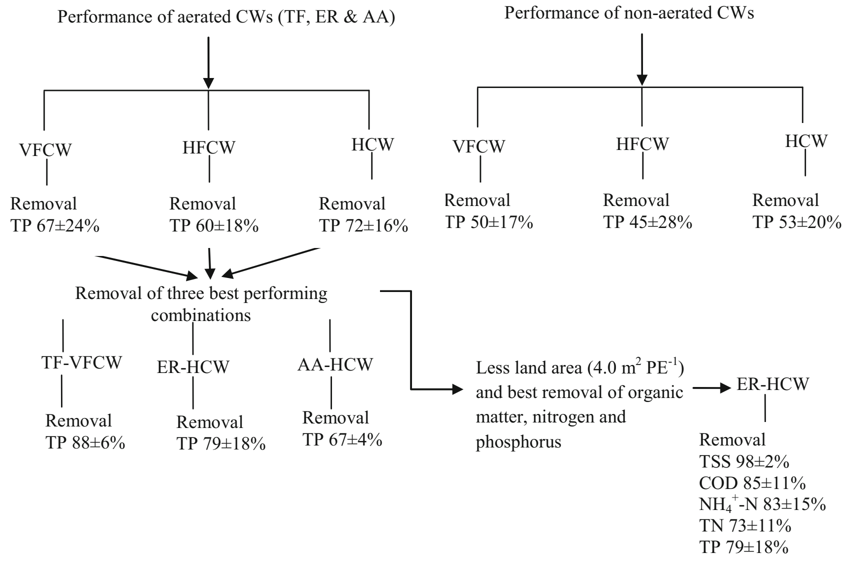


Fig. 6 Relationship between the studied factors and water quality parameters. **a** TP and area. **b** PO_4^{3-}-P and effluent DO. **c** PO_4^{3-}-P and HLR. **d** PO_4^{3-}-P and HRT

influent concentration of TP (46 mg L^{-1}) in two stages of HCW. Dong et al. (2012) reported that increase in HLR increased the influent load and high influent concentration of TP resulted in higher effluent concentration, which lead to decrease in TP removal. In most of the reported studies, sand and gravel are used as a substrate material, which have the lowest adsorption capacities of up to 2.45 and 3.6 g P kg^{-1}, respectively (Vohla et al. 2005).

Although, TP and PO_4^{3-}-P do not show significant correlation with HRT, it is evident that long HRT decreases the removal of TP and PO_4^{3-}-P (Fig. 5 and 6d). This finding is contradictory with the previous research that attributed the

Fig. 7 A graphical summary of removal efficiencies (mean and standard deviation) of different CWs examined in this study



higher removal of TP (Tao et al. 2010) and PO_4^{3-}-P (Sochacki and Miksch 2016) to longer HRT. Among the mechanisms of phosphorus removal from wastewater, the rates of phosphate uptake by the plants and adsorption onto the surfaces of the media are slow and moderate, respectively. The removal of phosphorus is decreased when the saturation of the adsorption media is reached, and even the effluent concentration could be increased compared with the influent concentration. In HCW, the contribution of VFCW was more for PO_4^{3-}-P removal compared with FEM-CW; consequently, the VFCW became the sink of PO_4^{3-}-P in non-aerated HCW (Sochacki and Miksch 2016). The application of IA could prevent the partially degraded organic matter from accumulating in the bed matrix, thus providing adsorption sites on the substrate media for phosphorus, which might be the cause of enhanced removal of PO_4^{3-}-P and TP with longer HRT (Tao et al. 2010; Sochacki and Miksch 2016). The enhanced removal of phosphorus might also be due to longer HRT that stimulated plant uptake of phosphorus (Tao et al. 2010; Sochacki and Miksch 2016).

Conclusions

1. The removal of TP showed large variation among different types of CWs and aeration methods. The TF-VFCW indicated the highest removal efficiency and removal rate with mean and standard deviation of 88 ± 6% and 2.6 ± 2.5 g m^{-2} day^{-1}, respectively, followed by the ER-HCW with values of 79 ± 18% and 1.3 ± 0.7 g m^{-2} day^{-1}, respectively. The removal remained lower in ER-VFCW with values of 48 ± 16% and 1.1 ± 0.6 g m^{-2} d^{-1}, respectively. The promising results with TF-VFCW and ER-HCW clearly demonstrate high potential for practical application of these systems for phosphorus removal. The removal efficiencies (mean and standard deviation) of different CWs examined in this study are summarized in Fig. 7.
2. The aerated CWs demonstrate higher phosphorous removal compared with the non-aerated systems, with overall mean and standard deviation estimated as 68 ± 20 and 48 ± 23%, respectively, and the removal rates were 1.1 ± 1.4 and 0.4 ± 0.4 g m^{-2} day^{-1}, respectively.
3. The TP removal does not exhibit significant correlation with factors including depth, HLR, OLR, HRT, and effluent DO but has negative correlation with the area. This negative correlation is contrary to the expectation that the systems with large land area will lead to more TP removal. Analogous to that, a significant positive correlation between PO_4^{3-}-P and HLR is contrary to some studies, which clearly demonstrated that increase in HLR decreased the removal of PO_4^{3-}-P and TP that was attributed to the limited adsorption capacity of the filter media. The negative correlation of TP and PO_4^{3-}-P with HRT is also contradictory with the some studies which attributed the enhanced removal of TP and PO_4^{3-}-P to long HRT. This indicates the cautious interpretation of the available evidence, indicating the need for more investigations and publication of data and findings on these aspects.
4. In majority of the studies, the removal of PO_4^{3-}-P is not reported; thus, the number of observations in the case of PO_4^{3-}-P was less, which can show high uncertainty of the results. Therefore, in future studies, the inclusion of these statistics will be supportive to attain more meaningful statistical analysis.
5. Various studies provided conflicting information regarding the effect of AA and ER on phosphorus removal specifically indicating the need of further investigation to better understand the distribution of oxygen for phosphorus removal.
6. ORP emerges as the crucial parameter in evaluation of oxic/anoxic conditions in CWs that aids in the phosphorus removal processes but was reported by few studies; therefore, it could be given more attention in future research.

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