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Review

# Constructed Floating Wetlands: A review of research, design, operation and management aspects, and data meta-analysis

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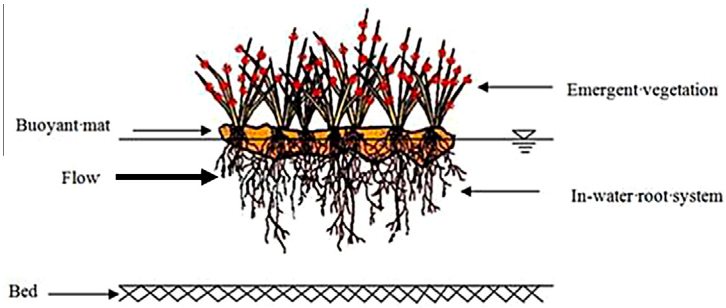
## HIGHLIGHTS

- Constructed Floating Wetlands.
- Water and wastewater treatment.
- Review of research, design, operation and management.

## GRAPHICAL ABSTRACT



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## ABSTRACT

This paper summarizes the state-of-the-art on Constructed Floating Wetlands (CFWs). An attempt has been made here to collect and organize current literature and provide an insight to most topics of the ongoing scientific conversation on CFWs. Several issues are discussed such as applications, construction materials, vegetation species, mechanisms for pollutant removal and management strategies. Raw data were extracted from studies and were imposed to statistical analysis in order to reveal correlations (Spearman's r coefficient) between total nitrogen (TN), total phosphorus (TP) and ammonium nitrogen ($NH_4^+$-N) concentration reduction and several operational or design parameters, e.g., vegetation aerial coverage, water depth, initial loading, Hydraulic Loading Rate (HLR) and Hydraulic Retention Time (HRT). TN concentration reduction correlated well with initial loading ($r = 0.841$; $p = 0.000$; $n = 28$) and showed a lower correlation with HRT ($r = 0.443$; $p = 0.013$; $n = 28$), and negative correlations with depth ($r = -0.690$; $p = 0.000$; $n = 28$) and HLR ($r = -0.528$; $p = 0.002$; $n = 28$). $NH_4^+$-N and TP concentration reductions correlated positively with initial loading ($r = 0.869$; $p = 0.000$; $n = 19$ and $r = 0.840$; $p = 0.000$; $n = 21$), and negatively with depth ($r = -0.812$; $p = 0.000$; $n = 19$ and $r = -0.773$; $p = 0.000$; $n = 21$) and HLR ($r = -0.608$; $p = 0.02$; $n = 19$; and $r = -0.558$; $p = 0.06$; $n = 21$). As the depth factor relates to the percent of root coverage in the water column, the aforementioned negative correlation for TP, TN and $NH_4^+$-N with depth could be interpreted as the rhizosphere effect. Multi-linear regression analysis was carried out for TN and TP removal, in an attempt to describe quantitatively TN and TP concentration reduction as function of design and operation parameters. CFWs seem to be an efficient technique for both wastewater treatment and natural water purification; however, further research is needed in order to better interpret system's behavior and optimize its efficiency.

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## Contents

## 1. Introduction

Natural floating wetlands occur around the word [1]. Constructed Floating Wetlands (CFWs), also called ‘planted floating system beds’, ‘artificial or vegetated floating islands’ or ‘ecological floating beds’, are variants of Constructed Wetlands. Yeh et al. [2] summarized the CFW concept and structure, focusing on various CFW applications, and used the term artificial floating islands (AFI). Chen et al. [3] comparatively assessed the advantages and disadvantages of CFWs, free-floating wetlands and soil based wetlands, and adopted the terminology hydroponic root mats (HRMs). Headley and Tanner [4] discussed the application of CFWs for stormwater treatment, and used the term Floating Emergent Macrophyte Wetlands (FTWs). Moreover, Fonder and Headley [5], in an attempt to describe and categorize this technology, used the technical term ‘Floating Emergent Macrophyte Treatment Wetlands’ (FEMTWs). In our review, we adopt the term ‘Constructed Floating Wetlands’, since it is most widely used in the literature.

CFWs consist of emergent vegetation established upon a buoyant infrastructure, floating on surface waters. The upper parts of the vegetation grow and remain primarily above the water lever, while the roots extend down in the water column, developing an extensive beneath water-level root system. Thus, the vegetation grows hydroponically, performing direct nutrient uptake from the water column [4,6]. The development of an extensive and dense root system is crucial for the performance of the system. Biofilm is attached on the roots and rhizomes, and as physical and biochemical processes take place, the system functions as a natural filter [7,8]. Fig. 1 presents a vertical section of a CFW.

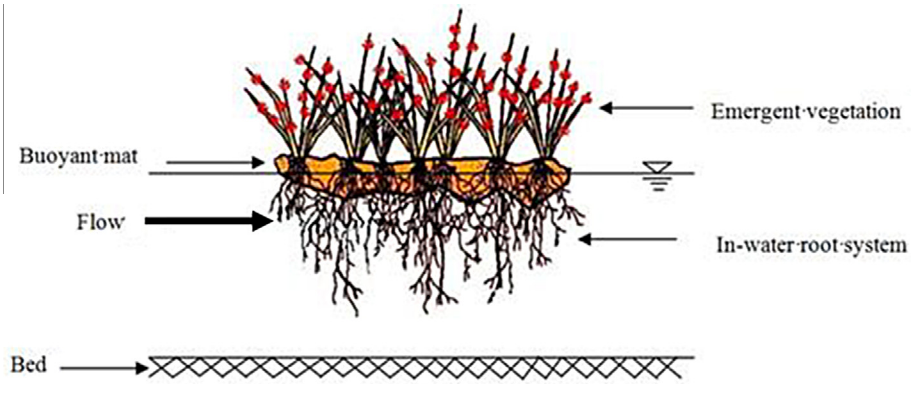

**Fig. 1.** Schematic of vertical section of Constructed Floating Wetlands.

This paper discusses field and pilot scale applications, as well as laboratory experiments on CFWs, and aims to provide a state-of-the-art overview regarding their technical design characteristics and their nutrient removal efficiency. The particular objectives were to: (1) summarize current research outcomes; (2) discuss in depth and enlighten the vegetation contribution to nutrient removal; and (3) evaluate the various design and operation parameters contributing to nutrient removal rates. Furthermore, a novelty in this review regarding CFWs is the provision of: (1) numerical results regarding CFWs efficiency; (2) correlations between removal reduction and design aspects; (3) discussion regarding phyto-uptake contribution in overall removal; and (4) discussion regarding harvesting and management strategies.

## 2. Materials and methods

### 2.1. Dataset formation

A comprehensive literature search was conducted in order to collect studies regarding CFWs (Table 1). Google Scholar and Scopus were the search engines used for collecting these studies. The main keywords used were: Constructed Floating Wetlands, floating islands, planted platforms and floated treatment wetlands. This online search comprises studies conducted up to date. The majority of these studies have been discussed and summarized in Section 3, Results and discussion.

Not all the studies presented in Table 1 could be used for further analysis since some did not present all needed data. A screening process was employed in order to select for data meta-analysis

**Table 1**
Summary of CFWs studies for treatment of various water/wastewater types, presenting author, scale of experiment, type of water/wastewater, plant species, average nutrient removal efficiency, and location.

| Study | Scale | Water/WW type | Plant species used | Average removal rates (%) | Location |
|---|---|---|---|---|---|
| [9] | Batch | Synthetic wastewater | *Lolium perenne* L. *Daytona* | COD: 85; TN: 45.3–57.9; NH$_4$: 86.5–92.7 | China |
| [10] | Microcosm | Primary treated sewage | *Cyperus papyrus* | TN: 90.4; NH$_4$: 89.3; TP: 84.5 | Uganda |
| | | | *Colocasia esculenta* | TN: 67.8; NH$_4$: 68.8; TP: 63.8 | |
| [11] | In situ application | River water | *Equisetum* sp., *Ipomoea aquatic Forsk* | COD: 79.3; NH$_4$: 83.6; TP: 87.5 | China |
| [12] | In situ application | Aquaculture effluent and river water | *Chrysopogon zizanioides*, *Typha latifolia*, *Sparganium erectum* | COD: 66; BOD$_5$: 52; TP: 65 | Italy |
| [13] | Mesocosm | Lake water | *Ipomonea aquatica* | TN: 66.4–76.5; NH$_4$: 58.7–68.9; TP: 45.7–61.7 | China |
| [14] | Microcosm | River water | *Festuca arundinacea* | TN: 90.1; NH$_4$: 86.3; TP: 72.1 | China |
| [15] | Mesocosm | Lake water enriched with nutrient solution | *Canna flaccid*, *Juncus effuses* | TN: 58–83.5; TP: 45.5–75 | South Carolina, USA |
| [16] | Mesocosm | Raw domestic wastewater | *Carex*>95% | COD: 52.9; TN: 42.3; NH$_4$: 34.9; TP: 22.1 | Belgium |
| [17] | Mesocosm | Refinery wastewater | *Lolium perenne Caddieshack* | COD: 62.2; TN: 62.2; TP: 63.1 | China |
| | | | *Lolium perenne Topone* | COD: 66; TN: 69.5; TP: 72.3 | |
| | | | *Lolium perenne* L. | COD: 62.6; TN: 64.1; TP: 68.5 | |
| | | | *Geophila herbacea O Kumtze* | COD: 52.2; TN: 59.1; TP: 55.7 | |
| [18] | Mesocosm | Nutrient solution | *Iris pseudacorus* | TN: 98; TP: 92 | Netherlands |
| | | | *Typha angustifolia* | TN: 57; TP: 23 | |
| [19] | Mesocosm | Swine wastewater | *Lolium multiflorum Lam 'Dryan'* | COD: 83.4; TN: 84; TP: 90.4 | China |
| | | | *Lolium multiflorum Lam 'Waseyutaka"* | COD: 80.7; TN: 80.3; TP: 89.9 | |
| | | | *Lolium multiflorum Lam 'Tachimasari'* | COD: 85.4; TN: 79.6; TP: 88.3 | |
| [20] | Mesocosm | Anaerobically digested flushed dairy manure wastewater | *Eichhornia crassipes* | TN: 84.5–91.7; NH$_4$: 99.6; TP: 82–98.5 | Florida, USA |
| [21] | Mesocosm | Domestic wastewater | *Typha angustifolia* | BOD$_5$: 48.5–76.1; NH$_4$: 50–86.4 | Shri Lanka |
| | | | *Canna iridiflora* | BOD$_5$: 63.5–85; NH$_4$: 58.4–81.6 | |
| [22] | Mesocosm | River water | *Canna* sp. | TN: 50.4; NH$_4$: 100 | China |
| [23] | Mesocosm | Meat processing wastewater | *Glyceria maxima* | TN: 46–49 | New Zealand |
| [24] | Mesocosm | Nutrient solution | *Canna* sp., *Calamus* sp. | TN: 76.94; NH$_4$: 93.50 (removal rates for batch experiment and rice straw substratum) | China |
| [25] | Mesocosm | Domestic wastewater | *Vetiveria zizanoides* (L.) *Nash* | BOD$_5$: 62.02–91.89; TN: 21.9–57.6; NH$_4$: 21.4–55; TP: 13.5–31.3 | Thailand |
| [26] | Mesocosm | Fertilizer | *Thailand angustifoliate cultivar* | NH$_4$: 86–99 | China |
| | | | *Jiangxi big leafage cultivar* | NH$_4$: 83–88 | |
| | | | *Panteng native cultivar* | NH$_4$: 81–90 | |
| [27] | Mesocosm | Lake water | *Ipomonea aquatica* | TN: 30.7; TP: 38.2 | China |
| [28] | Mesocosm | River water | *Oenanthe javanica* | TN: 90.8; NH$_4$: 96.7; TP: 76.5 | China |
| [29] | Mesocosm | Eutrophic pool water | *Lolium perenne var Top One* | COD: 66.8; TN: 55.6; NH$_4$: 62.8; TP: 87.1 | China |
| | | | *Lollium perenne var. Respect* | TN: 40.1 | |
| [30] | Mesocosm | River water | *Oenanthe javanica* | TN: 91.3; NH$_4$: 94.6; TP: 58 | China |
| [31] | Mesocosm | Stormwater | *Juncus effusus* and *Pontederia cordata* | TN: 15.7; TP: 47.7 | Florida, USA |
| [32] | Microcosm | Eutrophic pool water | *Oenanthe javanica D.C* and *Nasturtium officinale* | BOD$_5$: 83 | China |
| [33] | Microcosm | Nutrient solution | *Canna generalis* | COD: 58.2; BOD$_5$: 33.2; TN: 76.3; NH$_4$: 83.8; TP: 81.4 | China |
| | | | *Scirpus validus* | COD: 56.2; BOD$_5$: 32; TN: 90.5; NH$_4$: 75.8; TP: 80.8 | |
| | | | *Alternanthera philoxeroides* | COD: 69.7; BOD$_5$: 39.7; TN: 86; NH$_4$: 82.3; TP: 85.7 | |
| | | | *Thalia geniculata* | COD: 54.1; BOD$_5$: 30.8; TN: 54.5; NH$_4$; 84.3; TP: 78.9 | |
| | | | *Cyperus alternifolius* | COD: 40.5; BOD$_5$: 23.1; TN: 72.7; NH$_4$: 89.5; TP: 82.3 | |
| [34] | Microcosm | Synthetic river water | *Typha orientalis*, *Phragmites australis*, *Scirpus validus*, *Iris pseudacorus* | TN: 64; NH$_4$: 90.3; TP: 61 | China |
| [8] | Pilot scale | Aquaculture wastewater | *Ipomonea aquatica* | TN: 30.6; TP: 18.2 | China |
| [35] | Microcosm and in situ application in urban pond | Lake water | *Triarrhena lutarioriparia*, *Miscanthus sinensis*, *Anderss* sp., *Zizania caduciflora*, *Thalia dealbata*, *Vetiveria zizanoide*, Acorus calamus | TN: 50.3; NH$_4$: 59.4; TP: 86.5 | China |
| [36] | In situ application | River water | *Eichhrinia crassipes*, *Pisitia stratiotes*, *Jussiae reppens*, *Hydrocotyle verticillata*, *Hydrocharis dubia*, *Myriophyllum aquaticum*, *Potendaria cordata*, *Canna indica*, *Calla oalustris* | TN: 36.9; NH$_4$: 44.8; TP: 43.3 (removal rates regard the Summer-Autumn period) | China |
| [37] | Batch | Nutrient solution | *Oenanthe javanica* | COD: 17–43; TN: 31–64; TP: 8–15 | China |
| [38] | In situ application | Road runoff | *Carex Virgata* | TP: 50 | New Zealand |

**Table 1** (*continued*)

| Study | Scale | Water/WW type | Plant species used | Average removal rates (%) | Location |
|---|---|---|---|---|---|
| [39] | Mesocosm | Secondary treated sewage | *Canna* sp. | $NH_4$: 35–42 | Turkey |
| | | | *Cyperus papyrus* | $NH_4$: 24.6–33 | |
| | | | *Paspalum* sp. | Not provided | |
| [40] | Mesocosm | Stormwater | *Schoenoplectus tabernaemontani* | TN: 49.8; TP: 67.5 | Virginia, USA |
| | | | *Potendaria cordata* L. | TN: 49.1; TP: 68.6 | |
| [41] | Mesocosm | Lake water | *Acorus calamus* | TN: 36.3; $NH_4$: 44.3; TP: 35.7 | China |
| [42] | Mesocosm | River water | *Fragmites karka* | $BOD_5$: 40–50; TN: 45–50; $NH_4$: 45–55 | India |
| [43] | Mesocosm | River water | *Typha angustifolia* | TP: 39.2; TN: 67.5 | Singapore |
| | | | *Chrysopogon zizanioides* | TP: 19.1; TN: 40.8 | |
| | | | *Polygonum barbatum* | TP: 46; TN: 7.8 | |
| [44] | Mesocosm | River water | *Rumex acetosa Linn* | TN: 92.4–94.6; $NH_4$: 97–99.4 | China |
| [45] | Mesocosm | River water | *Canna indica* | COD: 32.4; TN: 42.3; TP: 32.7 | China |
| | | | *Acorus calamus* | COD: 28.9; TN: 38.4; TP: 28.9 | |
| | | | *Cyperus alternifolius* | COD: 25.2; TN: 33.2; TP: 24.9 | |
| | | | *Vetiveria zizanioides* | COD: 22.7; TN: 28.3; TP: 20.7 | |
| [46] | In situ application | Municipal sewage | *Zizania caduciflora* and *Canna generalis* | COD: 70.6; $NH_4$: 50.3; TP: 52.1 | China |
| [47] | Microcosm | Sewage lagoon effluent | *Phragmites mauritianus* | $NH_4$: 97.8; TP: 75.1 | Uganda |
| [48] | Pilot | Secondary effluent | *Cyperus papyrus* | $BOD_5$: 83.1; TN: 66.8; $NH_4$: 60.2; TP: 61.8 | Uganda |
| | | | *Miscanthidium violaceum* | $BOD_5$: 47.8; TN: 56; $NH_4$: 47.1; TP: 40.8 | |
| [49] | Pilot | Secondary effluent | *Cyperus papyrus* | TN: 72.5; $NH_4$: 75.4 | Uganda |
| | | | *Miscanthidium violaceum* | TN: 69.4; $NH_4$: 62 | |
| [50] | Pilot | Domestic wastewater | *Ipomonea aquatica* | TN: 25.4 | |

studies that fulfilled the following criteria: (1) studies written in English and published in journals included in Science Citation Index, with an impact factor greater than 0.5; (2) experiments that did not combine CFWs with other methods such as aeration, or immobilized microorganisms; (3) water/wastewater influent which was not purely a nutrient solution, but consisted either of wastewater (WW), eutrophic water, or natural water with added nutrients/fertilizers, and this, because synthetic solutions contain phosphorus and nitrogen in easily consumable forms, resulting in higher efficiency rates. Thus, 15 studies (Table 2) fulfilling the aforementioned criteria and comprising all needed data were used in meta-analysis, since they provide a more homogeneous data set and contain more reliable results. All statistical analyses refer to the dataset presented in Table 2.

The original data were modified in order to obtain a dataset of design depth, vegetation coverage, Hydraulic Retention Time (HRT), Hydraulic Loading Rate (HLR), initial loading, and TN/TP/$NH_4$-N concentration reductions ($\Delta C = C_{in} - C_{out}$), and are presented in Table 2. Design depth was used since the working depth was not available for all studies. All data provided in Table 2 present the average values either for influent concentrations, or effluent ones. In most cases, experiments expand throughout seasons, and thus, the temperature range is wide, so water or air temperature were not considered in the analysis, adding bias to the results as biological processes relate to temperature [40]. Removal rates were calculated as $R(\%) = \frac{C_{in} - C_{out}}{C_{in}}$. HLR was calculated, when not given, as the ratio of the flow (Q, $m^3$/d) divided by the surface area (A, $m^2$). In cases when the experiments were conducted at a non-flow state, HLR was calculated as $HLR = \frac{V}{A*HRT}$, where: V is the volume of the tank ($m^3$), A is the surface area of the tank ($m^2$), and HRT is the Hydraulic Retention Time (d). The vegetation coverage was calculated as the percent of the floating area to the total area. Data of Boonsong and Chansiri [25] were taken from Headley and Tanner [4]. Kyambadde et al. [49] and Kyambadde et al. [48] did not report the vegetation coverage; however, the pilot design is described as a horizontal sub-surface flow constructed wetland with hydroponically cultivated vegetation tied to a network of wooden pegs, indicating thus 100% coverage. Finally, for Zhou and Wang [28], removal rates refer only to the purification and not to the decay phase.

### 2.2. Statistical analyses

Basic statistical techniques have been employed to reveal correlations and system performance. In order to reveal the significance of flora species in system's performance, Levene's test for equality of variances has been applied for blank and vegetated cases. It is an one-way analysis of variance F-test $|x_{ij} - x_i|$, i.e., the absolute deviations of the $x_{ij}$ from their group mean $x_i$ [51] which usually stands out in terms of power and robustness for testing equality of variances between several populations [52]. Blank cases have been excluded from further analysis as they describe another technique (algae, protozoa).

In order to find out whether a certain plant species had a stable and comparable attitude among several experiments, the non-parametric Kruskal Wallis test was performed for removal rates, and as grouping variable, vegetation was used. Plants belonging to the same species were codified by a single number. For example, for TN dataset, *Oenanthe Javanica* [28,37,30] was given number 1, *Ipomonea aquatica* [13,50] was given number 2 etc. In a second run, the vegetation was codified regarding the experiment, and thus, the general establishment and growth conditions regardless of plant species used. For example, for Kansiime et al. [10] and Kyambadde et al. [48], who studied several species under the same conditions, vegetation was given a single number. For the comparison of more than two independent samples, the Kruskal-Wallis H test is a preferred procedure in many situations. For the aforementioned studies [10,48] further analysis was conducted using the average effluent values.

Spearman's r correlation coefficient measures the strength and direction, either decreasing or increasing, of an association between two or more variables. In order to quantify the relations between TN, $NH_4$-N and TP concentration reduction and the aforementioned operational and design factors, the Spearman correlation coefficient matrix was generated.

**Table 2**
Dataset for ammonium-nitrogen, total nitrogen and total phosphorus removal rates.

| Reference | Plant sp. | Vegetation cover | Depth (m) | HLR (m/d) | HRT (d) | $NH_4$-N | | | Total nitrogen | | | Total phosphorus | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | In (mg/L) | Out (mg/L) | Removal (%) | In (mg/L) | Out (mg/L) | Removal (%) | In (mg/L) | Out (mg/L) | Removal (%) |
| [22] | *Canna* sp. | 1.00 | 1.20 | 0.12 | 5.00 | 2.75 | 0.00 | 100.00 | 8.71 | 4.32 | 50.40 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.20 | 0.12 | 5.00 | 2.80 | 1.35 | 51.79 | 8.71 | 6.56 | 24.68 | [a] | [a] | [a] |
| [16] | *Carex* sp. | 0.50 | 1.20 | 0.164 | 11.00 | 16.10 | 10.80 | 32.92 | 21.8 | 13.1 | 39.91 | 2.16 | 1.77 | 18.06 |
| | Blank | 0.00 | 1.20 | 0.164 | 11.00 | 16.10 | 16.50 | −2.48 | 21.8 | 19.5 | 10.55 | 2.16 | 1.90 | 12.04 |
| [50] | *Ipomonea aquatica* | 1.00 | 1.10 | 0.063 | 16.00 | [a] | [a] | [a] | 20.00 | 4.90 | 75.50 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.063 | 16.00 | [a] | [a] | [a] | 20.00 | 8.90 | 55.50 | [a] | [a] | [a] |
| | *Ipomonea aquatica* | 1.00 | 1.10 | 0.125 | 8.00 | [a] | [a] | [a] | 31.96 | 19.52 | 38.92 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.125 | 8.00 | [a] | [a] | [a] | 31.96 | 11.62 | 63.64 | [a] | [a] | [a] |
| | *Ipomonea aquatica* | 1.00 | 1.10 | 0.250 | 4.00 | [a] | [a] | [a] | 29.40 | 27.00 | 8.16 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.250 | 4.00 | [a] | [a] | [a] | 29.40 | 22.80 | 22.45 | [a] | [a] | [a] |
| | *Ipomonea aquatica* | 1.00 | 1.10 | 0.375 | 2.70 | [a] | [a] | [a] | 29.40 | 26.70 | 9.18 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.375 | 2.70 | [a] | [a] | [a] | 29.40 | 25.90 | 11.90 | [a] | [a] | [a] |
| | *Ipomonea aquatica* | 1.00 | 1.10 | 0.500 | 2.00 | [a] | [a] | [a] | 31.96 | 26.60 | 16.78 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.500 | 2.00 | [a] | [a] | [a] | 31.96 | 25.90 | 18.96 | [a] | [a] | [a] |
| | *Ipomonea aquatica* | 1.00 | 1.10 | 0.625 | 1.60 | [a] | [a] | [a] | 20.00 | 19.20 | 4.00 | [a] | [a] | [a] |
| | Blank | 0.00 | 1.10 | 0.625 | 1.60 | [a] | [a] | [a] | 20.00 | 19.20 | 4.00 | [a] | [a] | [a] |
| [25] | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.104 | 7.00 | 30.14 | 15.00 | 50.23 | 38.40 | 19.40 | 49.48 | 5.20 | 4.10 | 21.15 |
| | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.104 | 7.00 | 32.70 | 14.70 | 55.05 | 46.92 | 19.90 | 57.59 | 6.26 | 4.30 | 31.31 |
| | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.145 | 5.00 | 30.14 | 18.50 | 38.62 | 38.40 | 23.50 | 38.80 | 5.20 | 4.50 | 13.46 |
| | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.145 | 5.00 | 32.69 | 19.40 | 40.66 | 46.92 | 23.00 | 50.98 | 6.26 | 5.20 | 16.93 |
| | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.242 | 3.00 | 30.14 | 23.60 | 21.70 | 38.40 | 30.00 | 21.88 | 5.20 | 4.40 | 15.38 |
| | *Vetiveria zizanoides* (L.) | 0.55 | 0.50 | 0.242 | 3.00 | 32.69 | 25.70 | 21.38 | 46.92 | 28.10 | 40.11 | 6.26 | 4.80 | 23.32 |
| [39] | *Canna* sp. | 1.00 | 0.20 | 0.06 | 1.00 | 110.70 | 72.10 | 34.87 | [a] | [a] | [a] | [a] | [a] | [a] |
| | *Cyperus* sp. | 1.00 | 0.20 | 0.06 | 1.00 | 110.70 | 83.50 | 24.57 | [a] | [a] | [a] | [a] | [a] | [a] |
| | *Canna* sp. | 1.00 | 0.20 | 0.03 | 2.00 | 110.70 | 64.50 | 41.73 | [a] | [a] | [a] | [a] | [a] | [a] |
| | *Cyperus* sp. | 1.00 | 0.20 | 0.03 | 2.00 | 110.70 | 74.30 | 32.88 | [a] | [a] | [a] | [a] | [a] | [a] |
| [47] | *Fragmites* sp. | 1.00 | 0.30 | 0.005 | 5.00 | 62.10 | 1.31 | 97.89 | [a] | [a] | [a] | 3.50 | 0.88 | 74.86 |
| | Blank | 0.00 | 0.30 | 0.005 | 5.00 | 62.10 | 3.00 | 95.17 | [a] | [a] | [a] | 3.50 | 2.07 | 40.86 |
| [49] | *Cyperus* sp. | 1.00 | 0.43 | 0.242 | 5.00 | 28.90 | 7.10 | 75.43 | 58.50 | 16.10 | 72.48 | [a] | [a] | [a] |
| | *Miscanthidium violaceum* | 1.00 | 0.43 | 0.242 | 5.00 | 28.90 | 11.10 | 61.59 | 58.50 | 17.90 | 69.40 | [a] | [a] | [a] |
| | Blank | 0.00 | 0.43 | 0.242 | 5.00 | 28.90 | 20.80 | 28.03 | 58.50 | 43.50 | 25.64 | [a] | [a] | [a] |
| [48] | *Cyperus* sp. | 1.00 | 0.35 | 0.115 | 2.70 | 19.10 | 7.60 | 60.21 | 31.00 | 10.30 | 66.77 | 23.80 | 9.10 | 61.76 |
| | *Miscanthidium violaceum* | 1.00 | 0.35 | 0.115 | 2.70 | 19.10 | 10.10 | 47.12 | 31.00 | 13.40 | 56.77 | 23.80 | 14.10 | 40.76 |
| | Blank | 0.00 | 0.35 | 0.115 | 2.70 | 19.10 | 10.70 | 43.98 | 31.00 | 14.90 | 51.94 | 23.80 | 13.30 | 44.12 |
| [30] | *Oenanthe javanica* | 0.56 | 0.48 | 0.014 | 15.00 | 8.37 | 0.46 | 94.56 | 18.32 | 1.59 | 91.32 | 0.80 | 0.34 | 58.00 |
| [28] | *Oenanthe javanica* | 1.00 | 0.38 | 0.0035 | 35.00 | 9.33 | 0.31 | 96.68 | 12.58 | 1.16 | 90.78 | 0.68 | 0.16 | 76.47 |
| | Blank | 0.00 | 0.38 | 0.0035 | 35.00 | 9.33 | 2.79 | 70.10 | 12.58 | 4.35 | 65.42 | 0.68 | 0.45 | 33.82 |
| [13] | *Ipomonea aquatica* | 0.14 | 1.80 | 0.16 | 7.00 | 2.16 | 1.13 | 47.69 | 5.15 | 1.96 | 61.94 | 0.97 | 0.36 | 62.90 |
| | *Ipomonea aquatica* | 0.14 | 1.80 | 0.22 | 5.00 | 2.16 | 1.30 | 39.82 | 5.15 | 2.29 | 55.53 | 0.97 | 0.43 | 55.67 |
| | *Ipomonea aquatica* | 0.14 | 1.80 | 0.37 | 3.00 | 2.16 | 1.50 | 30.56 | 5.15 | 2.80 | 45.63 | 0.97 | 0.51 | 47.42 |
| [37] | *Oenanthe javanica* | 1.00 | 0.75 | 0.200 | 3.00 | [a] | [a] | [a] | 3.76 | 2.59 | 31.12 | 1.25 | 1.17 | 6.40 |
| | *Oenanthe javanica* | 1.00 | 0.75 | 0.300 | 2.00 | [a] | [a] | [a] | 4.57 | 2.95 | 35.45 | 1.35 | 1.16 | 14.07 |
| | *Oenanthe javanica* | 1.00 | 0.75 | 0.600 | 1.00 | [a] | [a] | [a] | 7.94 | 2.86 | 63.98 | 1.54 | 1.34 | 13.00 |
| [10] | *Cyperus* sp. | 1.00 | 0.32 | 0.030 | 7.00 | 73.05 | 27.15 | 62.84 | 90.20 | 38.90 | 56.87 | 34.85 | 16.00 | 54.09 |
| | *Colocasia Esculenta* | 1.00 | 0.32 | 0.030 | 7.00 | 70.01 | 37.55 | 46.37 | 89.30 | 56.75 | 36.45 | 34.1 | 20.00 | 41.35 |
| | Blank | 0.00 | 0.32 | 0.030 | 7.00 | 69.30 | 60.90 | 12.12 | 88.85 | 83.60 | 5.91 | 31.5 | 31.05 | 1.43 |
| [15] | *Canna sp* & *Juncus* sp. | 0.95 | 0.51 | 0.190 | 3.00 | [a] | [a] | [a] | 0.85 | 0.14 | 83.53 | 0.08 | 0.02 | 75.00 |
| | *Canna sp* & *Juncus* sp. | 0.95 | 0.51 | 0.190 | 3.00 | [a] | [a] | [a] | 1.88 | 0.79 | 58.00 | 0.22 | 0.12 | 45.45 |
| [19] | *Lolium multiflorum* | 1.00 | 0.40 | 0.009 | 35.00 | [a] | [a] | [a] | 17.00 | 3.16 | 81.41 | 1.84 | 0.19 | 89.51 |
| | Blank | 0.00 | 0.40 | 0.009 | 35.00 | [a] | [a] | [a] | 17.40 | 5.36 | 69.20 | 2.16 | 0.62 | 71.30 |

[a] No data.

Moreover, in order to describe quantitatively the relationships among TN and TP removal and the other design and operational parameters, regression analysis was applied. In the multiple linear regression model, the dependent variable is described as a linear function of the independent variables $X_i$, as follows:

$$Y = a + b_1X_1 + b_2X_2 + \cdots + b_nX_n \quad (1)$$

where Y is the predicted value of the dependent variable, and $X_1$, $X_2 \ldots X_n$ are the independent variables. The dependent variables were either the TN or TP concentration reduction $\Delta C = C_{in} - C_{out}$ (mg/L), whereas the independent variables were: vegetation coverage, depth (m), influent concentration (mg/L), HLR (m/d) and HRT (d). In order to create the model, the standard enter method was used, considering that all variables inserted in the model were significant at $p < 0.05$.

## 3. Results and discussion

### 3.1. Applications and design parameters of CFWs

#### 3.1.1. Applications

The main purpose of CFWs is to improve water/wastewater quality. However, in situ applications may serve additional objectives such as creation of habitat for fish and birds, litoral zone protection, landscape improvement and tourism reinforcement [7,53]. CFWs are considered as an inexpensive low energy eco-technology [13,54] that has been tested at the field scale in lakes [41], urban stormwater ponds [31,40,54] and rivers [11,36,54]. In situ applications have been combined with several methods, such as constructed riparian wetlands [36] and the creation of small wells for Hydraulic Retention Time control [11]. In the field of river restoration, floating vegetation holds a great advantage over rooted options, as in situ remediation can be obtained without by-passing the flow.

Table 1 summarizes the most important scientific studies that test design parameters and efficiency of this technique. The majority of these studies have been designed at the microcosm/mesocosm scale. Some studies have been conducted at the pilot scale, while little attention has been given to full-scale field applications. The efficiencies of such systems have been tested to a great range of water/wastewater types, but most mesocosm studies have been conducted with synthetic wastewater. The suspended root system provides an advantage in resisting water level fluctuations, and thus, CFWs are most commonly installed in stormwater or retention ponds. Studies have been conducted in several countries over the five continents, including Australia, Belgium, Canada, China, France, Germany, India, Japan, Korea, New Zealand, Shri Lanka, Uganda, the USA, and the UK, among others.

Studies dealing with industrial wastewater treatment include, among others: petrochemical refinery wastewater [17], mining effluent [56], meat processing effluent [23], manure wastewater [20], swine farm effluent [19] and aquaculture effluent [12,57].

### *3.1.2. Design parameters*

Most significant design parameters include the vegetation, the percent of vegetation coverage, the growth media, the depth, and methods for achieving buoyancy. Table 3 provides most common representative methods of achieving buoyancy, plant establishment, and typical examples of substratum.

Removal efficiency of CFWs can be enhanced by adding a great range of supplements or combining various technologies, such as adding biofilm carriers [11,13,27,54], freshwater clam [13], immobilized microorganisms [14,29]. For instance, Li et al. [13] created a combined system, including freshwater clams, vegetation and biofilm carriers, that showed greater performance for TN, TP and ammonium removal than each element solo or in double combinations.

*3.1.2.1. Vegetation.* As presented in Tables 1 and 2, CFWs vegetated with different plant species show a great difference in pollutant removal. *Canna genus* is the most common species in CFWs, which seems to adapt equally well at several locations and climate zones, as it has been examined in the USA [15], Shri Lanka [21], China [22,24,33,45,46], Turkey [39] and New Zealand [38]. Various species of *Typha genus* have been tested in the Netherlands [18], Shri Lanka [21], China [34] and Singapore [43]. Several *Cyperus species* are also common in CFWs. They have been tested in China [33,45], Uganda [10,49,50] and Turkey [39]. Moreover, *Lollium* sp., *Zizania* sp. and *Chrysopogon* sp., belonging to *Poacea* family, have been successfully used in China [17,19,26,29,35,45,46], Italy [12], Singapore [43] and Thailand [25]. However, typical plants of constructed wetlands, such as *Carex*, *Juncus*, *Phragmites* and *Acorus*, have not been extensively studied. Whereas some plant species seem to adapt well at several locations, the non-parametric Kruskal-Wallis test revealed that when removal rates were grouped by plant species used both for TN (Asym Sig = 0.445) and TP (Asym Sig = 0.185), there was no evidence of stochastic dominance between the samples. Thus, it can be concluded that a certain plant species may adapt well in many locations, but does not have a stable and comparable attitude regarding nutrient removal.

Until now, most studies on floating plantation have been made on herbaceous species with a special focus on aquatic plants. The potential of using terrestrial vegetation in CFWs has been merely studied [53]. As terrestrial plants have a greater biomass, and longer and faster-growing root systems than aquatic plants [60,61], future research on surface water phytoremediation, through terrestrial plant cultivation, is needed. Plant adaptation, upper biomass and root development, toleration limits, and establishment of symbiotic relationships between plants and microorganisms should be further investigated.

In order to select plant species, Wang and Sample [40] established the following criteria: (1) native and non-invasive species; (2) perennial plants; (3) terrestrial plant species; (4) wetland plants or plants with ability to thrive in a hydroponic environment; and (5) plants with aerenchyma. Macrophyte species selection is critical, not only to pollutant removal, but also to the local ecosystem integrity. Although several invasive species have high nutrient uptake rates, it is likely that their negative impacts on the ecosystem or the costs of habitat restoration may be more significant than their other benefits.

**Table 3**
Various methods of achieving buoyancy, typical examples of substratum and common methods of plant establishment.

| Study | Floating frame/mat | Substratum | Raft area ($m^2$) | Plant establishment |
|---|---|---|---|---|
| [53] | PVC pipes (Φ 40 mm), ropes | None | 2.000 | Transplantation of seedlings and cutting method |
| [12] | Tech-IA patent | None | 0.450 | Unknown |
| [36] | PVC pipes (Φ 110 mm) or bamboos (Φ 100–150 mm), biofilm materials and plastic net | Soil and bamboo charcoal (v:v = 1:1) | Unknown | Transplantation into nylon rhizo-bags |
| [55] | BioHeaven patent | 1 part sand, 2 parts sphagnum peat, and 1 part compost, pH-neutralised with ground limestone | 0.360 | Transplantation of seedlings |
| [19] | High Density Polyethylene, foam plates | None | 0.200 | Cutting method |
| [37] | Foam sheets | None | 2.000 | Transplantation of seedlings |
| [58] | Extruded polystyrene, polyethylene mesh pot | Pozzolana (volcanic rock) | Unknown | Transplantation of seedlings |
| [40] | PVC pipes (Φ 38 mm), plastic mesh, pot holders, | Coir fiber | 0.290 | Unknown |
| [41] | Lake sludge, furnace slag | Perlite and cotton | 0.640 | Transplantation of seedlings |
| [13] | Polypropylane random copolymer plate and bottles | None | 2.000 | Transplantation of seedlings |
| [31] | Bio Heaven patent | Peat moss | 7.400 | Transplantation of seedlings |
| [38] | Recycled polyethylene terephthalate (PET) and expended foam | None | 50.00 | Unknown |
| [33] | Polyethylene foam, plastic bucket, ceramic pellets | Unknown | 0.135 | Transplantation of plants |
| [59] | Polyethylene foam | Sand and cotton | 0.025 | Transplantation of plants |

Successful biomass establishment seems to linearly and predominantly correlate to efficient nutrient removal rates [34,45,53]. Levene's test revealed that vegetation presence has a significant impact on $NH_4$-N (p = 0.045), TN (p = 0.01) and TP (p = 0.019) removal. Mean removal value for blanks was 5.42 mg $NH_4$-N/L, 8.42 mg TN/L and 2.4 mg TP/L, while with vegetation, removals almost doubled and reached 17.28 mg/L, 17.64 mg/L and 7.96 mg/L, respectively.

*3.1.2.2. Growth media.* Zhou and Wang [28] claim that plants not rooted in substrate are enforced to uptake nutrients directly from the water-column, and thus, perform better in nutrient uptake. However, coarse peat, coconut fiber, pumice, perlite, soil, bamboo charcoal, sand and compost have been used as growth media for plant establishment in CFWs [36]. To the best of our knowledge, no research has been carried out investigating the potential of adding absorptive material, such as zeolite in the substratum as in the case of rooted wetlands [62–66].

Cao and Zhang [24] examined the results for TN and $NH_4$ removal rates for floats planted with *Canna* sp. and *Calamus* sp., testing two substrates, rice straw and plastic filling, and absence of substrate. Rice straw performed significantly better regarding TN removal than the other two. Also, the total, as well as the nitrifying and denitrifying bacteria abundance, was greater when rice straw was used as substrate compared to plastic filling. Rice straw, as other bio-materials, can form a thick biofilm that functions as oxygen and carbon source, required for the nitrification/denitrification processes [24,67]. Nitrification occurs at the rice/straw interface where aerobic conditions exist, whereas denitrification takes place in the anoxic deeper biofilm layers.

A technical issue that emerges is that roots and rhizomes embed in growth media, and thus, below water plant tissues harvest/sampling accompanies plant damage [18,68]. Up to now, published data for plant uptake rates are based on aerial tissues or roots hanging under the floating mat, and thus, a research gap remains regarding whole plant nutrient distribution patterns [68]. Moreover, if a substratum is used, a specific design that prevents below-water tissues from contacting growth media is required, in order to obtain both whole plant harvesting and vegetation sustainability [68].

*3.1.2.3. Buoyancy.* In natural floating wetlands, self-buoyancy occurs either by the entrapment of gases within the mat or by air spaces between the roots [69]. A great number of alternative technologies have been tested to ensure the buoyancy of the floating frame, and patented mats are commercially available in Europe and the USA. These floating mats are made up by buoyant materials and have holes needed for plantation. Lynch et al. [70] set up a mesocosm experiment in order to investigate the TN and TP removal capacity of Beemat and BioHaven mats both planted with *Juncus effuses*. Over the entire study, Beemat managed to perform better (40% TN, 48% TP) than BioHaven (25% TN, 4% TP) in terms of net removal.

The most common technique in construction of floating frames or rafts is through sealed plastic pipes or tubes (made of PVC, PE and PP) or polystyrene foam pontoons [4]. However, a cheap and effective alternative for frame construction includes naturally buoyant materials, e.g., bamboo. Hu et al. [41] introduced a concept which combines dredged lake sludge and basic oxygen steel making furnace (BOF) slag in order to achieve flotation; lightweight, closed pore, expanded perlite was used as growth media. Seo et al. [71] indicated that buoyant or substratum material should be hydrophobic, as such materials enhance rapid bacterial adhesion and absorb nutrients, while desorption is almost negligible.

*3.1.2.4. Depth.* An issue that has to be considered is the selection of proper depth regarding root development. Selection and maintenance of proper water depths is vital both for preventing the plants from anchoring, and thus, losing the privilege of water fluctuation resistance, and for providing an adequate root cover over the water column. The root depth varies greatly according to plant species and to water/wastewater characteristics [4]. Tanner and Headley [55] reported maximum root depths ranging from 57 to 87 cm for emergent wetland vegetation.

*3.1.2.5. Coverage ratio.* The vegetation coverage percent, and thus the shading percent, affects greatly the dissolved oxygen concentration. Atmospheric diffusion is radically eliminated by vegetation cover [28]. Moreover, the growth of vegetation prevents light penetration in the water column, the population of phytosynthetic algal declines [72], and the root-attached biofilm will be predominantly composed of non-phytosynthetic bacteria, as the water column below the CFW is in complete shading [4]. Thus, in most studies, planted tanks contained lower DO than the blanks. Moreover, the vegetation coverage ratio has impact on pollutant removal rates as it is further discussed in Sections 3.2.2.1,3.2.2.2 and 3.2.2.3.

The coverage ratio is a parameter that varies greatly throughout the studies reviewed (Table 2). Many studies have used 100% coverage ratio [19,22,28], while others used 50% [30,38], or even less than 20% [13]. Floating Islands International, a company that provides commercial floating wetlands, suggests that a coverage ratio of 5–8% is sufficient for enhancing water quality [73].

### *3.2. Pollutant removal*

#### *3.2.1. Mechanisms for pollutant removal*

In CFWs, the suspended roots in the water column can physically remove nutrients either by incorporating them into their tissues through biosynthesis, or by settling, caused by rhizofiltration. Biosynthesis occurs both for N and P, while settling is the main process for P removal. $NH_4$-N removal in CFWs is mediated by anaerobic ammonium oxidation (anammox), nitrification, denitrification and plant uptake.

Moreover, Tanner and Headley [55] observed that TP removal rates depended greatly on the presence of fine suspended solids (FSS) in influent wastewater, indicating that sorption of Dissolved Reactive Phosphorus in fine suspended solids could be a significant pathway for TP removal, as FSS either adhere or entrap in the root matrix.

The phyto-uptake capacity depends on the anatomical and physiological properties of plant species, such as uptake efficiencies for nutrients, growth rate, translocation factor from below water to above water tissues, photosynthetic rates and root types [17,33,74]. The factors affecting phyto-uptake capacity are further discussed in Section 3.3.

The establishment of an extensive root matrix is crucial for the performance of the system. According to Kyambadde et al. [49], *Cyperus papyrus* (75.3%) managed to outperform *Miscanthidium violaceum* (61.5%) regarding $NH_4$-N removal due to its root structure. Weragoda et al. [21] highlighted that the root system formation affects nutrient removal rates. They concluded that *Typha angustifolia* showed better TN and TP removals due to its high and steady root growth that enhances water-plant interactions compared to *Canna iridiflora* whose root mat is thick and compact.

The rhizosphere effect requires that some microorganisms from wastewater/water attach on the root or rhizome surface as influenced by the chemotaxis, and form the so-called biofilm through a repeating proliferation process [33]. Oxygen and exudates that transfer from the upper biomass to the rhizome and the root surface create a substrate for microbial consortium colonization beneath CFWs [75], thus, removal efficiency greatly depends on the metabolism of biofilm of fungi, bacteria and beneficial algae that form along the suspended roots and mat in the water column [7,75,76]. It is thus crucial, in order to enhance nutrient removal efficiency, to establish a plant consortium with various bacterial colonies that enhance nutrient degradation [12]. Microbially driven processes, such as nitrification, denitrification and anaerobic ammonium oxidation, mediate both TN and $NH_4$-N removal in constructed wetland or floating island systems [34,44,77]. Sun et al. [22] confirmed that the removal efficiency of nitrogen was greatly enhanced by adding immobilized denitrifiers into the water of CFWs. Nevertheless, Zhang et al. [33] indicated that bacterial community parameters, such as the ribotype number and diversity index, were not correlated to pollutant removal, suggesting that the possession of biochemical genes does not necessarily mean that all these genes will be completely expressed in given environments or that the gene products will function equivalently.

In engineering systems, it is well known that $BOD_5$ or COD removal is dominantly mediated by the oxygen content due to the aerobic decomposition of pollutants [78]. Zhang et al. [33] argued that $BOD_5$/COD removal is highly related to the oxygen transfer rate. Internal oxygen transportation in plants through aerenchymous tissues and leakage from the root system is known for creating aerobic conditions in the rizosphere [79]. However, Tanner and Headley [55] found lower DO concentrations in planted units than in those containing artificial roots or in blanks. This difference was attributed to higher respiration rates by both vegetation and biofilm, concluding that respiratory oxygen demand was significantly greater to root oxygen release. In most studies, planted tanks contained lower DO than the blanks, since DO concentration is greatly affected by the percent of vegetation coverage, and thus, the shading percent. However, according to van de Moortel et al. [16], vegetated tanks had higher DO concentrations than the blanks; measurements indicated that oxygen leakage by roots followed a greater rate than oxygen diffusion in open tanks. Also, Wu et al. [34] stated that planted units had slightly greater DO concentration than unplanted ones.

### 3.2.2. Removal efficiency

The efficiency rate of CFWs, as of any other wastewater treatment technology, relies upon design features such as Hydraulic Reaction Time (HRT), Hydraulic Loading Rate (HLR), initial loading and temperature. However, in CFW systems, nutrient removal efficiency is also influenced by the CFW scheme structure, the depth, the vegetation percentage and the plant selection [13].

Table 1 presents 63 cases investigating efficiencies of TN removal, 53 cases for TP removal, 38 cases for $NH_4$-N removal and 13 cases for COD removal under several vegetation species and initial loading rates. As derived from Table 1, TN and TP removal averaged at 58% and 48.75%, respectively. $NH_4$-N removal averaged at 72.8%, while average COD removal was 57.8%.

*3.2.2.1. Total nitrogen removal.* As derived from Table 1, the average TN removal achieved in CFWs is 58%, with a minimum of 7.8% and a maximum of 98%. Vymazal [80], in a review that examined the comparative efficiency of various types of Constructed Wetlands, reported 54.8% mean TN removal efficiency for free floating CWs.

Spearman's coefficients presented in Table 4 show that TN concentration reduction correlates positively with influent concentration ($r = 0.841$; $p = 0.00$; $n = 28$) and Hydraulic Retention Time ($r = 0.443$; $p = 0.013$; $n = 28$), and negatively with depth ($r = -0.690$; $p = 0.00$; $n = 28$) and HLR ($r = -0.528$; $p = 0.002$; $n = 28$). From regression analysis the following Eq. (2) was derived:

$$\Delta C_{TN} = -2.8751 + 0.483\ C_{in} + 0.305\ \text{HRT}$$
$$(r^2 = 0.782;\ n = 28;\ p = 0.00;\ F = 44.752) \tag{2}$$

where: $\Delta C_{TN} = C_{in} - C_{out}$ is the TN concentration reduction (mg/L); $C_{in}$ and $C_{out}$ are the influent and effluent TN concentrations (mg/L); and HRT is the Hydraulic Retention Time (d).

In accordance with the results of Table 4, various researchers [13,25,50] showed that an increase in HRT over the same initial concentration, results in an increase in TN removal rates. Moreover, researchers [25,37,50] showed that an increase in initial loading seems to have a greater effect than a HRT decrease on enhancing removal efficiency. Fig. SM-1 [see Supplemental online material (SM)] presents a linear regression fit between influent TN concentration and TN concentration reduction ($\Delta C_{TN} = C_{in} - C_{out}$). Fig. SM-2 shows the relation between HRT and TN concentration reduction ($\Delta C_{TN} = C_{in} - C_{out}$) for low and high influent concentrations from various studies.

Interestingly, exception to the aforementioned pattern appeared in White and Cousins [15], who studied *Canna flaccid* and *Juncus effuses* removal rates over two growing seasons. In the second year, an increase in initial concentration resulted in lower removal rates, whereas the rest of the experimental design remained the same and plants were equally adapted. However, this could be attributed to a lower vegetation growth rate in the second year.

*3.2.2.2. Total phosphorus removal.* According to Table 1, TP removal ranged from 8% to 98.5% and averaged at 48.75%, being slightly higher than 42.1%, reported by Vymazal [80] as mean TP removal efficiency for free floating CWs.

Spearman's correlation coefficients regarding TP removal are presented in Table 5. TP concentration reduction correlated positively with influent concentration ($r = 0.840$; $p = 0.00$; $n = 21$) and negatively with depth ($r = -0.773$. $p = 0.01$; $n = 21$) and HLR ($r = -0.558$. $p = 0.06$; $n = 21$). Fig. SM-3 presents a linear regression

**Table 4**

Spearman's correlations matrix regarding TN concentration reduction. Bold numbers indicate strong correlations.

| | | Vegetation coverage | Depth (m) | HRT (d) | HLR (m/d) | Influent concentration (mg/L) | Concentration reduction (mg/L) |
|---|---|---|---|---|---|---|---|
| Vegetation coverage | Spearman's r | 1 | | | | | |
| | Sig. (<0.005) | | | | | | |
| Depth (m) | Spearman's r | −0.314 | 1 | | | | |
| | Sig. (<0.005) | 0.086 | . | | | | |
| HRT (d) | Spearman's r | −0.175 | −0.174 | 1 | | | |
| | Sig. (<0.005) | 0.347 | 0.350 | | | | |
| HLR (m/d) | Spearman's r | −0.015 | 0.528 | −0.776 | 1 | | |
| | Sig. (<0.005) | 0.937 | 0.02 | 0.000 | | | |
| Influent concentration (mg/L) | Spearman's r | 0.093 | −0.537 | 0.191 | −0.182 | 1 | |
| | Sig. (<0.005) | 0.620 | 0.002 | 0.303 | 0.328 | | |
| Concentration reduction (mg/L) | Spearman's | 0.071 | −**0.690** | **0.443** | −**0.528** | **0.841** | 1 |
| | Sig.(<0.005) | 0.704 | **0.000** | **0.013** | **0.002** | **0.000** | |

**Table 5**

Spearman's correlations matrix regarding TP concentration reduction. Bold numbers indicate strong correlations.

| | | Vegetation coverage | Depth (m) | HRT (d) | HLR m/d) | Influent concentration (mg/L) | Concentration reduction (mg/L) |
|---|---|---|---|---|---|---|---|
| Vegetation coverage | Spearman's r | 1 | | | | | |
| | Sig. (<0.005) | | | | | | |
| Depth (m) | Spearman's r | −0.634 | 1 | | | | |
| | Sig. (<0.005) | 0.001 | | | | | |
| HRT (d) | Spearman's r | −0.452 | 0.130 | 1 | | | |
| | Sig. (<0.005) | 0.030 | 0.553 | | | | |
| HLR (m/d) | Spearman's r | −0.296 | 0.675 | −0.497 | 1 | | |
| | Sig. (<0.005) | 0.170 | 0.000 | 0.016 | | | |
| Influent concentration (mg/L) | Spearman's r | 0.281 | −0.663 | −0.329 | −0.237 | 1 | |
| | Sig. (<0.005) | 0.194 | 0.001 | 0.125 | 0.276 | | |
| Concentration reduction (mg/L) | Spearman's r | 0240 | **−0.773** | −0.056 | **−0.558** | **0.840** | 1 |
| | Sig. (<0.005) | 0.270 | **0.000** | 0.798 | **0.006** | **0.000** | |

fit between influent TP concentration and TP concentration reduction ($\Delta C_{TP} = C_{in} - C_{out}$). Fig. SM-4 shows the relation between HRT and TP concentration reduction ($\Delta C_{TP} = C_{in} - C_{out}$) from various studies.

The introduction of depth and vegetation parameters in the regression equation implies the contribution of the plants in total phosphorus removal via the pathways described in Section 3.2.1. From linear regression analysis, the following Eq. (3) was derived, which includes influent concentration ($C_{in}$), HRT, vegetation coverage (Veg) and depth (d):

$$\Delta C_{TP} = -3.649 + 0.502\ C_{in} + 0.037\ \mathrm{HRT} - 1.642\ d + 2.349\ \mathrm{Veg}$$

$$(r^2 = 0.980;\ n = 22;\ p = 0.00;\ F = 195.27) \qquad (3)$$

where: $\Delta C_{TP} = C_{in} - C_{out}$ is the TP concentration reduction (mg/L); $C_{in}$ and $C_{out}$ are the influent and effluent TP concentrations (mg/L); d is the water depth (m); Veg is the vegetation coverage varying from 0 to 1; and HRT is the Hydraulic Retention Time (d).

*3.2.2.3. Ammonium nitrogen and COD removals.* According to Table 1, $NH_4$-N removal ranged from 24.57% to 100% and averaged at 72.8%. Spearman's coefficients regarding $NH_4$-N concentration reduction are shown in Table 6. Influent loading showed the strongest correlation (r = 0.869; p = 0.00; n = 19), followed by depth which showed a strong and negative correlation (r = −0.812; p = 0.00; n = 19), while vegetation cover (r = 0.684; p = 0.00; n = 19) and HLR (r = −0.608; p = 0.02; n = 19) also correlated significantly with ammonium reduction. Fig. SM-5 presents the linear regression between influent concentration and $NH_4$-N concentration reduction ($\Delta C_{NH4\text{-}N} = C_{in} - C_{out}$). Spearman's coefficients showed no significant correlation between HRT and $NH_4$-N removal efficiency. However, in many studies, an increase in HRT resulted in a slight increase in the removal rates [13,25,39,50].

Controversially to all the above, Xin et al. [30] reported that $NH_4$-N removal averaged at 94.6% in a batch experiment that lasted fifteen days, carried out during the winter, but significant difference in $NH_4$-N removal rates between the unvegetated and the vegetated cases was reported only for the first 4 days.

Another exception was presented by Li et al. [26] who investigated $NH_4$-N removal efficiency among three different species of water spinach, and concluded that all three were capable of achieving greater removal rates at a low initial loading and HRT, rather than at a high initial loading and HRT.

From Table 1, the average COD removal value was 57.8% and the maximum 85.4%.

### 3.3. Phyto-uptake contribution to overall removal

Phyto-uptake seems to depend greatly upon vegetation features, i.e., species selection, biomass development, nutrient storage capacity, root structure, and storage location (tissues or roots). According to Reddy and DeBusk [81], Vymazal [80] and Wang et al. [68], nutrient uptake rate and nutrient storage are mediated by biomass growth rate and the nutrient concentration in tissues, and are limited by the maximum accumulation potential of species.

There is an ongoing debate whether phyto-uptake is the principal contributor to nutrient removal in CFW systems. According to Vlek et al. [18], both TN and TP removal was mediated by plant uptake, as it counted for 49–74% for TN and 60–99% for TP. Similarly Kyambadde et al. [49] showed that *Cyperus Papyrus* L. plant uptake capacity was major for TN and TP removal, as it contributed 69.5% regarding TN and 88% regarding TP. However, Wu et al. [34] came to the conclusion that plant uptake was not the major factor for nutrient removal, since it ranged between 14.3% and 51.9% for N removal, and between 10.8% and 34.2% for P removal. Likewise,

**Table 6**

Spearman's correlations matrix regarding $NH_4$-N concentration reduction. Bold numbers indicate strong correlations.

| | | Vegetation coverage | Depth (m) | HRT (d) | HLR (m/d) | Influent concentration (mg/L) | Concentration reduction (mg/L) |
|---|---|---|---|---|---|---|---|
| Vegetation coverage | Spearman's r | 1 | | | | | |
| | Sig. (<0.005) | | | | | | |
| Depth (m) | Spearman's r | −0.844 | 1 | | | | |
| | Sig. (<0.005) | 0.000 | | | | | |
| HRT (d) | Spearman's r | −0.292 | 0.419 | 1 | | | |
| | Sig. (<0.005) | 0.167 | 0.041 | | | | |
| HLR (m/d) | Spearman's r | −0.559 | 0.649 | −0.156 | 1 | | |
| | Sig. (<0.005) | 0.005 | 0.001 | 0.446 | | | |
| Influent concentration (mg/L) | Spearman's r | 0.488 | −0.745 | −0.418 | −0.450 | 1 | |
| | Sig. (<0.005) | 0.016 | 0.000 | 0.042 | 0.027 | | |
| Concentration reduction (mg/L) | Correlation Coefficient | **0.684** | **−0.812** | −0.220 | **−0.608** | **0.869** | 1 |
| | Sig. (2-tailed) | **0.000** | **0.000** | 0.302 | **0.002** | **0.000** | |

Li et al. [17] concluded that the uptake capacity of four different perennial grasses differed slightly among them and contributed only around 4% and 10% to the overall TN and TP removal, respectively. Similarly, Zhu et al. [53] and Kyambadde et al. [48] showed that plant uptake capacity seemed to be a minor factor regarding overall TN and TP removals. Headley and Tanner [55] concluded that in none of their treatments, plant uptake was the major process for P removal. Finally, Borne et al. [38] suggested that plant uptake did not contribute significantly to overall P removal.

A number of studies refer to plant species contribution to nutrient removal. As different plant species have the potential of achieving different removal rates, the uptake capacity seems to have a great range of influence to overall removal efficiencies.

Headley and Tanner [55] tested four plant species (*Cyperus ustilatus*, *Juncus edgariae*, *Schoenoplectus tabernaemontani* and *Carex virgata*) regarding P uptake. Higher overall P uptake rates were observed for *Cyperus ustilatus* (0.00851 mg $m^{-2}$ $d^{-1}$) and *Juncus edgariae* (0.00520 mg $m^{-2}$ $d^{-1}$), while uptake was lower for *Schoenoplectus tabernaemontani* (0.00087 mg $m^{-2}$ $d^{-1}$) and *Carex virgata* (0.00050 mg $m^{-2}$ $d^{-1}$). According to White and Cousins [15], *Juncus effuses* uptake capacity was responsible for 28.3% of TN and 41.6% of TP removal, whereas *Canna flaccida* uptake accounted only for 16.4% of TN and 25.5% of TP removal, showing that *Juncus effuses* uptake contributed significantly to nutrient removal, especially for TP. Wang et al. [68] pointed out that storage capacity can differ greatly among species under the same cultivation conditions. *Pontederia cordata* L. accumulated P in tissues about fourfold higher than *Schoenoplectus tabernaemontani*. According to Vlek et al. [18], TN and TP removal efficiency was 74% and 60%, respectively, for *Iris Pseudacorus*, and 49% and 99%, respectively, for *Typha angustifolia*. Moreover, it has been found that a certain plant can be efficient in accumulating only a certain nutrient. According to Zhao et al. [14], *Tall festuca* was not capable of storing phosphorus efficiently but had a relatively high nitrogen mass uptake rate.

The effect of plant biomass, expressed as vegetation height or root surface area, has been addressed by several studies. Bu and Xu [45] studied the performance of *Canna indica*, *Accorus calamus*, *Cyperus alternifolius* and *Vetiveria zizanioides*, and provided the evidence that nutrient removal rates were significantly and highly correlated to vegetation height. Zhu et al. [53] showed that TN and TP uptake capacity of four herbal species (*Oenannthe javanica*, *Gypsophilia* sp., *Rodhea japonica*, *Dracaena sanderiana*), two shrubs (*Gardenia jasminoides* var. *grandiflora* and var. *prostate*) and one tree (*Salix babylonica*) differed significantly. *Salix babylonica* and *Gypsophilia* showed dramatically higher uptake capacity compared to all other species, ranging from twofold for both TN and TP compared to *Oenannthe javanica* and to 8-fold for TN and 5-fold for TP (on the average) compared to the rest of the species. This difference has been attributed to the total plant biomass development, as *Salix babylonica* established 6-fold biomass, and to TP/TN root uptake that seems to be the factor that differs greatly among these two species and the others. Kyambadde et al. [49] showed that the uptake capacity of *Cyperus Papyrus* L. (69.5% for TN and 88% for TP) was higher than the uptake capacity of *Miscanthidium violaceum* (15.8% for TN and 30.7% for TP), considering that the root surface of *Cyperus Papyrus* was 3-fold that of *Miscanthidium violaceum*. According to Wu et al. [34], *Scirpus validus* and *Iris Pseudacorus* performed slightly better than *Typha* and *Phragmites* regarding the uptake capacity due to their higher biomass productivity and tissue nutrient concentrations. According to Vlek et al. [18], *Iris Pseudacorus* performed better in TN uptake than *Typha angustifolia*. This difference was attributed to plant growth rates, as *Iris* biomass increased threefold and *Typha* only doubled, and to the initial loading rates that were significantly higher in *Iris pseudacorus* tanks.

Table 7 presents mass uptake percentages found in several studies. High values have been recorded in studies carried out for a short period. Vlek et al. [18], Zhou and Wang [28], Karnchanawong and Sanjitt [50] and Wen and Recknagel [59] mention high values for TN and TP mass uptake capacity (g $m^{-2}$ $d^{-1}$) but vegetation was established for short periods, i.e., 91, 66, 60 and 76 days, respectively. This may be attributed to the fact that vegetation biomass increases rapidly during the initial growth phase, thus accumulating nutrients at a high rate. Another issue that has to be considered is that some of these studies regard aerial tissue harvesting and not root harvesting, thus explaining the low uptake rates (e.g. [43]), since plant roots are sinks for nutrients and especially for phosphorus.

### 3.4. Management strategies

Zhou and Wang [28] indicated that system efficiency is enhanced by regular harvesting, as the purification phase is followed by the decay phase. If biomass is not harvested before the decay face, nutrients incorporated into plant tissues may reenter water [13,35,79].

Constructed Wetland research has adequately studied vegetative behavior. However, plants growing in soilless environment may develop quite different growth patterns [68]. CFW vegetation may develop thinner roots in order to facilitate nutrient acquisition, establish great below-water tissues and allocate more resources to them [82,83]. Reddy and DeBusk [81] reported that more than half of the total nitrogen concentration of emergent species could be stored in roots and rhizomes. White and Cousins [15] and Tanner and Headley [55] concluded that about half of nutrients stored in plants were cited in roots and below ground tissues. Wang et al. [68] concluded that only harvesting above-water tissues is incapable of employing the complete removal potential of CFWs as significant proportions of nutrients are located in roots, especially in low-nutrient availability environments. As shoot harvesting is vital in the manner of preventing senescence, and thus, nutrient reintroduction in the water column, whole plant harvesting should be thoroughly examined as a CFWs management tool.

Moreover, as plants pass through different growth stages, absorbed nutrients are remobilized and translocated to different plant parts [82]. Although there is not a general pattern describing seasonal changes of nutrient distribution in vegetation [84], aerial tissues tend to have the highest nutrient concentrations in the growing phase [80]. As plants move to mature and senescence phase, nutrients descend to below water tissues. This translocation rate varies widely and is dependent on many environmental factors. According to Vymazal [84] more than 50% of areal nutrient concentrations can be translocated during that phase. Meuleman et al. [85] reported that TN and TP removal efficiency could increase from 9% and 6% to 20% and 25%, respectively, if the above ground tissues were harvested in September and not in the following months, as in the winter, nutrients translocate to below-ground tissues. Wang et al. [68] state that the nutrient concentration in the upper biomass reaches the highest level in the summer, whereas in September nutrients translocate to below ground tissues.

As plant harvesting is a technique for removing nutrients from the system, both vegetation behavior (tendency in accumulating nutrients in tissues or roots) and seasonal patterns in nutrient allocations have to be examined in order to optimize the system's efficiency.

Harvested biomass could be used directly as animal or human food source [14]. Zhao et al. [14] measured chemical composition of aboveground tissue regarding crude protein, crude fiber, Ca, Mg, Fe, Mn, Zn, Cu, Pb and Cr and As, and concluded that, according to the National Research Council (NRC, 2000) and China Feed Data-

**Table 7**
Plant N/P mass uptake rates and plant uptake percentage. Columns with mass uptake rates refer to nutrient accumulation in plant tissues and roots and are derived from mass balance equations. They are derived by multiplying the nutrient concentration in tissues (mg $g^{-1}$) with dry plant biomass density (g $m^{-2}$) and divided by the days in which the experiment was conducted. Columns referring to uptake percentage (%) refer to mass uptake (g $m^{-2}$) regarding load reduction in water phase (g $m^{-2}$).

| Study | Plant Species | N Plant mass uptake (g $m^{-2}$ $d^{-1}$) | N plant uptake (%) | P Plant mass uptake (g $m^{-2}$ $d^{-1}$) | P plant uptake (%) |
|---|---|---|---|---|---|
| [53] | *Oenanthe javanica* | 0.016692[a] | [b] | 0.001285[a] | [b] |
| | *Gypsophila* sp. | 0.030154[a] | [b] | 0.0019[a] | [b] |
| | *Rohdea japonica* | 0.003923[a] | [b] | 0.000477[a] | [b] |
| | *Dracaena sanderiana* | 0.013231[a] | [b] | 0.0006[a] | [b] |
| | *Gardenia jasminoides* var. *Grandiflora*, | 0.004692[a] | [b] | 0.000577[a] | [b] |
| | *Gardenia jasminoides* var. *Prostrate* | 0.004923[a] | [b] | 0.000546[a] | [b] |
| | *Salix babylonica* | 0.034462[a] | [b] | 0.002546[a] | [b] |
| [15] | *Canna flaccida* | 0.22[a] | 16.4 | 0.014[a] | 25.5 |
| | *Juncus effusus* | 0.39[a] | 28.3 | 0.024[a] | 41.6 |
| [17] | *Geophila herbacea O Kuntze* | [b] | 2.8 | [b] | 10.9 |
| | *Lolium peren cv 'Caddieshack'* | [b] | 4.5 | [b] | 12.3 |
| | *Lolium perenne* L. | [b] | 3.3 | [b] | 9.3 |
| | *Loliurn perenne Topone* | [b] | 6.1 | [b] | 19.6 |
| [76] | *Scripus californicus* and *Potendaria cordata* | 0.036 | | 0.00015 | |
| [14] | *Festuca arundinacea* | 0.0558 | 55.8 | 0.0025 | 2.5 |
| [59] | *Myriophyllum aquaticum, Paspalum paspalodes and Ranunculus repens* | [b] | [b] | 0.043–0.086 | [b] |
| [28] | *Oenanthe javanica 'Blume'* | 2.47 | [b] | 0.38 | [b] |
| [48] | *Cyperus papyrus* | [b] | 28.5 | [b] | 11.2 |
| | *Myscanthidium violaceum* | [b] | 15 | [b] | 9.3 |
| [55] | *Carex virgata* | [b] | [b] | 0.00050 | [b] |
| | *Cyperus ustulatus* | [b] | [b] | 0.00851 | [b] |
| | *Juncus edgariae* | [b] | [b] | 0.00520 | [b] |
| | *Schoenoplectus tabernaemontani* | [b] | [b] | 0.00087 | [b] |
| [47] | *Phragmites mauritianus* | 0.015 | 19 | 0.04 | 37 |
| [81] Cited in [59] | *Eichhornia crassipes* | [b] | [b] | 0.243 | [b] |
| | *Duckweed* | [b] | [b] | 0.087 | [b] |
| | *Azolla* sp. | [b] | [b] | 0.033 | [b] |
| [9] | *Lolium perenne* L. *Daytona* | [b] | 18.17 | [b] | [b] |
| [50] | *Ipomonea aquatica* | 0.18–0.51[a] | 15–44 | [b] | [b] |
| [27] | *Ipomonea aquatica* | b | 7.5 | [b] | 8.8 |
| [43] | *Typha angustifolia* | 0.0162 | [b] | 0.00157 | [b] |
| | *Chrysopogon zizanioides* | 0.00174 | [b] | 0.00016 | [b] |
| | *Polygonum barbatum* | 0.00282 | [b] | 0.0004 | [b] |
| [34] | *Typha orientalis* | 0.044[a] | 21 | 0.013958[a] | 14.31 |
| | *Phragmites australis* | 0.0271[a] | 14.29 | 0.010708[a] | 10.76 |
| | *Scriprus validus* | 0.095[a] | 45.52 | 0.011875[a] | 32.27 |
| | *Iris pseudacorus* | 0.11[a] | 51.89 | 0.011542[a] | 34.17 |
| [40] Cited in [18] | *Pontederia cordata* L. | [b] | [b] | 0.00118 | [b] |
| | *Schoenoplectus* sp. | [b] | [b] | 0.00025 | [b] |
| [49] | *Cyperus papyrus* L. | [b] | 69.5 | [b] | [b] |
| | *Miscanthidium violaceum* | [b] | 15.8 | [b] | 30.7 |
| [18] | *Typha angustifolia* | 0.0132[a] | 48 | 0.0005[a] | 73 |
| | *Iris pseudacorus* | 0.2044[a] | 74 | 0.0056[a] | 60 |

[a] mass uptake was given as mg/$m^2$ and was divided by tissue sampling interval (days). In certain cases where there has been only one tissue sampling, e.g., Vlek et al. [18], the mass uptake (g $m^{-2}$) was divided by the whole experiment duration that was 91 days.
[b] Not provided.

base (2009) standards, harvested biomass could be used to feed livestock. Nonetheless, national levels for hygenical standards differ and such an approach may result in metal bioaccumulation. Such a utilization of biomass requires further research assessing the impacts of long-term consumption of elevated state nutrients and metals. Moreover, biomass could be utilized in agriculture or in order to produce energy via bioenergy plants [35].

## 4. Summary and conclusions

CFWs appear as a promising technique for water/wastewater treatment. It has been mainly studied in mesocosm laboratory experiments, and most in situ applications regard stormwater ponds. While CFWs hold a great advantage over rooted options in river restoration, as they can be applied without by-passing the flow, they have been poorly studied.

There are many commercial products (mats) available for achieving buoyancy; however, PVC pipes or natural buoyant materials (e.g., bamboo) are a reliable and cheap alternative for flotation. Most studies have used growth media in order to establish vegetation, but to the best of our knowledge, no research has been carried out investigating the potential of adding absorptive material, such as zeolite in the substratum as in the case of rooted wetlands. Research has been conducted mainly on herbaceous species and especially aquatic plants. The potential of using terrestrial vegetation needs to be addressed. Zhu et al. [53] showed that a tree (*Salix babylonica*) managed to establish significantly greater biomass than other herbaceous species, and thus, showed increased TN and TP uptake capacity.

The pollutant removal processes that take place in CFW systems are: biosynthesis, settling and biofilm metabolism. Settling, caused by the root system, is the main route for P removal.

From a biological point of view, vegetation and biofilm growth rely on ambient compound concentrations. Also, biofilm metabolism depends on ambient nutrient availability. Spearman's correlations showed that initial loading had the strongest correlation with TN ($r = 0.841$; $p = 0.00$; $n = 28$), TP ($r = 0.840$; $p = 0.00$; $n = 21$), and $NH_4$-N ($r = 0.869$; $p = 0.00$; $n = 19$) concentration reductions. While plant uptake occurs both for N and P, $NH_4$-N removal is mediated by biofilm metabolism (anaerobic ammonium oxidation, nitrification, and denitrification). Meta-analysis results indicate the occurrence of these processes. TN concentration reduction equation includes HRT and initial loading as parameters. A developed TP concentration reduction equation includes vegetation cover, depth and initial loading, thus showing that phyto-uptake and settling – caused by the roots – are the pathways for TP removal.

The contribution of phyto-uptake in the overall removal is a quite controversial topic, as researches argue on its significance. We have noticed that significantly high phyto-uptake values have been recorded in studies carried out for a short period (less than four months). Moreover, studies where only aerial tissues were harvested, possibly include an underestimation of the whole plant uptake capacity, and show low values. Thus, the wide range of mass phyto-uptake rates presented in Table 7 can be due to differences in the experiment duration and to aerial or root harvesting.

The literature suggests that for some species significant proportions of nutrients are located in roots. As shoot harvesting is vital for preventing senescence, and avoiding nutrient reintroduction in the water column, whole plant harvesting should be examined as a CFWs management tool. In order to locate the optimal period for vegetation harvesting, nutrient seasonal translocation has to be considered.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cej.2016.09.140.

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