Article

Using Constructed Floating Wetlands to Remove Nutrients from a Waste Stabilization Pond

Isaac Huth ^{1,*}, Christopher Walker ^{2,3,†} , Ramraj Kulkarni ^{1,†} and Terry Lucke ^{3,4,†} ¹ Unitywater, Maroochydore, QLD 4558, Australia; ramraj.kulkarni@unitywater.com² Covey Associates Pty Ltd., Maroochydore, QLD 4558, Australia; chrisw@covey.com.au³ UniSA STEM, UniSA STEM, University of South Australia, Adelaide, SA 5001, Australia; tlucke@csu.edu.au⁴ Department of Engineering, Charles Sturt University, Bathurst, NSW 2795, Australia

* Correspondence: Isaac.Huth@unitywater.com; Tel.: +61-4-3980-1615

† These authors contributed equally to this work.

Abstract: This study reports the biomass accumulation, plant nutrient concentration, and nutrient uptake rates of plants in a constructed floating wetland (CFW) installed for a sewage treatment application in Australia. Plant biomass accumulation was estimated based on field samplings throughout the duration of the study. Analysis of samples of each plant species was also completed to estimate the mean plant tissue nutrient content. The plant biomass accumulation estimate and the mean plant tissue nutrient concentration were then used to estimate the total nutrient uptake for each species. Each of the species were found to differ in biomass accumulation and plant tissue nutrient concentration and the distribution of biomass and nutrients between the shoots and roots. The nutrient uptake rates varied between the species, with *B. articulata* having the greatest nutrient uptake rates (shoots: N, 104 ± 31.5 g/m², P, 12.9 ± 3.87 g/m²; roots: N, 23.9 ± 7.23 g/m², P, 5.54 ± 1.67 g/m²). Harvesting of the four CFW islands after 375 days of growth removed an estimated 23.2 kg of N and 2.97 kg of P. The results of this study indicate that the use of CFWs with carefully selected plant species can successfully remove significant amounts of nutrients from domestic wastewater.

Keywords: constructed floating wetlands; plant nutrient uptake; sewage treatment; plant harvesting

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1. Introduction

Constructed floating wetlands (CFWs) are an emerging water treatment technology that is gaining popularity worldwide. CFWs are also referred to as ‘floating treatment wetlands’, ‘ecological floating beds’, and ‘artificial floating islands’ [1,2]. CFWs comprise a buoyant structure that floats on the surface of a body of water and supports media to facilitate plant growth [3].

The roots of the CFW plants grow into the water column below the floating structure, where they have access to nutrients required for growth, similar to a hydroponic system. The roots also provide substantial surface area for the growth of microbial biofilm [4], which is a matrix of diverse microbes adhered to the plant roots and other microbes by extracellular polymeric substance [5]. The roots and biofilm within the water column allow nutrients to be removed from the water column via various processes, including direct uptake and assimilation into plant tissues [6,7].

Other chemical, physical, and biological processes also function to remove pollutants from the water column [5]. Previous research [8–10] has shown that CFWs can be used to improve the quality of various effluent types, including stormwater, domestic wastewater, and agricultural runoff. CFW studies have been undertaken at the mesocosm, pilot, and field scale [1,11,12]. However, studies that consider the use of CFWs for the treatment of sewage at the field scale are limited.

Bibliometric analyses completed by Pavlineri et al. [1], Colares et al. [13], and Sharma et al. [14] compared various studies related to the application of CFWs. Of the studies included in this analysis, only one study [15] was found that assessed CFWs at the field scale treating raw wastewater. Sharma et al. [14] observed that most studies on CFWs have been conducted in the laboratory or greenhouse, so real condition results are very limited. Furthermore, to the best of our knowledge, research on the biomass production, plant nutrient concentrations, or nutrient uptake of plants grown in full-scale CFW-treated sewage has not been published to date.

As highlighted by the three CFW review papers mentioned above, research on the use of CFWs for the treatment of domestic sewage at the field scale is limited. This field study investigated the effectiveness of using CFWs to remove pollutants from domestic sewage in a waste stabilization pond (WSP) in Australia. WSPs are a sewage treatment system used in many countries that utilize microbiological, photosynthetic, biochemical, physicochemical, and hydrodynamic processes to remove pollutants from wastewater [16]. It was hypothesized that the CFW plants used in the study may enhance pollution removal efficiency and improve overall treatment performance in the WSP.

In this field study, the plant growth (shoots and roots), biomass growth, and pollutant uptake rates of five different wetland plants were monitored over a period of 375 days to determine nutrient uptake rates and also evaluate their effectiveness in removing pollutants from domestic sewage. The results of the study are presented in the following sections.

2. Materials and Methods

2.1. Study Site

This study was undertaken in a sewage treatment plant at Kenilworth in Queensland, Australia (26°34'53.9" S, 152°43'22.2" E). The treatment plant consists of a preliminary treatment facility (PTF) followed by three WSPs of varying sizes (Figure 1), with the terminal pond discharging into a subsurface flow wetland. Incoming sewage is screened in the PTF at the southwest of the site to remove large debris and solids.

Figure 1. Study site showing CFWs in Pond 3 and flow direction between ponds.

The screened sewage then enters the WSP system via the primary facultative pond (Pond 1—Figure 1). Sewage from Pond 1 then discharges into the secondary facultative pond (Pond 2), followed by the terminal maturation pond (Pond 3). The water surface level of each pond decreases from Pond 1 to Pond 3, allowing the sewage to be transferred

between the ponds via overflow pipes, which prevents backflow and enables the ponds to operate in series. However, the retention time and movement of sewage through the system are controlled by the overflow weir in Pond 3 and therefore dependent on the treatment plant inflows. Treated sewage is then discharged via a pump from Pond 3 to the downstream subsurface flow wetland for further polishing and removal of nutrients prior to downstream discharge.

The WSP receives an influent load of approximately 450 kL/week from the local population equivalent of 350, which increases up to 1500 kL/week during peak tourism periods at Easter and Christmas. The influent sewage is considered to be 'low strength', with median pretreatment values of 79 mg/L for total suspended solids, 9 mg/L for total nitrogen, and 5 mg/L of total phosphorus. However, this WSP historically experiences high pH levels (>9.0) and persistent cyanobacterial algal blooms.

2.2. Plant Selection Pilot Study

As studies on using CFWs and plants to remove pollutants from sewage are rare, particularly in Australia, there was limited direction on which plants may have been suitable for this trial. A literature review identified 10 potential plant species that may have been appropriate for the field trial, namely: *Phragmites australis* (Common Reed), *Baumea juncea* (Bare Twig Rush), *Chrysopogon zizanioides* (Vetiver), *Carex appressa* (Tall Sedge), *Ficinia nodosa* (Knobby Club-rush), *Lepironia articulata* (Grey Rush), *Sarcocornia quinqueflora* (Samphire), *Baumea articulata* (Jointed twig rush), *Eleocharis equisetina* (Chinese water chestnut), and *Imperata cylindrica* (Blady grass).

In order to test the suitability of these 10 plants, a pilot study was initiated approximately three months before the field trial to monitor their growth in the treatment pond (Figure 2). After three months' growth, the four plants that appeared to have the best growth were selected for the field trial. These were *Baumea articulata*, *Carex appressa*, *Chrysopogon zizanioides*, and *Eleocharis equisetina*.

Figure 2. Pilot study to evaluate the suitability of 10 potential plant species.

2.3. CFW Configuration

In January 2019, 88 CFW modules (a proprietary product of Clarity Aquatic) were installed in the terminal pond (Pond 3, easternmost pond) at the Kenilworth sewage treatment plant (Figure 1).

Four CFW islands were constructed, with each island made up of 22 CFW modules having an individual size of 2.35×2.35 m. Each island covered approximately 121 m^2 of the pond surface area (Figure 3A). The total area ($\sim 485 \text{ m}^2$) covered by the four islands was approximately 8.8% of the pond surface area (5510 m^2). Each CFW module contained 15 planting media baskets ($560 \text{ L} \times 380 \text{ W} \times 170 \text{ H mm}$), and each basket was filled with scoria gravel (lightweight volcanic rock) to provide support to the plant tube stock during the early establishment growth phase (Figure 3).

Figure 3. (A) *Baumea* plants installed in Island 1; (B) 3 plants in each planting basket.

Four different plant species were initially trialed in the study, namely *Baumea articulata*, *Carex appressa*, *Chrysopogon zizanioides*, and *Eleocharis equisetina*. However, the *E. equisetina* plants did not survive, and these plants were replaced with *P. australis* in June 2019. Each island contained a single plant species, and each of the baskets was planted with three plants of a single species (Figure 3B), which equated to a planting density of 8.15 plants/m^2 over the entire island area. Floating covers were also installed between each island to further reduce algal growth by inhibiting sunlight exposure.

2.4. Plant Growth Monitoring

In order to evaluate the plant response and growth rates of the individual plant species in the sewage, the plants were monitored for a period of 12 months from January 2019 to January 2020 using a similar method to that used by Schwammberger et al. (2019). The original study plan only allowed for intensive and continual plant monitoring and analysis for a period of eight months (January–August 2019) due to budgetary and logistical constraints. However, additional funding was secured during the study, which allowed for a number of extra monitoring events to be included and the study timeline to be extended until January 2020, which resulted in just over one year (375 days) of data.

Field measurements consisted of measuring a selection of in situ plants' shoot and root lengths fortnightly from January to June, then monthly until August 2019, and then a final measurement in January 2020. Ten planting baskets were randomly selected for monitoring plant growth on each island. The process included removing the planting baskets from the modules and measuring the height of the shoots above the level of the media and the length of the roots below the base of the media basket (Figure 4).

In addition to plant growth monitoring, a selection of plants was also removed fortnightly and taken to the laboratory to assess their biomass accumulation. Ten randomly selected plants were removed in the first and last sampling event, and five randomly selected plants were removed in intermediate sampling events for biomass assessment. In each sampling event, new plants were replanted in place of removed plants to maintain the planting density throughout the study. While replacing the plants may have affected the results slightly, the number of plants replaced was only between 0.5% and 1.0% of the overall total number of plants on each island. This was considered insignificant when compared to the general variation in plant growth results.

Figure 4. (A) Early shoot growth monitoring; (B) later root growth monitoring.

Each removed plant was thoroughly rinsed with tap water to remove biofilm, sludge, scoria, and any biota. The plant shoot and roots were separated and the lengths of each were recorded along with the wet weights. The plant shoots and roots were then dried for a minimum of seven days at 80 °C and the plant dry weights were recorded. All samples were retained for selection in further nutrient analysis.

2.5. Plant Nutrient Analysis

A selection of the dried plant samples described above was prepared and sent to the University of Queensland (Australia) laboratories for nutrient analysis using a similar method to that used by Schwammberger et al. [17]. Five of the ten dried plant samples were collected in January and August, and three of the five dried plant samples collected from the intermediate sampling visits were randomly selected for nutrient analysis. Three samples of each plant were selected for the final additional sample collection in January 2020. Both the roots and shoots of the selected samples were analyzed for nutrient content. Nutrient content was determined via gas chromatography–mass spectroscopy (GCMS) techniques and assessed the plant tissues concentration of nitrogen (N) and phosphorus (P).

2.6. Biomass Accumulation Calculation

The total biomass uptake for each species' shoots and roots was estimated based on the samples collected from the field. The mean dry weight of the collected samples was calculated for the shoots and roots of each species for each sampling period. The mean dry weight of the shoots and roots for each species was then multiplied by the planting density to estimate the total dry mass accumulated in each species' shoots and roots. The total biomass accumulation (kg/m^2) for each species was then estimated via Equation (1):

$$\text{BM} \frac{\text{kg}}{\text{m}^2} = \text{DW} \frac{\text{kg}}{\text{plant}} \times d \frac{\text{plant}}{\text{m}^2}, \quad (1)$$

where BM is the total dry biomass of plant material per square meter, DW is the estimated mean dry weight (mass) per plant shoots or roots, and d is the planting density.

2.7. Plant Nutrient Uptake

The plant nutrient uptake (kg/m^2) was estimated by multiplying the estimated biomass accumulation (Equation (1)) for the shoots and roots of each species at each sampling period by the mean plant tissue nutrient concentrations for the same sampling period as per Equation (2):

$$\text{TU} \frac{\text{kg}}{\text{m}^2} = \text{BM} \frac{\text{kg}}{\text{m}^2} \times \text{NC}\%, \quad (2)$$

where TU is the total uptake of a nutrient and NC% is the mean concentration of a given nutrient in the plant material. BM is the total dry biomass of plant material per square meter calculated via Equation (1). Due to budget constrictions, nutrient analysis was not performed for all sampling periods.

3. Results

3.1. Plant Growth

Three of the four original macrophyte species used in the study were found to establish successfully in the CFWs. However, the *E. equisetina* plants did not survive, and the entire island was replaced with *P. australis* in June 2019. *P. australis* was a late addition to the research study, hence the results represent six months of growth, as opposed to over a year for the other species.

Shoot growth was observed to be considerably different between the species with *B. articulata* and *P. australis* showing greater shoot growth in comparison to both *C. appressa* and *C. zizanioides* (Figure 5). This was also reflected in the study field measurements for each species.

Figure 5. Shoot growth of the four plant species in January 2020: (A) *B. articulata*, (B) *C. appressa*, (C) *C. zizanioides*, and (D) *P. australis*.

3.2. Plant Biomass

The shoot and root biomass accumulation generally increased for all plants during the study (Figure 6). *B. articulata* had the greatest biomass accumulation of the four plant species. More biomass was found in the shoots of the *B. articulata* than the roots, with biomass values of $5.80 \pm 0.459 \text{ kg/m}^2$ and $1.55 \pm 0.145 \text{ kg/m}^2$, respectively.

Despite only having a six-month growth period, *P. australis* also accumulated substantial biomass. Similar to *B. articulata*, *P. australis* accumulated more biomass in the shoots than the roots, with biomass accumulation values of $2.14 \pm 0.473 \text{ kg/m}^2$ and $1.05 \pm 0.018 \text{ kg/m}^2$, respectively. Results for *C. appressa* were lower, with more biomass accumulation in the shoots ($0.909 \pm 0.070 \text{ kg/m}^2$) than the roots ($0.779 \pm 0.028 \text{ kg/m}^2$). Biomass accumulation for *C. zizanioides* was low in both the shoots ($0.651 \pm 0.063 \text{ kg/m}^2$) and the roots ($0.234 \pm 0.056 \text{ kg/m}^2$) and shoots

Figure 6. Calculated mean dry biomass (kg/m² ±SD) accumulation for each species (please note different y-axis scales).

3.3. Plant Nutrient Concentration

The average N and P concentrations in the plant tissues were found to vary throughout the study for the roots and shoots of each species (Figure 7). Concentrations of N ranged between 0.414% and 2.71% (*w/w*%). The mean N tissue concentration at the completion of the study was greater in the shoots than the roots for all species, with the exception of *C. zizanioides*, where N concentrations were approximately equal.

Figure 7. Plant tissue nitrogen concentration *w/w*% (±SD) for each species.

P concentrations also varied throughout the study for the shoots and roots of each plant species (Figure 8). The mean concentrations of P in the shoots and roots of each species ranged between 0.106% and 0.443% ($w/w\%$). The mean P tissue concentration at the completion of the study was greater in the shoots than the roots for all species, with the exception of *B. articulata*, where P concentrations were greater in the roots than the shoots.

Figure 8. Plant tissue phosphorus concentration $w/w\%$ ($\pm$ SD) for each species.

3.4. Plant Nutrient Uptake

The plant uptake of N (g/m^2) differed considerably between species and between the shoots and roots of each species (Figure 9). The mean N uptake at the completion of the study was greater in the shoots than the roots for all species. The N uptake was greatest in *B. articulata* for both the shoots and roots. Mean N uptake in *B. articulata* increased from an initial $0.960 \pm 0.061 \text{ g}/\text{m}^2$ to $104 \pm 31.5 \text{ g}/\text{m}^2$ for the shoots and from $0.0425 \pm 0.035 \text{ g}/\text{m}^2$ to $23.9 \pm 7.23 \text{ g}/\text{m}^2$ for the roots. The N uptake for *P. australis* was observed at $52.5 \pm 26.2 \text{ g}/\text{m}^2$ for the shoots and $17.1 \pm 8.50 \text{ g}/\text{m}^2$ for the roots at the completion of the study, despite only having six months of growth. N uptake in *C. appressa* increased from an initial $0.236 \pm 0.052 \text{ g}/\text{m}^2$ to $21.6 \pm 6.28 \text{ g}/\text{m}^2$ for the shoots, and from $0.103 \pm 0.044 \text{ g}/\text{m}^2$ to $12.3 \pm 3.63 \text{ g}/\text{m}^2$ for the roots. N uptake for *C. zizanioides* increased from an initial $0.606 \pm 0.15 \text{ g}/\text{m}^2$ to $12.2 \pm 3.89 \text{ g}/\text{m}^2$ for the shoots and from $1.59 \pm 1.1 \text{ g}/\text{m}^2$ to $4.30 \pm 1.76 \text{ g}/\text{m}^2$ for the roots.

P uptake rates also differed between the plant species and between the roots and shoots (Figure 10). For all species, P uptake was higher in the shoots of the plants than in the roots. The P uptake was greatest for *B. articulata*, increasing from $0.019 \pm 0.010 \text{ g}/\text{m}^2$ to $12.9 \pm 3.87 \text{ g}/\text{m}^2$ for the shoots and from $0.008 \pm 0.0073 \text{ g}/\text{m}^2$ to $5.54 \pm 1.67 \text{ g}/\text{m}^2$ for the roots during the study. Despite having only six months of growth, *P. australis* P accumulation was the second highest, increasing from $0.0454 \pm 0.093 \text{ g}/\text{m}^2$ and reaching $7.69 \pm 3.85 \text{ g}/\text{m}^2$ in the shoots and increasing from $0.0302 \pm 0.017 \text{ g}/\text{m}^2$ to $2.82 \pm 1.40 \text{ g}/\text{m}^2$ in the roots at the completion of the study, despite only having six months of growth. *C. appressa* P accumulation increased from $0.0537 \pm 0.013 \text{ g}/\text{m}^2$ to $3.04 \pm 0.892 \text{ g}/\text{m}^2$ in the shoots and from $0.0158 \pm 0.0091 \text{ g}/\text{m}^2$ to $1.61 \pm 0.475 \text{ g}/\text{m}^2$ in the roots. P accumulation was lowest for *C. zizanioides*, which increased from $0.160 \pm 0.046 \text{ g}/\text{m}^2$ to $2.20 \pm 0.730 \text{ g}/\text{m}^2$ in the shoots and from $0.156 \pm 0.11 \text{ g}/\text{m}^2$ to $0.517 \pm 0.191 \text{ g}/\text{m}^2$ in the roots.

Figure 9. Nitrogen uptake in g/m^2 (mean $\pm$ error) for each plant species (please note different y-axis scales).

Figure 10. Phosphorus uptake in g/m^2 (mean $\pm$ error) for each plant species (please note different y-axis scales).

4. Discussion

4.1. Biomass Accumulation

Total biomass accumulation was found to vary between species, with *B. articulata* showing the greatest biomass accumulation, followed by *P. australis*, *C. appressa*, and *C. zizanioides* (Figure 6). The total biomass accumulation of *B. articulata* was approximately 2.3, 4.4, and 8.3 times greater than *P. australis*, *C. appressa*, and *C. zizanioides*, respectively.

The results demonstrate that the total biomass accumulated by plants within a CFW structure can be highly affected by species selection. Previous research [18,19] has shown that this can be attributed to differences in the morphology and physiology of different plant species.

Similar biomass accumulation differences were found by Zhu et al. [19], who compared the growth characteristics of seven species grown in a simulated CFW placed in a river receiving wastewater. Zhu et al. [19] reported variances of up to tenfold in the total dry mass accumulation of the seven plant species. Tanner and Headley [18] compared biomass accumulation of four species in a mesocosm study with artificial stormwater and found biomass accumulation to vary by up to 3.8 times between the species.

It is possible that the longer duration of the current study (217 days for *Phragmites*, 375 days for all others) in comparison to the 130-day duration for Zhu et al. [19] and 230-day duration for Tanner and Headley [18] played some role, allowing differences in the species to become more pronounced. Further, it is likely that biomass accumulation in this study was also influenced by high nutrient availability in the wastewater.

The patterns in biomass accumulation also differed in species, but generally, more biomass was stored in the plant shoots than in the roots. Final shoot-to-root biomass ratios were approximately 3.7 for *B. articulata*, 2.8 for *C. appressa*, 2.0 for *P. australis*, and approximately equal (1.2) for *C. zizanioides*. In high nutrient environments, plants tend to accumulate more of the plant biomass in the shoots relative to the roots [8,20]. White and Cousins [20] noted that greater accumulation in the shoots is likely a plant response to the presence of abundant nutrients, reducing the plants' need to expand the plants' roots. The opposite of this has also been found, where plants accumulate more biomass in the plant roots relative to the plant shoots in low nutrient environments such as stormwater ponds [21]. This is known as Optimal Allocation Theory, which suggests that plants' resources are allocated to the plant part, which will uptake the limiting resources [22].

The shoot-to-root ratios found in the present study appear to be in line with previous findings. Winston et al. [8] reported shoot-to-root ratios ranging between 0.4 and 6.3 from five plant species grown in CFW-treated stormwater. Tanner and Headley [3] also reported shoot-to-root ratios between 3.7 and 4.5 from four species through a mesocosm study.

The relatively high shoot-to-root ratio of *P. australis* in comparison with the other species used in this study and others is likely due to a combination of factors, such as a shorter growth phase (six months), nutrient availability within the pond, climate, and species physiology and morphology.

4.2. Nutrient Concentration in Plant Tissues

Similar to the biomass accumulation, nutrient concentrations within the plant tissues also varied between species and the plant roots and shoots over the course of the test (Figure 7). This indicates that the nutrient concentration within the plant tissue may be influenced by a number of factors. Schwammberger et al. [17] suggested that the nutrient concentration within the plant tissue may be positively correlated to the nutrient concentration in the in situ water environment. Therefore, it was hypothesized that the nutrient concentration of the plant tissues in the current study would be greater than the concentrations found in previous studies using stormwater or simulated waters, and this appears to be the case.

N concentrations were found to range between 0.414% and 2.71%, with a mean of 1.71% median value of 1.78% for the shoots and roots of each species (Figure 7). The P concentrations were lower, ranging between 0.106% and 0.443%, with a mean of 0.25% and median value of 0.245% (Figure 7). N concentrations were greater in the shoots in comparison to the roots for each species (Figure 7), while P concentrations were greater in the shoots, except for *B. articulata* (Figure 8). No explanation was found as to why *B. articulata* stored more P in the roots than the shoots.

There are no current research results available for the nutrient concentration of plants grown in a full-scale CFW in a sewage environment, so it is difficult to directly compare

these results. However, N and P concentrations have previously been reported from mesocosm and field-scale studies using stormwater and simulated stormwater. Tanner and Headley [3] reported the concentration of N and P in the shoots and roots of plants in a mesocosm study using artificial stormwater. They found that the N and P concentrations were greater in the plant shoots in comparison to the roots. Plant N concentrations ranged between 0.8% and 1.4%, while the P concentrations ranged between 0.06% and 0.17% [3]. These results conflicted with that of Winston et al. [8], who reported the N and P concentrations of five species from two stormwater pond CFW systems. Winston et al. [8] reported N and P concentrations being greater in the below-mat biomass in comparison to the above-mat biomass for four of the five species. N and P concentrations were 1% or less for the above-mat biomass and between 1% and 2% for the below-mat biomass [8]. As the N and P concentrations in the stormwater for the Tanner and Headley [3] and Winston et al. [8] studies were considerably less than in the present study, the larger concentration of nutrients in the plant tissues of the current study was not unexpected. This is in line with results from Schammburger et al. [17] who suggested a correlation between water and plant nutrient content, supporting the Optimal Allocation Theory.

4.3. Nutrient Accumulation

The total plant uptake of N and P was found to differ between the species with greater uptake in the plant shoots relative to the plant roots (Figures 9 and 10). This is consistent with the findings of Garcia Chance, et al. [6] and Spangler et al. [23]. *B. articulata* was found to have the greatest uptake of both N (shoots: 104 ± 31.5 g/m², roots: 23.9 ± 7.23 g/m²) and P (shoots: 12.9 ± 3.87 g/m², roots: 5.54 ± 1.67 g/m²). *B. articulata* was followed by *P. australis*, which had a greater proportion of the uptake in the shoots (N: 52.5 ± 26.2 g/m², P: 7.69 ± 3.84 g/m²) in comparison to the roots (N: 17.1 ± 8.50 g/m², P: 2.82 ± 1.40 g/m²). The nutrient uptake in the shoots of *C. appressa* was less (N: 21.6 ± 6.28 g/m², P: 3.04 ± 0.892 g/m²), with similarly low levels in the roots (N: 12.3 ± 3.63 g/m², P: 1.61 ± 0.475 g/m²). *C. zizanioides* results were also low in both the shoots (N: 12.2 ± 3.89 g/m², P: 2.20 ± 0.730 g/m²) and roots (N: 4.30 ± 1.76 g/m², P: 0.518 ± 1.91 g/m²).

Colares et al. [13] completed a bibliometric analysis of floating wetland studies, inclusive of a comparison of reported nutrient uptake rates from various studies. Previous research that considered plant growth and nutrient uptake is limited to applications such as stormwater treatment and mesocosm-scale studies. While the results of such studies may not be directly comparable to CFWs used for sewage treatment, these studies provide some quantification of plant growth and nutrient uptake for CFW installations. Prior to the current study, the greatest reported N uptake by CFW plants was found by Garcia Chance and White [24], who reported a total N uptake (shoots and roots combined) of 45.4 g/m². Likewise, the greatest P uptake previously reported was 28.3 g/m² by Wang et al. [22]. However, as these studies were not focused on CFWs for a sewage treatment application at the field scale, the findings are not directly comparable.

At the completion of the study after 375 days of growth, it was estimated that across the shoots and roots of the four plant species, 30.1 kg of N and 4.39 kg of P were removed. Due to the greater biomass accumulation and higher concentration of nutrients in the shoots relative to the roots, the majority of the nutrient accumulation was contained in the shoots. It was estimated that 23.2 kg of N and 2.97 kg of P were removed in the plant shoots across the four CFW islands. The majority of the N and P removal was via *B. articulata* and *P. australis*.

In addition to the removal of nutrients via the CFW plants, nutrients may also be removed via numerous chemical, physical, and biological processes [5]. Due to the numerous and unquantifiable potential nutrient removal pathways in the WSP system, a mass balance was not completed for the system over the duration of the study, and therefore, the portion of pollutants removed from the system apart from plant uptake was not able to be accurately estimated. Discussion on the fate of pollutants removed from the WSP system

outside of plant sequestration is outside of the scope of the present paper; however, this may be considered and quantified in future research.

4.4. Harvesting Recommendations

This study has demonstrated that certain CFW plants can remove pollutants from domestic sewage by sequestering the pollutants within the plant tissues. However, after the pollutants have been sequestered by the plants, plant harvesting is required to prevent the nutrients re-entering the water as the plant biomass starts decaying [13,20].

Previous literature has suggested that plant harvesting of both roots and shoots should be used to maximize nutrient removal in comparison to shoots only harvesting [3,20,25]. While it is theoretically possible to harvest the plant roots from CFW systems, it can be difficult, time consuming, and costly. Harvesting only the plant shoots appears to be the most practical and cost-effective option in most cases. Harvesting the shoots may also assist the plants to regrow from the remaining root systems. However, this would depend on the ability of the plant to survive a shoot-only harvest and to regrow to a similar size, which would require additional research. This study, along with others [3,17], has shown that the shoots of the plants contained greater amounts of nutrients than the plant roots, which is beneficial from a harvesting perspective.

Harvesting of plant biomass may emerge as a primary component of the operation and maintenance of CFWs in the future [25]. Pavlineri et al. [1] suggested that the optimal period for biomass harvesting should consider the seasonal translocation of nutrients. However, due to the relatively short duration and location of the current study, these seasonal effects were not observed. Additionally, biomass increases had a much greater effect on total plant nutrient uptake rates than changes in plant tissue nutrient concentrations. Therefore, an appropriate biomass harvesting strategy would typically involve harvesting the plants after the maximum growth had been estimated. The point of maximum growth may be estimated through frequent measurement of various parameters, including the shoot and root lengths or density.

Based on the results of our study using *B. articulata* and *P. australis* CFW plants in Southeast Queensland, we suggest that the optimal harvesting regime for these two plants would be carried out biannually, at the start and conclusion of the growing season in subtropical climates (September to May). This is in line with previous suggestions from Weragoda et al. [26], who proposed harvesting plants two months after maximum shoot height and production had been reached to optimize nutrient removal.

5. Conclusions

This full-scale field study examined the use of four different plant species in CFWs to remove nutrients from domestic sewage treated in a WSP. This is the first field study that quantifies the plant biomass accumulation, plant nutrient concentration, and nutrient uptake of a variety of CFW plants grown in a WSP.

Biomass accumulation varied between the plant species and was greatest in *B. articulata*. Biomass accumulation was greater in the plant shoots for *B. articulata*, *P. australis*, and *C. appressa*, while the biomass accumulation was approximately equal between the shoots and roots of *C. zizanioides*. Plant tissue nutrient concentrations varied over the duration of the study, with a median N concentration value of 1.78% and a median P concentration value of 0.245%.

Plant nutrient uptake was found to be more dependent on the plant biomass than changes in the nutrient concentrations. The nutrient uptake rates varied between the species, with *B. articulata* having the greatest nutrient uptake.

The results of this study indicate that the use of CFWs with carefully selected plant species can successfully remove significant amounts of nutrients from domestic wastewater. More research is required to quantify the water quality improvement in the pond due to the CFW plants.

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Conflicts of Interest: Authors Terry Lucke and Chris Walker both declare a financial interest in Clarity Aquatic Pty Ltd., the company that distributes the CFW product used in this study. However, this manuscript does not discuss or examine the CFW product or its performance in any way. Hence, we declare no conflicts of interest with any aspect of this study.

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