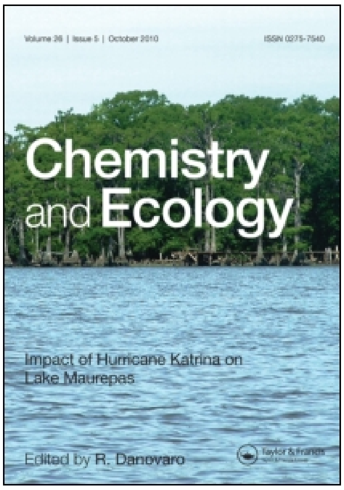

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Efficiency of coconut coir-pith as an alternative substrate in the treatment of submerged macrophyte wetland systems in tropical conditions

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The effects of coconut coir-pith as an alternative substrate material in submerged macrophyte wetland systems were investigated in three similar pilot-scale wetlands (WL1, WL2 and WL3) planted with *Hydrilla verticillata*. The substrate layers of WL1 and WL3 were river sand and coconut coir-pith, respectively, whereas that of WL2 was a mixture of river sand and coir-pith (ratio 1 : 1). The influent and effluent water-quality parameters were examined weekly to identify the effects of coir-pith on the treatment process. The results showed that the total nitrogen removal efficiency was higher in WL2 (52.3%) and WL3 (62.1%) than in WL1 (29.1%). The most efficient removals of biodegradable organic compounds (54.4%) and total dissolved solids (40.5%) were encountered in WL2, whereas the maximum total suspended solids (66.4%) and conductivity (38.5%) reductions were found in WL3. However, the PO_4^{3-}–P removal efficiency was only slightly improved in WL2 (74.2%) and WL3 (74.4%) over WL1 (68.7%). Microbiological investigations revealed that WL2 and WL3 were more efficient in removing *Escherichia coli* than WL1. Statistical analyses by ANOVA showed that the water treatment efficiencies of WL2 and WL3 were substantially better than WL1 ($p < 0.05$).

Keywords: adsorption; coconut coir-pith; organic carbon; submerged macrophytes; substrate; water reclamation

1. Introduction

Much effort has been spent in identifying useful techniques that increase water treatment activity in wetland systems. The effects of changing nutrient concentration [1], inorganic carbon concentration [2,3], water level fluctuation [4,5] and a surplus of decaying plant species [6] are some of the areas that have been investigated during the last few decades.

The impact of external organic carbon supplements on the performance of water treatment was investigated, focusing on emergent macrophytes in particular [7]. The significant contribution of heterotrophic denitrifying bacteria, which use these organic compounds in the removal of nitrogen is currently well understood [8]. However, the higher adsorption capacities of these

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alien materials in wetland systems [9] have improved substrate activities in nutrients removal by enhanced adsorption [10]. In addition, a positive correlation between plant biomass and the presence of surplus organic matter in sediment has been demonstrated [11]. Consequently, accelerated growth of macrophytes may also improve the natural purification activity in wetlands [7].

Coir-pith has been studied extensively to elucidate its chemical and physical characteristics [12]. The coconut tree (*Cocos nucifera*) is a member of the palm family and grows in tropical climates. Its fruit consists of coconut husk, shell and kernel from outside to inside respectively. Coir pith is byproduct of the coconut industry and comes from the outer part of the fruit, i.e. husk. The husk is mainly made of fibre and hence coco-pith contains fibres and a dust of organic materials. Coir fibre consists of lignin and cellulose particles ranging in size from 0.2 to 2.0 mm. Most importantly, it has a capacity for cation exchange, gas adsorption, ammonium nitrogen adsorption and pH buffering (3.7–10.4). Hydroxyl and carboxyl branches of the long cellulose chain provide the cation-adsorption capacity of coir-pith. A previous experiment showed that coir-pith can adsorb 516 and 573 mmol $N \cdot kg^{-1}$ at pH 4.6 and 5.1, respectively [12]. Further, coir-pith can be used to adsorb ammonium nitrogen from wastewater [13] and then employed in agriculture soil to release ammonium as a fertiliser. However, investigation into the effects of coir-pith in a submerged plant wetland for nutrient removal is required.

We speculate here that the surplus organic carbon supplied by coconut coir-pith may support tertiary wastewater treatment, which requires more efficient denitrification [13]. However, the treatment efficiency of submerged macrophyte systems supplemented with coconut coir-pith is not yet well documented. Consequently, this experiment was conducted to determine the optimum ratio of river sand to coconut coir-pith to use as the substrate layer in submerged macrophyte wetland systems and to evaluate its effectiveness in wastewater treatment.

2. Material and methods

A preliminary experiment (EXP1) was conducted to determine the correlation between the percentage of coir-pith in a substrate and the growth characteristics of *Hydrilla verticillata*. Growth of *H. verticillata* was monitored in 5 L microcosms with five different ratios of river sand to coconut coir-pith (by weight, sand/coir 5 : 0, 4 : 1, 3 : 2, 2 : 3 and 1 : 4). Plant stems 15 cm long were planted in each microcosm. Plants were harvested at 1 week intervals for a period of 45 days and oven dried at 70 °C for 48 h until they reached a constant weight to determine the dry mass of the plants.

Based on the results of the above preliminary experiment to optimise the river sand and coir-pith ratio, a pilot-scale experiment (EXP2) was conducted. Three wetlands (5.0 m long and 1.0 m wide, respectively, at the ground surface level with a trapezoidal cross-section area of 0.45 m^2 perpendicular to the flow direction) were used to treat domestic wastewater from a student hostel at the University of Peradeniya, Sri Lanka, for an experimental period of four months. The existing wastewater treatment facility (Figure 1) had been developed to function as an integrated system with a septic tank and two parallel subsurface flow emergent plant wetlands of *Scirpus grossus*, followed by three pilot-scale wetlands planted with submerged macrophytes [14].

The substrate layers of the pilot-scale wetlands were supplemented with river sand only (WL1), river sand and coir-pith in equal quantities by volume (WL2), and coir-pith only (WL3). A substrate layer 10 cm thick was laid on the bottom of cement-coated floors. The hydraulic retention time was maintained at four days to provide sufficient contact time for interactions among macrophytes, the substrate and wastewater contaminants.

H. verticillata was planted in all three wetlands with an initial plant length of 15 cm, keeping a 10 cm gap between each bundle of three plant stems. Wetlands were fed initially with tap water

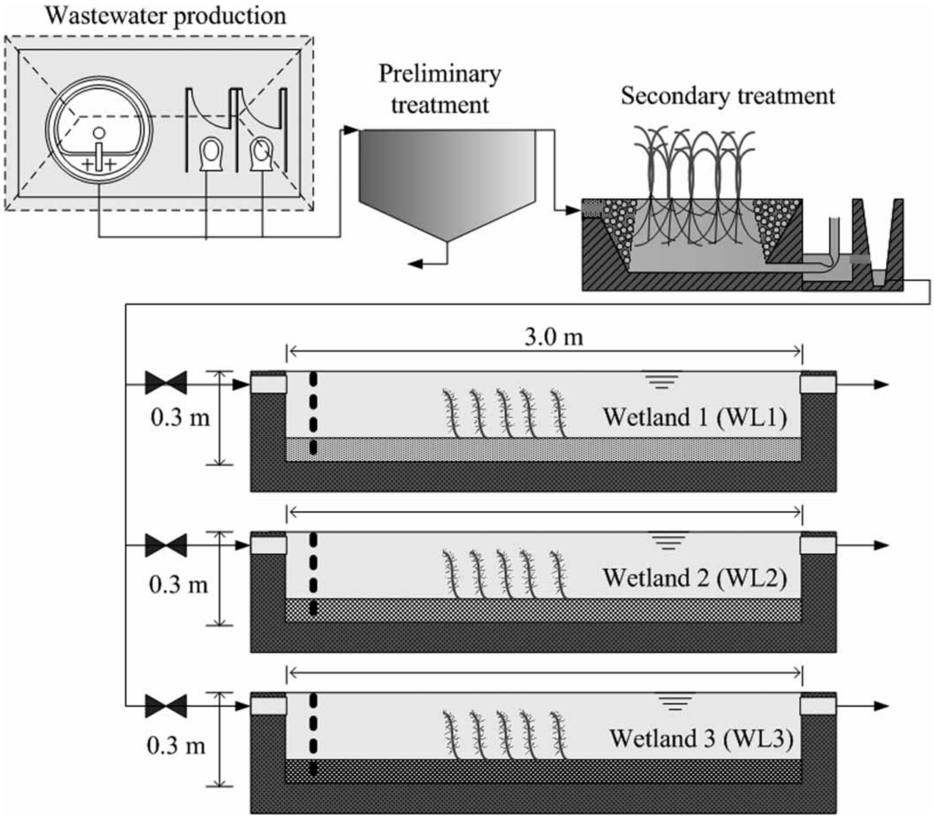

Figure 1. Experimental set-up showing three parallel wetlands in a series of treatment processes with primary and secondary treatment units in tandem (WL1, river sand only; WL2, river sand/coir-pith = 1 : 1; WL3, coir-pith only) in EXP2.

for 14 days to avoid high nutrient loading during the establishment of plants before sending partially treated secondary wastewater. The entire system was allowed to run for four weeks after introducing wastewater for acclimatisation. Subsequently, influent and effluent water samples were collected weekly at the outlet of each wetland and transferred to the laboratory. In addition, on-site measurements of temperature and pH were taken.

NH_4^+-N, NO_3^--N, total nitrogen (TN), PO_4^{3-}-P, biodegradable organic compounds (BOD_5), total dissolved solids (TDS), total suspended solids (TSS), pH, dissolved oxygen (DO), temperature, conductivity and faecal coliforms in the samples were quantified at 7 day intervals for a period of 70 days. ANOVA was used to evaluate whether a significant difference in nutrient-removal efficiencies of coconut coir-pith and river sand existed.

3. Results and discussion

3.1. *Effects of coir-pith on growth of macrophytes (EXP1)*

In EXP1, the maximum average growth rate of *H. verticillata* was observed when the substrate composition of river sand/coir-pith was 3 : 2 (Figure 2). Neither material alone supported the growth of macrophytes well. River sand might not have enough nutrients for plant growth in the early stages. By contrast, excessive added compounds from the coir-pith might have affected

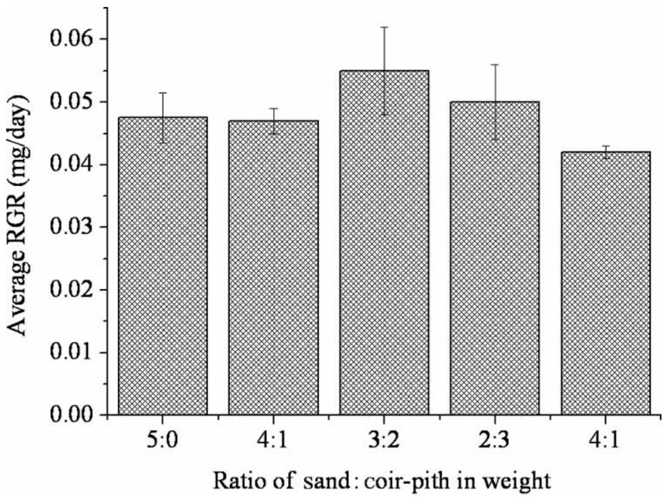

Figure 2. Average relative growth rates (RGR) of *Hydrilla verticillata* in different sand/coir-pith combinations in substrate in EXP1 ($n = 6$).

the macrophytes negatively because the substrate layer became suspended when the coir-pith proportion increased and caused instability for plant growth. However, coir-pith and sand in equal proportions as the substrate might have encouraged the growth of macrophytes, because coir-pith contains equal portions of lignin and cellulose and is rich in potassium and micronutrients such as Fe, Mn, Zn and Cu [15].

3.2. *Comparison of water treatment efficiencies in coir-supplemented pilot-scale wetlands with others (EXP2)*

The temperature of the influent remained almost constant ($\cong 24\,^{\circ}$C) during the experimental period, whereas the pH of the three wetlands was marginally higher at the outlet than at the inlet. The average influent and effluent water-quality parameters of each wetland are shown in Table 1. A relatively higher fluctuation in the influent water-quality parameters was encountered during the experimental run due to fluctuations in the number of facility residents and environmental factors, such as rainfall intensity and evapotranspiration. The pH of the three wetlands increased due to the effects of photosynthesis. The highest pH was encountered in WL2, where the maximum growth of macrophytes was identified. Therefore, a correlation between plant activity and the alkalinity of the effluent was established. The lowest pH was observed in WL3 due to the weakly functioning acidic groups released by coir-pith [12]. No considerable difference was observed between the dissolved oxygen (DO) concentrations of influent and effluent during the whole experimental period. However, the biological oxygen demand (Table 1) was comparatively greater in WL2 and WL3 than in WL1. The relatively large surface area of the wetlands facilitated the dissolution of oxygen in water to maintain a constant DO concentration.

3.3. *Nitrogen removal efficiency*

The maximum removal efficiency of NH_4^+-N in EXP2 was observed in WL2 (Table 1). The removal efficiency was marginally reduced in WL3, which had only coir-pith as the substrate, whereas the lowest removal was encountered in WL1, which had only river sand. However, the overall NH_4^+-N removal efficiency was higher in all three pilot-scale wetlands than usually expected values due to

Table 1. Influent and effluent water-quality data of three different pilot-scale wetlands with sand (WL1), coir-pith+sand (WL2) and coir-pith (WL3) in EXP2 ($n = 10$).

		Concentration				Removal efficiency (%)		
Parameter	Units	Inflow	WL1	WL2	WL3	WL1	WL2	WL3
pH	–	5.9 ± 0.9	6.7 ± 0.7	7.0 ± 0.6	6.5 ± 0.7	–	–	–
DO	$mg \cdot L^{-1}$	6.8 ± 1.4	6.5 ± 1.5	6.2 ± 1.5	6.7 ± 1.3	–	–	–
BOD_5	$mg \cdot L^{-1}$	17.9 ± 9.0	11.4 ± 6.2	8.2 ± 3.5	9.7 ± 3.1	36.2	54.4	45.6
NH_4^+-N	$mg \cdot L^{-1}$	41.5 ± 9.7	9.2 ± 10.3	2.9 ± 1.3	4.5 ± 3.9	77.5	93.0	89.0
NO_3^-N	$mg \cdot L^{-1}$	0.34 ± 0.2	1.18 ± 1.0	1.03 ± 1.1	1.08 ± 0.7	−242	−200	−215
TN	$mg \cdot L^{-1}$	241 ± 82	171 ± 66	115 ± 59	91 ± 52	29.1	52.3	62.1
PO_4^{3-}-P	$mg \cdot L^{-1}$	1.7 ± 0.6	0.5 ± 0.4	0.4 ± 0.3	0.4 ± 0.2	68.7	74.2	74.4
TDS	$mg \cdot L^{-1}$	187 ± 51	117 ± 52	111 ± 51	114 ± 36	37.6	40.5	39.0
TSS	$mg \cdot L^{-1}$	109 ± 85	67 ± 47	38 ± 35	37 ± 34	37.5	65.4	66.4
Conductivity	($\mu s \cdot cm^{-1}$)	391	246	250	241	37.1	36.1	38.5
Faecal coliforms	(CFU$\cdot$ 100 mL^{-1})	8613	5902	623	867	31.5	92.8	89.9

Note: DO, dissolved oxygen; BOD_5, biodegradable organic compounds; TN, total nitrogen; TDS, total dissolved solids; TSS, total suspended solids.

a higher rate of nitrification [8]. The NO_3^--N concentration was increased in the effluent compared with that of influent because of the almost complete nitrification. Usually, nitrification takes place more rapidly than denitrification in submerged plant macrophyte systems due to the favourable conditions prevailing in the daytime. Hence, the relatively higher concentration of NH_4^+-N in the influent made the effluent NO_3^--N concentration increase compared with the influent. However, actual NO_3^--N removal efficiency must be very high because almost all the nitrified NH_4^+-N was removed via the denitrification process (Table 1).

TN removal efficiencies in the pilot-scale wetlands with coir-pith were always higher than that in the wetland with only river sand ($p < 0.05$). It has been reported that the carbon/nitrogen ratio should be at least 5:1 for complete nitrogen removal in a wetland system [7]. Accordingly, surplus carbon from external sources may enhance the denitrification process, particularly at the lower organic concentrations of the influent. Denitrification might have occurred predominately in the substrate rather than the water due to the higher possibility for the formation of anoxic conditions in the substrate under eutropic conditions. Consequently, the surplus of readily available organic compounds in the substrate may have led to better removal of TN from the system. This may have resulted in a higher TN removal rate in WL2 and WL3 than WL1 ($p < 0.05$).

The greater adsorption capacity of coir-pith might also have enhanced TN removal in WL2 and WL3 [12]. However, TN removal efficiency improved with the increasing percentage of coconut coir-pith in the substrate up to a certain point. The effects of coir-pith in the substrate did not vary significantly at higher concentrations in EXP1 (coir-pith % > 50) (Figure 3).

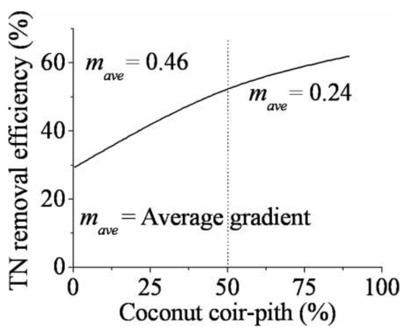

Figure 3. Change in total nitrogen removal efficiency with percentage of coconut coir-pith in the substrate in EXP1.

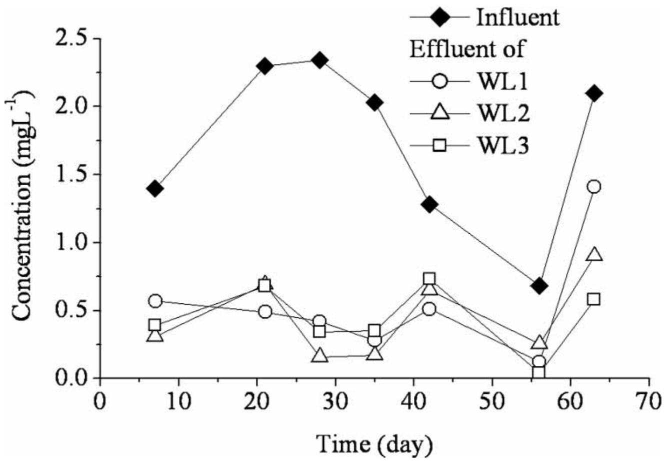

Figure 4. Changes in influent and effluent concentrations of PO_4^{3-}-P during the study period in EXP2 (WL1, river sand only; WL2, river sand/coir pith = 1 : 1; WL3, coir pith only).

In order to obtain a complete biochemical process, the influent composition should be balanced, with an $BOD_5/N/P$ ratio, for example, in the feed wastewater of 100 : 5 : 1 [16]. The influent of this experiment contained a ratio of BOD_5/inorganic N/PO_4^{3-}-P of 100 : 230 : 11. Consequently, incomplete removal of nitrogen in the system due to lack of easily biodegradable organic matter for denitrification could be expected.

3.4. *Phosphorus removal efficiency*

Phosphorous is considered to be the controlling nutrient of eutrophication in ecological systems because N can be fixed from the atmosphere, whereas P has no other route of entry than the inflow. The major mechanisms for P removal are plant uptake or retention in the soil. All three pilot-scale wetlands were efficient enough to remove >65% of the influent PO_4^{3-}-P. Approximately 40–60% removal of P in wastewater can be expected depending on the type of wetland. However, P removal efficiency was not improved by the introduction of coconut coir-pith as an alternative substrate material [13]. Only a marginal improvement could be observed in WL2 and WL3 over WL1 (Table 1). Growth of *H. verticillata* was not improved to a level that would have had a significant effect on the PO_4^{3-}-P removal mechanism of the amended pilot-scale wetlands. Thus, the effect of direct plant utilisation of free orthophosphate did not vary with the presence of surplus organic carbon [8].

The PO_4^{3-}-P removal efficiency decreased during the later stage of the experimental run, especially in WL1 (Figure 4). Even though the effluent PO_4^{3-}-P concentration did not increase with fluctuations in the influent concentration, it followed the same pattern as the influent after the 35th day following the commencement of analysis. The removal efficiency of PO_4^{3-}-P might be reduced over time because adsorption is a saturable process. Even though the removal capacities of all three pilot-scale wetlands remained the same during the experimental period, the end results showed a greater difference. This might be due to the lower adsorption capacity of river sand than the coir-pith used in the experiment.

3.5. *Removal of organic compounds and dissolved and suspended solids*

The removal efficiency of biodegradable organic compounds (BOD_5) was significantly higher in WL2 than WL1 ($p < 0.05$). The removal of organic matter might have taken place principally due to aerobic or anaerobic microbiological decomposition or mineralisation. In fact, mineralisation of soluble and fine particulate material might occur readily in biofilms, whereas the mineralisation of coarse particulate organic matter might take place primarily in sediments [16]. Certainly, the wastewater used in the experiment had undergone prior treatment during the early processes, and only fine and soluble particles remained in the influent prior to entering the pilot-scale wetlands. Accordingly, the biological processes occurring in biofilms might have been encouraged by the addition of coir-pith because the highest removal was encountered in WL2. However, the coir-pith worked better when it was mixed with sand rather than when it was used alone in the substrate (Table 1). This may be due to the higher growth rate of *H. verticillata* in mixed substrates than in a single substrate (Figure 2). Dense macrophytes might have supported BOD_5 removal well with the addition of a proportionately greater DO concentration in the system. Sedimentation may have played a vital role in removing organic matter first from the wastewater [17] and then the degradation of settled organic matter might have come into play.

The removal efficiency of total suspended solids (TSS) was better in both coir-pith pilot-scale wetlands than in the system with river sand alone. Suspended solids (SS) may lead to the presence of organic and inorganic particles in water. The tropical climate that is suitable for the growth of algal blooms might have contributed greatly to SS in wastewater, causing a larger organic fraction at the tertiary level. However, SS removal in a wetland system is a physical process. It may consist of sedimentation, aggregation and surface adhesion [17]. Removal of the largest and heaviest particles might not take place in the wetlands because they have already been removed in the previous steps. However, the removal efficiency of relatively smaller and lighter particles might have been enhanced by the macrophytes in WL2 because it demonstrated the best growth of *H. verticillata*. The introduction of coir-pith into the submerged system did not improve the efficiency of removal of total dissolved solids (TDS). Similarly, the removal efficiency of conductivity was not increased and showed a nonaligned character related to the introduction of coir-pith. Therefore, the availability of coir-pith did not have any substantial impact on the removal of dissolved organic and inorganic compounds.

The presence of faecal coliforms (FC) can be correlated with BOD and TSS [18]. Pathogenic bacteria and viruses are removed by mechanisms such as predation, sedimentation, absorption and die-off due to unfavourable environmental conditions, including UV light and temperatures unfavourable for cell reproduction. In addition, an increase in pH will help to reduce the number of coliforms. The experimental observations found a large number of FC in the influent (Table 1). However, the microbiological treatment efficiency was improved in the two pilot-scale wetlands with the coconut coir-pith compared with the wetland with only river sand. A greater removal efficiency of FC (*E. coli*) (>80%) was observed in WL2 and WL3. By contrast, the removal efficiency was low (30%) in WL1, in which only river sand was used as the substrate material.

4. Conclusion

The experiment demonstrated very evidently the increased treatment activity of coconut coir-pith-supplemented submerged wetlands in wastewater reclamation. The best removal efficiencies in terms of total nitrogen and total suspended solids were encountered in the wetland with only coconut coir-pith as an alternative substrate material. Removal of the biological oxygen demand and ammonium was better when a mixture of river sand and coconut coir-pith was used as the substrate. However, the introduction of coir-pith did not increase the removal of phosphate–phosphorus, dissolved solids and conductivity in the submerged macrophyte systems used for wastewater treatment.

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