The use of palm kernel shell (PKS) as substrate material in vertical-flow engineered wetlands for septage treatment in Malaysia

Valerie Siaw Wee Jong and Fu Ee Tang

ABSTRACT

In this study, the treatment of septage (originating from septic tanks) was carried out in a pilot-scale, two-staged, vertical-flow engineered wetland (VFEW). Palm kernel shells (PKS) were incorporated as part of the VFEW's substrate (B-PKS), to compare its organic matter (OM) and nitrogen (N) removal efficiency against wetlands with only sand substrates (B-SD). The results revealed satisfactory OM removal with >90% reduction efficiencies at both wetlands B-PKS and B-SD. No increment of chemical oxygen demand (COD) concentration was observed in the effluent of B-PKS. Ammonia load removal efficiencies were comparable (>91% and 95% in wetland B-PKS and B-SD, respectively). However, nitrate accumulation was observed in the effluent of B-SD where PKS was absent. This was due to the limited denitrification in B-SD, as sand is free of carbon. A lower nitrate concentration was associated with higher COD concentration in the effluent at B-PKS. This study has shown that the use of PKS was effective in improving the N removal efficiency in engineered wetlands.

Key words | faecal sludge, nitrogen, palm kernel shell, vertical engineered wetland

Valerie Siaw Wee Jong (corresponding author)
Fu Ee Tang
Curtin University Sarawak Campus,
CDT 250, 98009 Miri,
Sarawak,
Malaysia
E-mail: *Valval.jong@gmail.com*

INTRODUCTION

The widespread usage of individual septic tanks in Malaysia results in large amounts of septage, which is the predominant type of faecal sludge generated. Low-technology and cost-effective systems that harness natural processes have increased in popularity as such systems have been proven to achieve equally good results for wastewater treatment. Vertical-flow engineered wetlands (VFEWs) have gained importance as a technically feasible approach for sludge dewatering and mineralization.

On wetlands, while the sludge dries by evaporation, the growing reeds derive nourishment and moisture from the sludge, both stabilizing the sludge and reducing its volume. However, limited research on the performance of VFEWs in a tropical climate have been reported to date, especially for septage treatment (Koottatep *et al.* 2001; Paing & Voisin 2005; Vincent *et al.* 2011), and the understanding of factors (both system design parameters and operational practices) that contribute to the efficiency of the system. This paper presents an investigation of the effects of using palm kernel shell (PKS) as part of the wetland substrate for treatment of pre-treated local septage, using pilot-scale, two-staged, VFEWs.

The major removal mechanisms for total nitrogen are microbial nitrification and denitrification processes (Korkusuz *et al.* 2005). The limitations of conventional wetland substrate (gravel) in terms of nitrogen removal have encouraged the use of alternative materials. Previous research had found several types of organic solids that can be used as wetland media, as well as providing carbon to support the denitrification process. Organic substrates like maize cobs, green waste, wheat straw, and soft and hard wood were used as external carbon sources to increase denitrification rates (Cameron & Schipper 2010).

As Malaysia is a leading country in the palm oil industry, a large amount of palm oil by-products, such as PKS, are generated. It is estimated that 0.4 million ton of PKS is created for every 1 million ton of palm oil produced (Bt Fuadi *et al.* 2012). Owing to its high volatile and carbon contents (about 18% w/w) (Aik & Jia 1998), it is theorized that PKS could contribute additional carbon internally to improve

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nitrate removal from the septage, via the coupled nitrification–denitrification process.

METHODS

The system consists of pilot-scale VFEWs set in an open field beside the Curtin University Sarawak Campus sewage treatment plant, under a semi-transparent roof to shelter the system from rainfall. The system comprises two stages of VFEWs and storage tanks as shown in Figure 1.

The first stage consisted of three VFEWs aimed at solid–liquid separation. Septage was stored in two elevated receiving tanks and gravity-fed into the first stage wetlands on a weekly basis. Septage for the plant was obtained from a local environmental service provider and sourced from residential and communal septic tanks, which receive only blackwater. Coarse materials were removed from the septage before storage by simple filtration to screen out the gross solids. The receiving tanks were fitted with a mechanical mixer to homogenize the septage before being loaded onto the first stage wetlands.

The resulting filtrate from the first stage wetlands was stored in the effluent collection tank before being piped into the second stage wetlands ('B' wetlands) for further treatment. At this second stage wetlands, pumps and timers were used to control the filtrate feeding frequency and volume of loading for each session. The results from B wetlands, which pertain to the use of PKS are presented in this paper. The B wetlands were filled with limestone aggregates as the drainage layer, overlaid by a 300 mm thick intermediate stratum of PKS, topped with pea gravel, and covered by a layer of sand. The wetlands with PKS are denoted as B-PKS, while the wetlands with sand and without PKS are denoted as B-SD. The macrophyte used at all stages in the study was *Phragmites karka*, a common reed found locally.

In this study, loading was carried out in batch mode and in intermittent mode, where the designated volume of influent was fractioned into smaller doses and applied at stipulated intervals. Owing to space constraints, only the intermittent mode results are presented and discussed here. Under this mode, the wetlands were fed four times daily, at a hydraulic loading rate of 8.75 cm/d, while the effluent was allowed to drain freely.

The influent and effluent of each wetland at each stage were collected and analyzed weekly for the following water quality parameters: total solids, total suspended solids, total volatile solids, total volatile suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), nitrite–nitrogen (NO_2-N), nitrate–nitrogen (NO_3-N), and ammonia–nitrogen (NH_4-N) with a spectrophotometer based on USEPA-approved standard procedures for wastewater analyses. Removal efficiencies were obtained by calculating the influent pollutant load reduction from the effluent at each treatment stage. *In-situ* tests such as pH, temperature, dissolved oxygen (DO), oxidation-reduction potential (ORP) and electric conductivity (EC) were also carried out weekly on the influent before each feeding and on effluents immediately after collection. Here, due to space constraints, only selected results are presented.

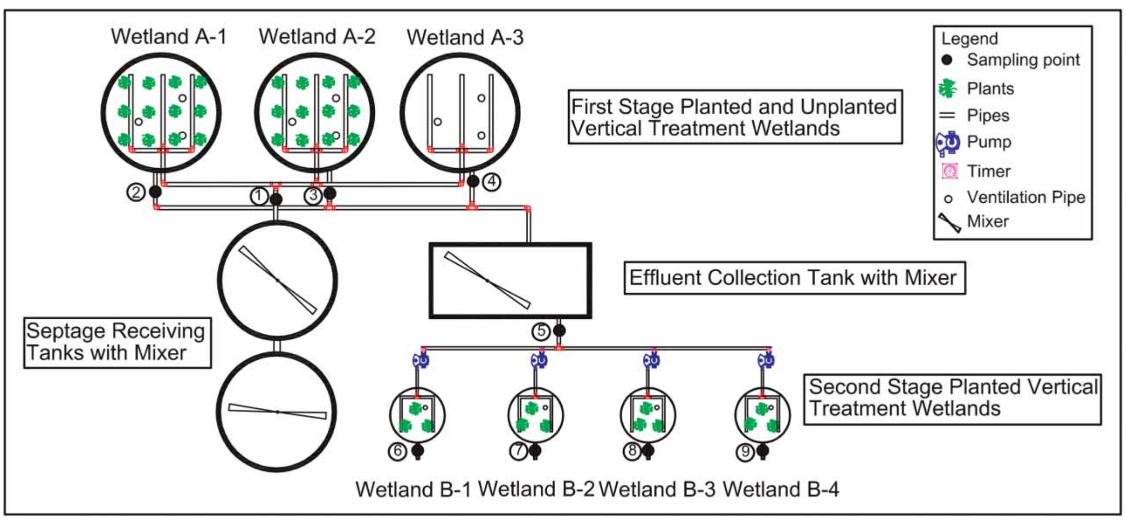

Figure 1 | Schematic diagram of the experimental set-up.

For analysis of the collected results, one-way analysis of variance (ANOVA) tests were conducted to assess the obtained data. Post hoc multiple comparison tests were also performed using Tukey's family error rate. The level of significance was set at $P < 0.05$.

RESULTS AND DISCUSSION

Physico-chemical parameters

Table 1 shows the physico-chemical characteristics of the pre-treated septage and the corresponding wetlands effluent from the B-PKS and B-SD beds. A significant increase in the DO and ORP values of the treated effluent was observed, as shown in Table 1. This indicated that the wetland influent, which was pre-treated septage from the first stage of the experimental rig, was oxidized. This could be attributed to good substrate design and the intermittent feeding strategy, which aided the oxygenation of the wetland influent. The EC values were also observed to increase. Effluent from wetland B-SD was found to have lower pH and higher EC values than that of wetland B-PKS. This could be due to the possible interactions between the substrate with the biofilm, which released water-soluble salts, increasing conductivity.

Table 1 | Physico-chemical parameter statistics for the pre-treated septage (influent), and effluent from wetland B-PKS and B-SD

		Statistics			
Parameter	**Sampling point**	***N****	**Range**	**Mean**	**Std dev.**
Temperature (°C)	Influent	10	25.10–29.50	27.08	1.31
	B-PKS	10	24.50–31.50	27.65	2.13
	B-SD	10	24.70–30.70	27.47	2.04
pH	Influent	10	7.12–8.05	7.50	0.26
	B-PKS	10	6.77–7.09	6.90	0.11
	B-SD	10	6.54–6.98	6.73	0.15
DO (mg/L)	Influent	10	0.50–2.54	1.32	0.68
	B-PKS	10	2.51–7.59	4.70	1.40
	B-SD	10	3.66–5.74	4.56	0.65
ORP (mV)	Influent	10	– 262–215	–	–
	B-PKS	10	118–403	–	–
	B-SD	10	101–387	–	–
EC (mS/cm)	Influent	10	1.70–2.17	1.94	0.16
	B-PKS	10	1.98–2.50	2.13	0.16
	B-SD	10	2.25–3.11	2.57	0.27

**N* is the number of samples collected and analyzed for each parameter during the study period.

Organic matter removal

The influent and effluent organic matter (OM) statistics for the two beds are reported in Table 2. During operation, clogging was not observed in either wetland B-PKS or B-SD. Both beds demonstrated comparable filterability, attaining similarly good removal of organic compounds for both feeding regimes.

Generally, the performance of the beds in both COD and BOD_5 removal was satisfactory, with more than 90% reduction in both B-PKS and B-SD wetlands. Both beds were able to appreciably reduce COD regardless of substrate materials, producing effluent with a mean of 145 mg COD/L for B-SD and 199 mg COD/L for B-PKS under intermittent loading (Table 2). This suggests that the organic pollutants exist mostly in particulate form, which facilitates filtration by the substrate media in the vertical wetlands.

The subsurface flow wetland system has been recognized as the constructed wetlands with the best filtration efficiency (Rousseau *et al.* 2004). This is because the processes controlling contaminant retention in a constructed wetland sediment could be abiotic (physical and chemical) and/or biotic (microbial and phytological) (Davis 1995), where settleable organics are primarily removed by physical deposition, sedimentation and filtration on top of the beds.

Wetland B-PKS uses organic substrate (PKS) as the treatment media, which acted as a carbon source that could potentially release soluble OM into the bed effluent, thereby increasing COD content in the outflow water. However, no increment of COD concentration and mass were observed in the effluent of wetland B-PKS, apart from achieving slightly lower COD reduction efficiencies than wetland B-SD.

In terms of BOD_5 removal efficiencies, wetland B-SD produced effluent with the lowest strength of BOD_5, which ranged between 0.66 and 6 mg/L or 0.05 and 0.42 g/m^2 d (Table 2). Analysis of the experimental results showed that the BOD_5 elimination efficiencies between B-PKS and B-SD beds varied significantly, with the SD beds greatly out-performing the PKS beds. The BOD_5 removal efficiencies in terms of load reduction percentages between B-PKS and B-SD ranged from 95% to 99.6% and 98% to 99.8%, respectively. The differences between the PKS and SD beds were statistically important, indicating the

Table 2 | COD and BOD5 concentration and load statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS and B-SD

Parameter			Range	Mean (±SD)	MRR	RE (%)
COD	Conc. (mg/L)	Influent	1,692.00–8,734.00	4,860.00 (± 2,693.03)		
		Eff. B-PKS	120.00–370.00	199.00 (± 69.51)		93.71
		Eff. B-SD	80.00–260.00	145.00 (± 56.22)		95.16
	Load (g/m^2 d)	Influent	148.05–764.23	425.25 (± 235.64)		
		Eff. B-PKS	7.78–26.90	14.58 (± 5.21)	410.67	94.64
		Eff. B-SD	5.17–18.97	10.43 (± 4.30)	414.82	95.97
BOD_5	Conc. (mg/L)	Influent	163.80–473.40	247.31 (± 84.65)		
		Eff. B-PKS	0.96–17.40	7.89 (± 5.64)		96.87
		Eff. B-SD	0.66–6.00	3.85 (± 1.95)		98.41
	Load (g/m^2 d)	Influent	14.33–41.42	21.64 (± 7.41)		
		Eff. B-PKS	0.08–1.19	0.56 (± 0.39)	21.08	97.47
		Eff. B-SD	0.05–0.42	0.27 (± 0.14)	21.37	98.72

No. of samples = 10.
MRR = Mass removal rate; RE = Removal efficiency.

superiority of the SD wetlands over the PKS wetlands in terms of BOD_5 reduction.

Sand has a significantly greater surface area than that of PKS, in which the subsequent thicker sand layer in wetland B-SD presents more attachment area for biofilm affixation, which allows for oxygen renewal by diffusion to remove contaminants. In addition, sand assists in decelerating the downflow of influent, allowing for a longer contact time between the influent, the substrates and the plant roots.

A significant correlation was found between the COD and BOD_5 influent loading rates (ILR) and their corresponding mass removal rates (MRR) ($R^2 > 0.99$, $P < 0.001$, as shown in Tables 2 and 3). The positive linear correlations of the organic loading rate and the reduction rate for both B-PKS and B-SD suggested no inhibitory effect of the treatment with PKS. The regression lines indicated high predictability of the wetland performances, with more than 99% of the variation in the data for OM MRRs correlating with the strength of the incoming OM load (Figures 2 and 3).

Nitrogen removal

The results in Table 3 demonstrate the influence of PKS presence, as an additional carbon source in the wetlands, on various N fractions removal efficiency. Generally, higher NH_4-N mean concentration-based removal efficiencies were found in beds without PKS (B-SD). However, no statistically significant differences were found with the ammonia removal efficiencies between the two beds, indicating that the PKS and sand were equally effective in reducing ammonia content with the same substrate depth. Good ammonia removal was observed (Table 3), presumably via nitrification as the major removal pathway.

Nitrification is heavily dependent on the presence of DO (Ong *et al.* 2010), and this suggested that both the B-PKS and B-SD wetlands had had significant amounts of atmospheric oxygen supplied into the substrate via diffusion and convection. Effluent DO was found to range between 2.5 and 7.6 mg (Table 1). The intermittent feeding strategy had clearly improved the effluent quality with the increased DO content, resulting in high nitrification efficiencies. Although it is well known that ammonia oxidizers compete poorly with aerobic heterotrophic microorganisms, the additional carbon source (PKS) in the substrate, which contributed to greater growth and biomass of heterotrophs, did not significantly deteriorate the ammonia removal efficiencies. This could be attributed to the ample oxygen supply that repressed the competition between nitrifiers and the heterotrophs for oxygen intake.

The VFEWs have a high hydraulic gradient in the substrate due to influent downflow direction and greater oxygen flux for nitrification. The application of the influent, together with the vertical drainage of the feed, restored aerobic conditions in the bed, regardless of the substrate material. The NH_4-N MRR of the B-PKS bed was 11 g/m^2 d with a mean NH_4-N input of 11 g/m^2 d. Sand-filled beds yielded the NH_4-N removal efficiency of 99%, while the B-PKS achieved NH_4-N removal efficiency as high as 97% (Table 3). Such removal rates were relatively similar compared to results from a 3-staged hybrid engineered wetland system treating mechanically pre-treated wastewater (Saeed & Sun 2011).

Table 3 | *N* concentration and load statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS and B-SD

Parameter			Range	Mean (±SD)	MRR	RE (%)
NH_4-N	Concentration (mg/L)	Influent	68.34–197.96	127.96 (± 40.66)		
		Eff. B-PKS	0.00–9.70	3.40 (± 9.70)		96.59
		Eff. B-SD	0.00–2.80	0.92 (± 1.08)		99.26
	Load (g/m^2 d)	Influent	5.98–17.32	11.20 (± 3.56)		
		Eff. B-PKS	0.00–0.74	0.25 (± 0.27)	10.95	97.11
		Eff. B-SD	0.00–0.20	0.06 (± 0.07)	11.13	99.41
Org-N	Concentration (mg/L)	Influent	63.77–436.00	146.72 (± 106.40)		
		Eff. B-PKS	2.88–43.58	19.30 (± 14.07)		85.28
		Eff. B-SD	11.88–77.76	37.35 (± 20.13)		71.97
	Load (g/m^2 d)	Influent	5.58–38.15	12.84 (± 9.31)		
		Eff. B-PKS	0.21–2.83	1.39 (± 1.00)	11.45	87.86
		Eff. B-SD	0.91–6.20	2.84 (± 1.56)	9.99	75.77
NO_3-N	Concentration (mg/L)	Influent	1.10–69.30	33.78 (± 28.92)		
		Eff. B-PKS	4.20–71.20	21.87 (± 21.45)		
		Eff. B-SD	23.20–94.00	56.55 (± 23.99)		
	Load (g/m^2 d)	Influent	0.10–6.06	2.96 (± 2.53)		
		Eff. B-PKS	0.29–6.11	1.65 (± 1.80)		
		Eff. B-SD	1.71–7.15	4.05 (± 1.80)		
TN	Concentration (mg/L)	Influent	165.00–628.00	309.17 (± 128.00)		
		Eff. B-PKS	13.00–79.00	44.70 (± 22.49)		83.10
		Eff. B-SD	53.00–142.00	94.90 (± 29.43)		64.24
	Load (g/m^2 d)	Influent	14.44–54.95	27.05 (± 11.20)		
		Eff. B-PKS	0.97–6.70	3.30 (± 1.77)	23.75	85.51
		Eff. B-SD	3.99–10.20	6.78 (± 2.17)	20.27	70.65

No. of samples = 10.
MRR = Mass removal rate; RE = Removal efficiency.

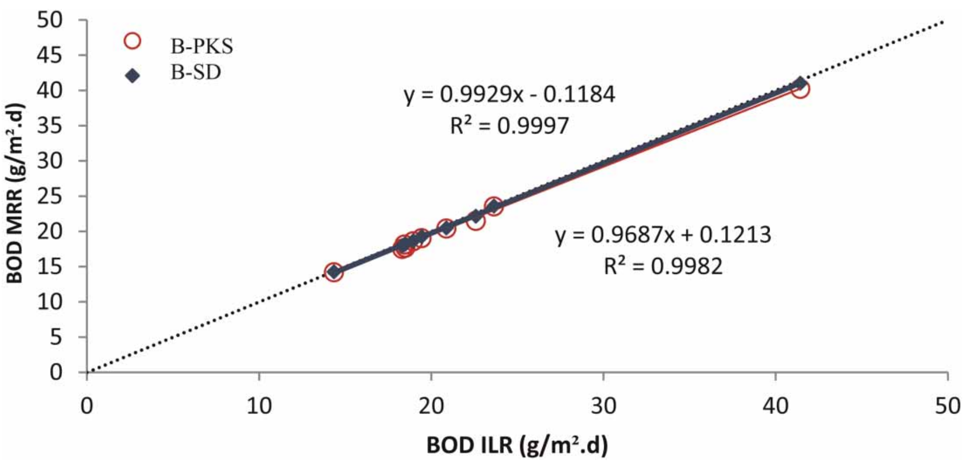

Figure 2 | Regression graph of BOD_5 MRR against ILR for B-PKS and B-SD units under intermittent loading mode. The dotted line represents complete removal.

Owing to the coupled effect of ammonia and nitrite oxidation during the nitrification process, nitrate was accumulated when the denitrification process was hindered. As shown in Table 3, nitrate accumulation was observed in wetland B-SD where PKS was absent. Denitrification can be induced with oxygen levels less than 0.2 mg/L, a sufficient supply of nitrate and carbon food, and the presence of a physical site where the bacteria required in the process can attach (Horne 1995). Thus, denitrification can typically be limited by the availability of NO_3, O_2 or labile organic carbon. Organic

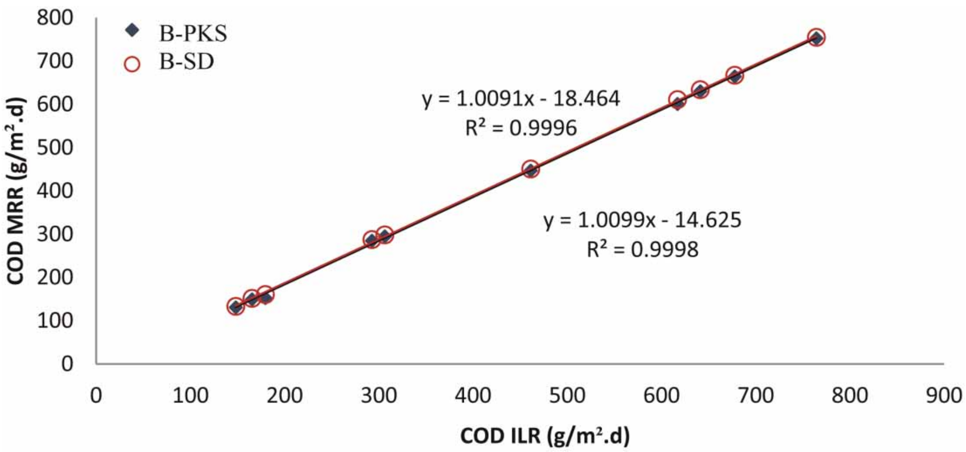

Figure 3 | Regression graph of COD MRR against ILR for B-PKS and B-SD units under intermittent loading mode. The dotted line represents complete removal.

carbon in the designed wetland was supplied by the PKS, which was added as part of the bed substrate. Here, the organic carbon source acted not only as a C substrate for denitrifiers, but also depleted DO levels via aerobic respiration, creating anaerobic microsites that support denitrification (Janke 1985; Jorgensen & Revsbech 1985). The B-SD wetlands had a significantly higher nitrate content in the effluent, most likely as a result of a lower rate of denitrification to convert the inorganic nitrogen component into gaseous N_2. In the sand-aggregate wetland B-SD, the absence of organic carbon appeared to limit denitrification.

The nitrogen fractions in the wetlands effluent were also determined. In wetland B-PKS, the fractions were 46.1% for NO_3-N, 45.8% for organic nitrogen, and 8.1% for ammonia–nitrogen. However, the NO_3-N in the wetland B-SD dominated by 60.2%, with a relatively lesser content of organic nitrogen (38.9%) and ammonia–nitrogen (0.9%). The results from the study revealed that nitrate pooling was more evident in wetland B-SD where deficient carbon was clearly the limiting factor to denitrification process.

The presence of a higher nitrate content in the effluent of wetland B-SD was also supported by the differences in the EC values in the effluent of the two beds. From Table 1, the effluent of wetland B-SD had EC ranging from 2.25 to 3.11 mS/cm, which was higher compared to the effluent of wetland B-PKS, with EC varying between 1.98 and 2.50 mS/cm. In addition, the pH values of the effluent in wetland B-SD were also slightly lower (6.54–6.90) for wetland B-SD than for wetland B-PKS (6.77–7.09) as a result of nitrate accumulation and the production of H+ ions during OM mineralization.

The average NH_4-N reduction efficiency was high (>96% for concentration and >97% for mass, Table 3) for both wetlands fed under a similar feeding regime, indicating that nitrification was not the limiting step for effective TN removal. Instead, denitrification appeared to be the limiting factor, especially in the wetlands without PKS (wetland B-SD). PKS may play a dual role in denitrification, as it supports the heterotrophic metabolism of denitrifying bacteria (effectively providing extra C for denitrifiers' consumption), and also the oxygen consumption in the wetlands, with the degradation of the organic C, which creates the anaerobic microsites necessary for denitrification (Hamersley *et al.* 2001).

Total load removal for TN at wetland B-PKS was 86% (Table 3), accounting for 5.7 g of TN removed accordingly per cycle (at MRR of 24 g/m^2/d). The wetland with the inclusion of PKS achieved significantly higher TN removal rates compared with other studies carried out on wetlands filled with organic substrate: TN removal of 7.2–15.8 g N/m^2 d by wood mulch substrate (Saeed & Sun 2011); average TN removal of 14.2 g N/m^2 d by woodchip filter (Ruane *et al.* 2012), demonstrating the efficiencies of the PKS-filled vertical beds in removing incoming N load. High N removal rates could be linked to the high nitrification in the VFEWs, which is often the limiting step for nitrogen elimination, and the availability of organic carbon from the PKS that fostered denitrification.

However, the N removal was also highly dependent on loading rates (Tanner & Sukias 2003). The high N removal efficiency of the wetlands in this study could be due to the higher influent N load applied to the beds compared to other studies. A plot of TN MRR against TN ILR showed that a strong linear correlation ($R^2 >$ 0.99, $P < 0.001$, as shown in Figure 4) was observed between the wetlands ILR and MRR for TN at both wetlands B-PKS and B-SD,

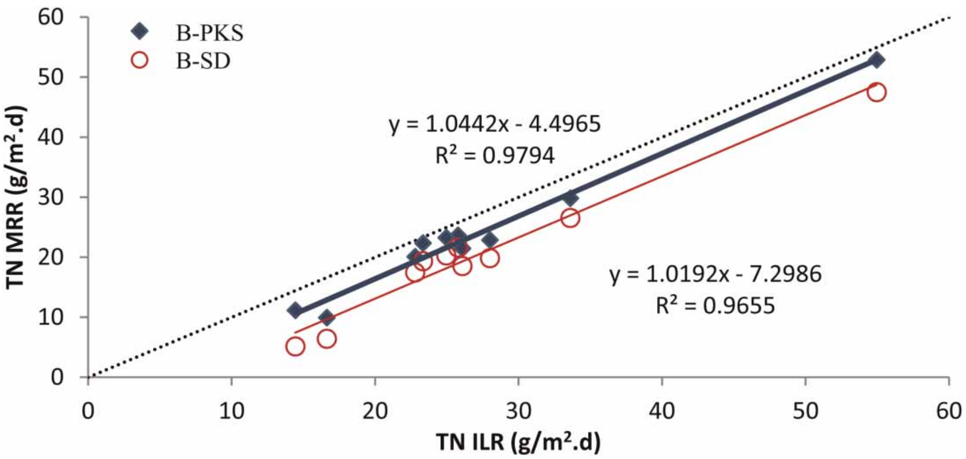

Figure 4 | Regression graph of TN MRR against ILR for B-PKS and B-SD units under intermittent loading mode. The dotted line represents complete removal.

which suggested that the ILR for nitrogen influenced its MRR significantly. The close fit of the points to the regression line also indicate remarkably constant areal MRRs for TN (Figure 4).

CONCLUSION

A high relative NO_3-N removal was achieved with the presence of PKS; NO_3-N accumulation was observed in the effluent of wetland B-SD where PKS was absent, with mean NO_3-N content at approximately 2.5 times more than observed in the effluent of wetland B-PKS. The inclusion of PKS as part of the wetland substrate was proven to elevate nitrate removal from the septage where the PKS had effectively functioned as an additional carbon supplier in the wetland for enhanced denitrification. The use of PKS, which is a waste product, shows promise for engineered wetland systems to treat septage. However, further studies would be needed to obtain sufficient and reliable data from pilot- and field-scale wetland systems to confirm the order of magnitude of the organic substrate's lifespan. The study outcomes suggested high predictability of pollutant removal rates according to the incoming pollutant mass at all wetlands, with near constant areal removal rates for almost all the tested pollutants under the applied regime.

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