Use of broken brick to enhance the removal of nutrients in subsurface flow constructed wetlands receiving hospital wastewater

Simachew Dires, Tarekegn Birhanu and Argaw Ambelu

ABSTRACT

Eight horizontal subsurface flow pilot scale artificial wetlands were constructed to evaluate the effectiveness of broken brick to remove nutrients from hospital wastewater. The average total suspended solids (TSS), 5-day biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), NH4-N, NO_3-N, and phosphate percent removal efficiency of constructed wetlands were, respectively, 93.2%, 90.4%, 83.7%, 64%, 64.3%, 52.1% and 56.1% in the dry season and 89.7%, 85.8%, 82.9%, 66%, 62.7%, 56.1% and 59.5% in the rainy season. Broken brick bed wetlands provide better removal efficiency of TKN, ammonia, nitrate, and phosphate with an average removal rate of 73%, 71.3%, 79.6% and 77.1% in the dry season and 74.7%, 70.7%, 70.9% and 73.6% in the rainy season, respectively, and it provides better adsorption sites for ammonium, nitrate, and phosphate. *Typha* with the broken brick bed significantly improved ($P < 0.05$) the treatment performance of the constructed wetland systems for the removal of ammonia, nitrate, and phosphate. The seasonal variation could not significantly influence the removal of all the pollutants, but better performance of nitrate and phosphate was achieved in a dry season. Use of locally available broken brick as a substrate media can increase the nutrient removal efficiency of wetlands at a cheaper cost when applied in full scale constructed wetlands.

Key words | broken brick, constructed wetland, gravel, nutrients, wetland plants

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INTRODUCTION

The treatment of wastewater has been a great concern in developing countries, since waterborne diseases such as cholera and other diarrheal illnesses have been persistent problems for the continuous death of children and poor families (Naik & Stenstrom 2012). The cost of construction for conventional wastewater treatment plants and the policy for mitigating environmental pollution have been the major barriers for the implementation of conventional technologies in many third world countries (UNWWDR 2017). Moreover, the supreme challenge in the water and sanitation sector in these countries would be the implementation of low-cost wastewater treatment plants that would be applied in a small community with the requirement for less skillful personnel and technical expertise (Almuktar *et al.* 2018). It is, therefore, essential that a treatment plant that is an economical, efficient and sustainable technology be inaugurated in developing regions (Wang *et al.* 2014; UNWWDR 2017).

Among the treatment systems, constructed wetlands (CWs) as a reasonable option have recently received considerable attention to treat a wide variety of wastewater throughout the world (Skrzypiecbcef & Gajewskaad 2017). They are applied to clean up not only municipal wastewaters but also agricultural effluents, landfill leachates, storm water, polluted river water, urban runoff, food wastes, abattoir effluent, acid mine drainage, industrial effluents, and petrochemicals (USEPA 2000; GIZ 2011; Vymazal 2011; Qasaimeh *et al.* 2015; Skrzypiecbcef & Gajewskaad 2017). They are complex, well-established, self–contained, integrated and environmentally friendly alternative treatment systems that use natural processes (USEPA 2000). CWs involve water, wetland vegetation, gravel/soils, the environment and their associated microbial assemblages for sewage treatment, pollution control and environmental improvements (Qasaimeh *et al.* 2015). The main advantages of CWs over the other solutions in developing countries are

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their high-quality effluent production for multi-purpose reuses as well as their sustainability in self-remediation and self-adaptation to the surrounding conditions and environment (Almuktar *et al.* 2018).

Several researchers have intensively reviewed the removal mechanisms for nitrogen and phosphorus in subsurface flow (SSF) wetlands (Vymazal 2007; Martin *et al.* 2012; Albalawneh *et al.* 2016). There is limited nitrogen removal in SSF wetlands as a result of the lack of oxygen in the infiltration beds (Gupta *et al.* 2016). This totally restricts the nitrification process of wetlands, and its removal mostly depends on denitrification, assimilation, volatilization, and plant uptake through microbial activity (Shi *et al.* 2018). Based on the filtration materials used, adsorption and burial also play a great role in retaining nitrogen in the beds of CWs (Shi *et al.* 2018). Harvesting of plant biomass is another removal mechanism since nitrogen is an essential plant nutrient and is stored as organic content in the wetland vegetation (Wu *et al.* 2013). The removal of phosphorus in CWs occurs through various processes such as adsorption on the media surface, precipitation, retention in sediments and plant uptake (Avsar *et al.* 2007; Vymazal 2007). Adsorption has been considered to be the most important mechanism for phosphorous removal based on a substrate media type (Bama *et al.* 2013).

The important adsorbents that have been tested for phosphorous removal as a CW substrate include broken brick (Wang *et al.* 2012; Mateus *et al.* 2016), basic oxygen furnace slag (BOFS) (Hussain *et al.* 2015), biochar (Gupta *et al.* 2016), dolomite (Zibiene *et al.* 2015), laterite (Mansing & Rout 2013), zeolite, limestone, calcite and other substrates rich in iron, aluminum and calcium (Yun *et al.* 2015). Broken brick is well known to remove phosphorus as it has a greater surface area to provide better adsorption (Mateus *et al.* 2016). Additionally, Wang *et al.* (2012) stated that it is a good medium for the enrichment of microorganisms and growth of plants in CWs. The contents and chemical forms of broken brick could also be the principal factors for phosphorus removal by the precipitation process (Wang *et al.* 2012). There are few reports on the phosphorus absorption potential of broken brick as a substrate of vertical flow wetlands for municipal and industrial wastewaters. However, such absorbents have not been thoroughly investigated in SSF wetlands for the treatment of complex wastewaters generated from health care institutions. Therefore, the aim of the current study is to evaluate the efficiency of a pilot-scale SSF CW with broken brick as the filter media in removing nitrogen and phosphorus from the wastewater.

MATERIALS AND METHODS

The experiments were carried out from December 2016 to December 2017 in the compound of Hawassa University Referral Hospital, Hawassa City, Southern Ethiopia, which is located at 7.06° latitude and 38.48° longitude with an elevation of 1,697 meters above sea level. Its climate is tropical with an average annual rainfall of 945 mm. During the data collection period, the hospital had around 350 beds in six wards and 200 to 350 patients were visiting per day. Eight parallel pilot-scale SSF wetlands were constructed with cement blocks of 4 m × 1.2 m and with a depth of 0.6 m (Figure 1). The efficiency of two growing media, namely gravel and broken brick, were evaluated. Burnt bricks were ground into a uniform particle size of 20–25 mm. Based on the guidelines of GIZ (2011) and USEPA (2000), coarse gravel of 40 to 50 mm in diameter was arranged at the inlet and outlet zones of the wetlands in order to prevent clogging and facilitate wastewater distribution. The main treatment zone of five CWs was filled with gravel and the other three with broken brick substrate having a particle size of 20–25 mm at a depth of 45 cm

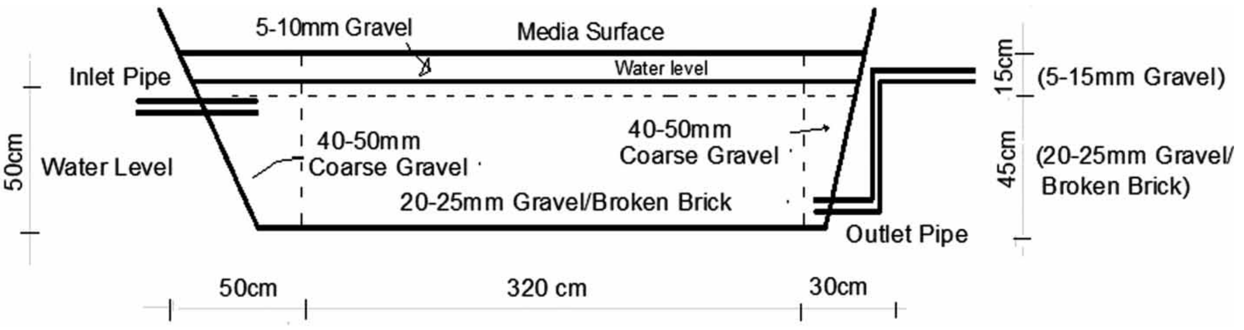

Figure 1 | Cross-sectional representation of the constructed wetland and its dimensions.

(Figure 1). The upper top layer (15 cm) of all wetlands was filled with gravel of 5–10 mm to provide better rooting of plants.

Four of the gravel bed wetlands were planted with emergent macrophytes including cattails (*Typha domingensis*), *Cyperus papyrus*, dark green bulrush (*Scirpus atrovirens*) and sugarcane (*Saccharum officinarum*), which are known to be suitable for use in CWs (Vymazal 2011; Mateus *et al.* 2016). Two broken brick wetlands were also planted with *Typha domingensis* and *Cyperus papyrus*. The remaining two from both substrates were left unplanted to act as the control (Table 1 and Figure 2). Part of the primarily treated wastewater was pumped into a temporary collection tank prior to entering the experimental wetland. The wastewater was then allowed to flow constantly into each bed at a loading rate of 237.6 liters/day for one consecutive year. The bed capacity measured from the porosities of the gravel and the broken brick filter was 950.4 liters, with 4 days' hydraulic retention time (HRT).

Wastewater treatment performance was monitored over six sampling periods, i.e. three times in the dry season (November to December 2017) and three times in the rainy season (June to August 2017) on a monthly base. A total of six composite samples from inflow wastewater and 48 composite samples from outflow wastewater were collected simultaneously. The wastewater samplings were undertaken three times a day with a three hour interval in the morning and afternoon (9:00 AM, 12:00 AM and 3:00 PM) in 250 ml cleaned and sterile screw-capped containers and transported with a cold box (≈4 °C) and stored in a refrigerator at 4 °C. Then all the samples pooled into 500 ml sized cleaned and sterilized containers to be analyzed within 24 hours. Wastewater parameters were analyzed according to APHA (1998) standard methods.

The Fisher's Least Significant Difference test was used to determine any significant differences in the mean influent and effluent values of parameters, and pollutant removal efficiencies of the wetlands with different vegetation combinations were also compared. A *p*-value of less than 0.05 was considered significant. A comparison between wastewater analysis results for planted and unplanted cells in broken brick and gravel bed during the dry and rainy seasons was performed to evaluate the effect of seasons and the plant/media combination on the pollutants' removal.

RESULTS AND DISCUSSION

The average removal percentage of total suspended solids (TSS) is shown in Figure 3. Influent suspended solids concentration was ranged from 335 ± 22 mg/l in the dry season to 306 ± 11.7 mg/l in the rainy season. Its level in

Table 1 | Dimension and features of CWs

Parameter	CW1	CW2	CW3 (control)	CW4	CW 5	CW6	CW7	CW8 (control)
Type of bed	Broken brick	Broken brick	Broken brick	Gravel	Gravel	Gravel	Gravel	Gravel
Type of reed	Papyrus	*Typha*	No plant	Sugar cane	*Typha*	Papyrus	Bulrush	No plant

Figure 2 | Picture of the pilot-scale SSF wetlands to treat hospital wastewater.

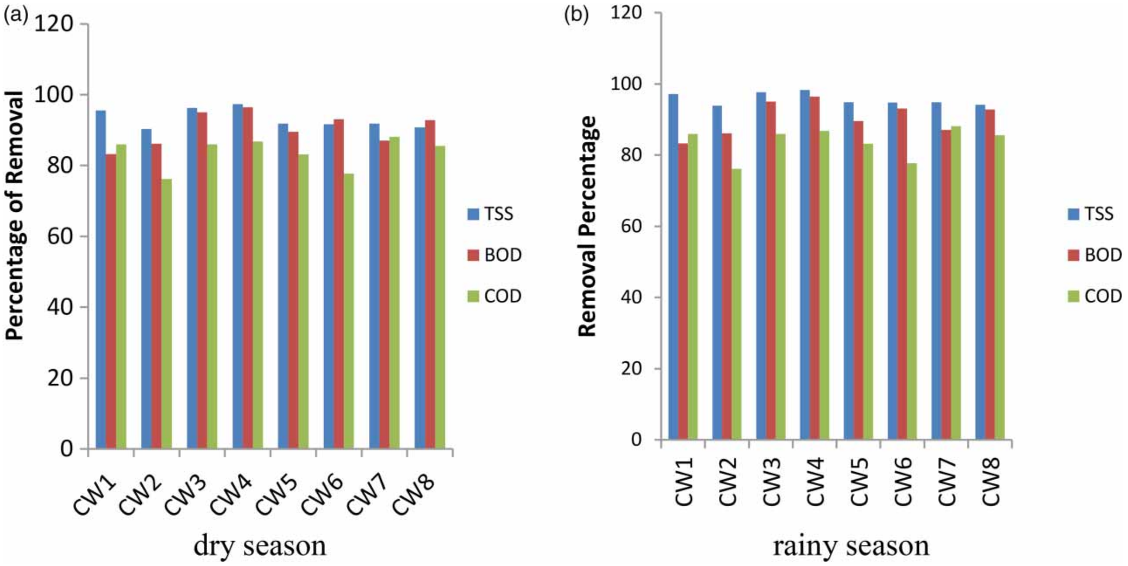

Figure 3 | Organic matter removal efficiency of the constructed wetlands.

influent was significantly higher than in the effluent ($P < 0.05$) throughout the study period. Gravel-based beds containing different plants managed to reach the removal values of 90.7–97.3% in a dry season and 84.6–95.3% in a rainy season (Figure 3). Similarly, the removal percent of wetlands containing broken brick as substrate reached 90.3% and 96.3% in the dry season and 88.7% and 93.1% in the rainy season. These high suspended solids removal rates were consistent with others' reports (Andreo-Martínez *et al.* 2016; Gupta *et al.* 2016). The best performance was attained by the sugar cane planted gravel bed wetland with an almost constant removal rate above 97% and an average effluent concentration of less than 10 mg/l.

There was no statistical difference between media types in the removal of TSS among the eight wetlands in dry and rainy seasons, which agrees well with the findings of Prost-Boucle *et al.* (2015) and Wang *et al.* (2017). Moreover, there was no significant difference observed between the performance of the planted and unplanted wetlands in both substrates. Similar recent studies done in Cameroon and Korea also confirmed that plants usually have no effect on the removal of suspended solids (Martin *et al.* 2012; Gupta *et al.* 2016). The similarity in TSS treatment between planted and unplanted systems in this study persisted in all seasons of the year for both the broken brick and gravel bed wetlands. This result agrees well with the results of Elfanssi *et al.* (2018). This result confirmed that TSS removal is greatly attributed to physical processes like mechanical filtration and microbial breakdown of the organic portion of suspended solids (Gupta *et al.* 2016). Additionally, flocculation and settling of colloids by sedimentation, straining, physical capture, and adsorption onto the substrate play a great role in their reduction (USEPA 2000).

Influent 5-day biochemical oxygen demand (BOD5) concentration was 221 ± 31.3 mg/l in the dry season and 185 + 11.6 mg/l in the rainy season. The BOD5 levels in the influent were significantly ($P < 0.0001$) higher than in the effluent in both planted and unplanted CWs. Gravel-based beds containing different plants managed to reach a removal of BOD5 of 87–96.5% in the dry season and 83.6–95.5% in the rainy season (Figure 3). Correspondingly, there was a higher percent removal of BOD5 in broken brick bed wetlands that ranged from 83.3% to 95% in the dry season and 79.2% to 95.5% in the rainy season. A similar report by Gikas *et al.* (2007) showed that the mean BOD5 removals were 89% and 93.5% for temperatures below and above 15 °C, respectively. The best performance was attained by the sugar cane planted gravel bed wetland, with an almost constant removal rate above 96.5% and an average effluent concentration of less than 10 mg/l.

The average chemical oxygen demand (COD) concentration of influent wastewater was 713 ± 36.5 mg/l in the dry season and 673 ± 31.9 mg/l in the rainy season. The average COD removal efficiency of both planted and unplanted wetlands ranged from 76.2% to 88.1% in the dry season and 75.8% to 88.4% in the rainy season, which is consistent with other researchers' findings (Martin *et al.* 2012). With respect to BOD5 and COD, the wetlands didn't show a performance difference throughout the different seasons of the year. Comparable findings were also reported by Prost-Boucle *et al.*

(2015) and Wang *et al.* (2017). The least significant difference (LSD) test analysis for percent removal of BOD5 and COD showed no significant difference in the planted and unplanted cells. Therefore, it can be said that the presence of macrophytes did not lead to an increase in the wetland performance in terms of BOD5 and COD reduction. Likewise, the vegetated cells in both substrates did not differ significantly ($P > 0.05$), which agrees well with the results of Mairi *et al.* (2012). Thereby, bacterial degradation may play a key role in the removal of BOD and COD in horizontal subsurface flow (HSSF) CWs (Abdul & Ganapathyvenkatasubramanian 2016). The organic matter in wastewater was dominantly degraded by facultative and anaerobic heterotrophic microorganisms in the wetland reactors due to a minimum oxygen concentration in the bed (USEPA 2000). Furthermore, filtration, adsorption, sedimentation, and oxidation are also responsible for organic matter reduction in wetlands (Lee *et al.* 2004; Skoczko *et al.* 2017).

Nitrogen removal efficiency was only modest in SSF CWs. The results of this study showed that broken brick bed wetlands provide better removal of nutrients than gravel beds. The average concentration of total Kjeldahl nitrogen (TKN) in the inflow wastewater was 86.3 ± 11.7 mg/l in the dry season and 98 ± 3 mg/l in the rainy season. The level of TKN in inflow wastewater was significantly higher ($P < 0.05$) than in the wetlands outflow in both seasons. In the dry season, broken brick bed planted wetlands exhibited a higher removal percentage of TKN (75.6%) than unplanted broken brick bed wetland (67.7%). Similarly, planted gravel bed wetlands achieved higher TKN removal (61.6%) than unplanted gravel bed wetland (46.8%) in the same season. Both planted and unplanted broken brick bed cells had significantly higher ($P < 0.05$) removal efficiency than unplanted gravel bed wetland in rainy season. Moreover, *Typha* plants in broken brick bed wetland revealed significantly higher ($P < 0.05$) removal efficiency than bulrush plants in gravel bed wetland in the rainy season. A maximum of 76.5% to 79% of TKN removal was achieved by *Typha* species, which is in agreement with other literatures (Sun *et al.* 2009; Basker *et al.* 2014). This result indicated that the removal of nitrogen in CWs is mainly due to the plant uptake in the planted wetlands compared to denitrification, which occurs in the unplanted wetlands under anoxic conditions (Vymazal 2007). However, there was no significant difference in the removal percentage of TKN between planted and unplanted gravel bed wetlands, which is comparable to the reports of Sirianuntapiboon & Jitvimolnimit (2007).

The concentration of $NH4^+$-N in the effluent after the CWs treatment varied from 16.6 ± 4.1 to 30.9 ± 0.5 mg/l in the dry season and 16.1 ± 4.3 to 30.1 ± 0.9 mg/l in the rainy season. The level of NO_3-N in hospital wastewater was very low, with an average concentration of 0.9 ± 0.2 mg/l in the dry season and 1.1 ± 0.5 mg/l in the rainy season. The concentrations of both NH_4^+-N and NO_3-N in the influent were significantly higher ($P < 0.05$) than in the effluent in both seasons, which was in agreement with others (Cui *et al.* 2016). This study showed that the type of media has an influence on the removal of both NH_4^+-N and NO_3-N. It was revealed that the wetlands with broken brick were more efficient compared to the wetlands with gravels (Figure 5 and 6). A similar study by Abdul & Ganapathyvenkatasubramanian (2016) also showed that a good removal performance was achieved by using brickbats as a CW media.

Typha in the broken brick bed wetland significantly improved ($P < 0.05$) the treatment performance of the constructed wetland systems for $NH4^+$-N and NO_3-N compared to *Typha* in a gravel bed wetland (Figure 4). Likewise, *C. papyrus* in broken brick had higher removal performance than *C. papyrus* in a gravel bed (Figure 5). This might be due to the higher potential of broken brick for the enrichment of microorganisms and growth of plants as well as its adsorption capability for pollutants (Wang *et al.* 2012). The higher elimination rate of ammonium can also be explained by the higher cation exchange capacity of broken brick (Yang *et al.* 2016). Moreover, *Typha* in broken brick wetland exhibited a higher removal percentage of NH_4^+-N (77.4%) and NO_3-N (88.9%), which were significantly greater ($P < 0.05$) than those of planted and unplanted gravel bed wetlands in both seasons. In the rainy season, broken brick bed wetlands had significantly ($P < 0.05$) higher removal efficiency than unplanted gravel bed wetlands. In a similar study, $NH4^+$-N removal was significantly improved in planted systems compared to unplanted systems ($P < 0.05$) (Caselles-Osorio *et al.* 2017). Likewise, Martin *et al.* (2012) showed that the vegetated wetland had higher removal efficiencies for nitrate than the non-vegetated control in both seasons. Villalobos *et al.* (2013) and Rana & Laura (2014) also explained that plants have a positive influence in the removal of ammonia and nitrate by direct assimilation or uptake and indirectly due to translocation of oxygen from the upper parts of the plants to the roots, which facilitates the nitrification of ammonia. Sugarcane planted wetland also had significantly ($P < 0.05$) higher removal efficiency of ammonium than unplanted gravel bed wetland. In a similar study, better nutrient removal was reported in sugar cane planted CWs (Mateus *et al.* 2016). Compared to the other wetlands, the

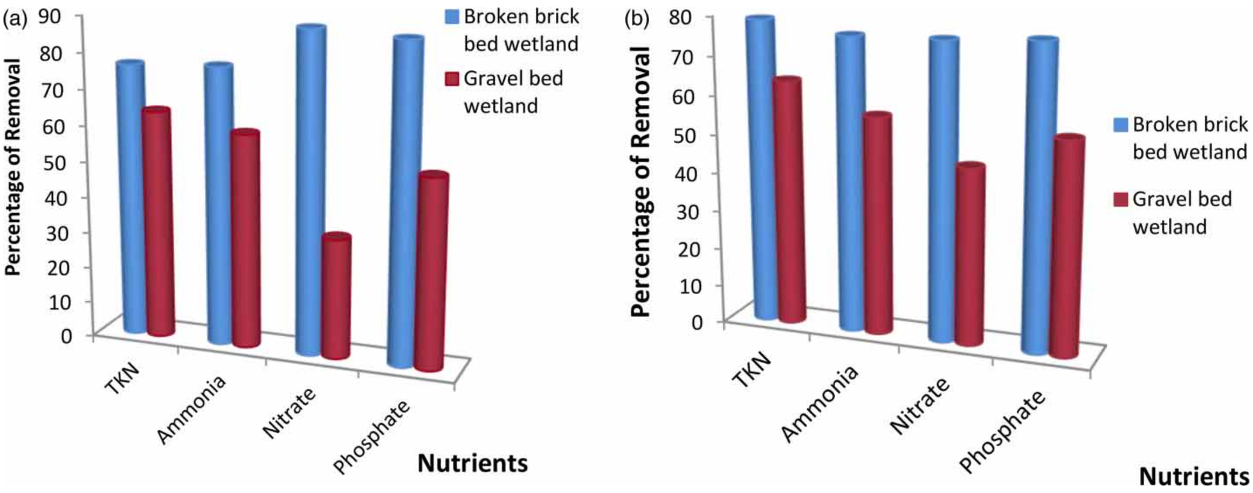

Figure 4 | Comparison of nutrient removal percentage of broken brick and gravel bed *Typha* planted wetlands. (a) Dry season. (b) Rainy season.

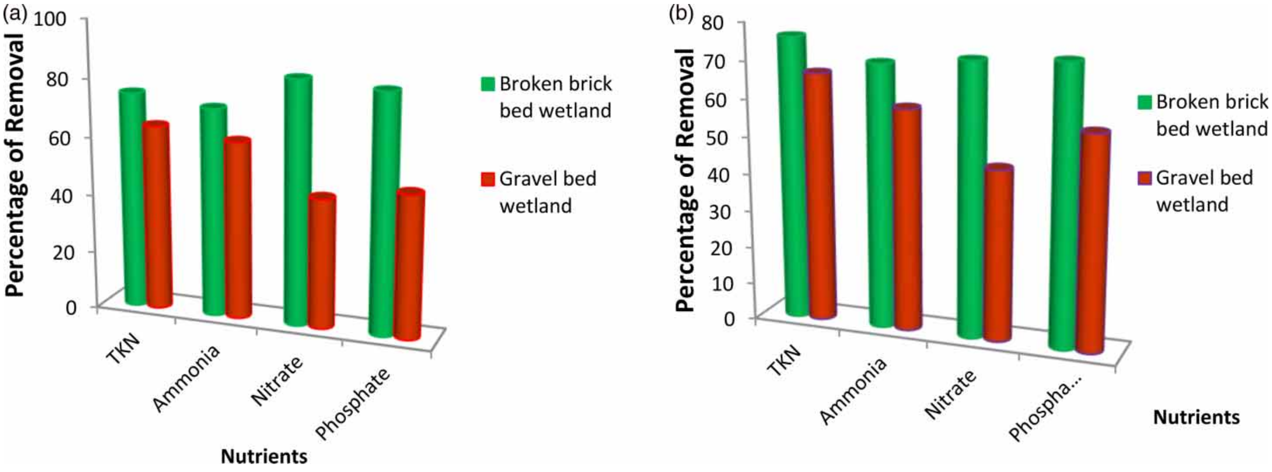

Figure 5 | Comparison of nutrient removal percentage of broken brick and gravel bed *C. papyrus* planted wetlands. (a) Dry season. (b) Rainy season.

lower removal of ammonia and nitrate was observed in the unplanted gravel bed wetland in both seasons. This could be due to the fact that the nitrification/denitrification processes may have been limited by inadequate microbial activity in an unplanted medium.

The core removal mechanisms of nitrogen in CWs include nitrification/denitrification, volatilization, ammonification, plant uptake, and matrix adsorption (Vymazal 2007). However, the nitrification process in HSSF wetlands is usually considered to be limited due to lower oxygen concentration released by plant roots, and the available small concentration is mostly consumed by competitive microorganisms to degrade organic matter (Gupta *et al.* 2016). Additionally, the oxygen released from roots in the anaerobic condition was too low to enhance ammonia oxidation (Keffala & Ghrabi 2005). Denitrification seems to be the dominant mechanism of removal in this study due to the fact that the anoxic and/or anaerobic condition, as well as the pH and temperature of wastewater, is conducive for denitrification (Shi *et al.* 2018). Adsorption of nitrogen ions by brick media may also play a part in its removal. In general, according to Wu *et al.* (2013) and the present study, plant uptake and sediment storage were the key factors limiting nitrogen removal.

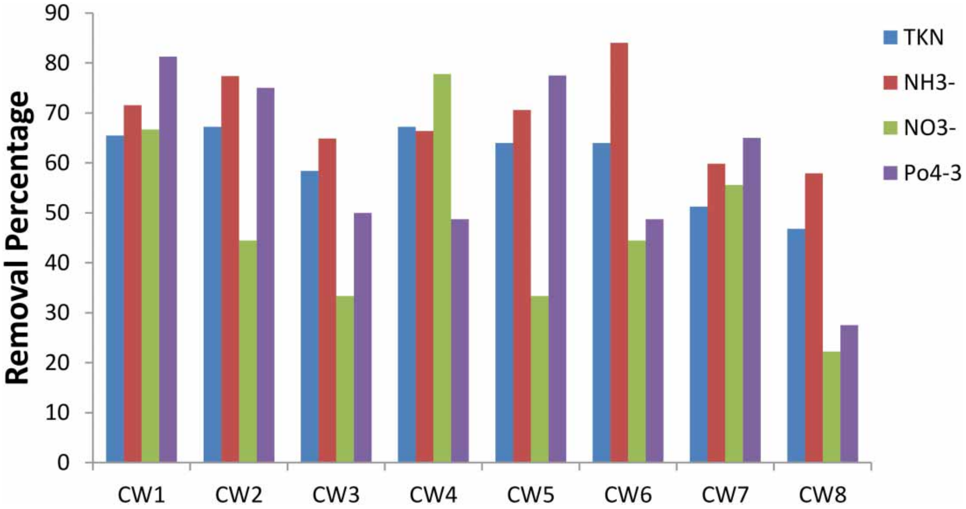

Figure 6 | Nutrient removal efficiency of CWs during the dry season.

The average phosphate concentration of the inflowing wastewater was 8 ± 1.4 mg/l in the dry season and 13.4 ± 4.9 mg/l in the rainy season. The obtained data for phosphate removal from each wetland is summarized in Figure 6 and 7. The planted wetlands with broken brick media had significantly ($P < 0.05$) higher average removal efficiency (84.4%) of phosphate compared to the wetlands with gravel beds (47.5) in a dry season. *Typha* plants in broken brick bed wetland significantly ($P < 0.05$) removed more phosphate (77.6% in a rainy season and 87.7% in a dry season) than unplanted gravel bed wetland. A similar study reported by Sun *et al.* (2009) showed that phosphorus removal rate reached 88.9% by cattail (*Typha*). Likewise, a higher performance was also reported by Mateus *et al.* (2016). Abdul & Ganapathyvenkatasubramanian (2016) and Wang *et al.* (2012) showed that a vertical flow wetland with broken brick media achieved 80% to 90% phosphorus removal. The result indicated that plants and broken brick media must work together for a better removal of phosphate, suggesting a synergistic mechanism. In the dry season, the unplanted broken brick wetland also had significantly ($P < 0.05$) higher removal efficiency of phosphate than an unplanted gravel bed wetland.

It is well known that broken brick substrate has better phosphorus removal abilities as they have a greater surface area to provide better adsorption (Mateus *et al.* 2016). Additionally, Wang *et al.* (2012) stated that broken brick plays a vital role in the enrichment of microorganisms

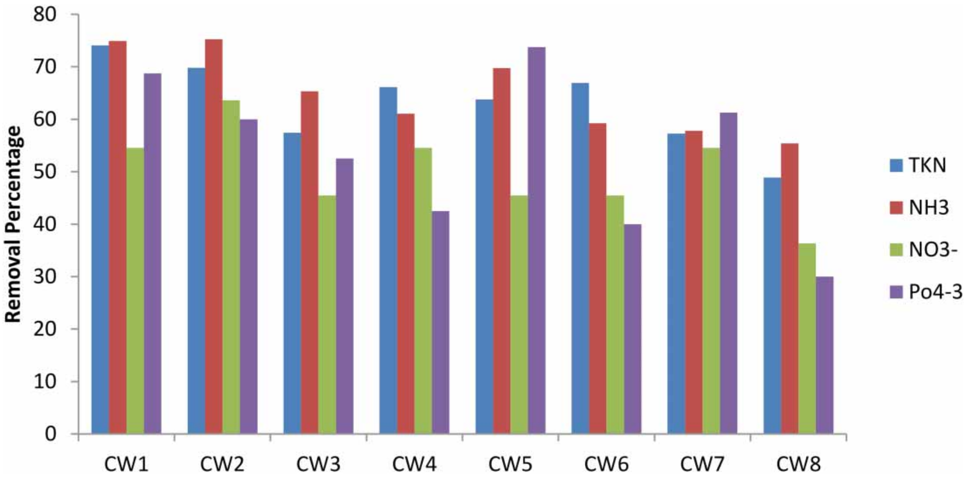

Figure 7 | The nutrient removal efficiency of wetlands during the rainy season.

and growth of plants as a filter medium in CWs. The contents and chemical forms of broken brick could also be the principal factors for phosphorus removal by precipitation process (Wang *et al.* 2012). Phosphorus precipitation can also occur when the wastewater comes into contact with available clay minerals, aluminum, iron and calcium in the substrate, as explained by Albalawneh *et al.* (2016). There was no significant difference between planted and unplanted gravel bed wetlands in the removal of phosphate in the dry season. Similarly, in the rainy season, planted and unplanted broken brick and gravel bed wetlands didn't have a significant difference in phosphate removal. This supports the fact that the plants have limited ability for the uptake of phosphate and that adsorption or precipitation by bed media contributes to phosphorus removal (Mateus *et al.* 2016). On the other hand, phosphorus removal was dependent on water temperature. In this study, better removal of phosphate was recorded in planted broken brick wetlands during the dry season than in the rainy season. Similarly, Villalobos *et al.* (2013) stated that seasonal variations strongly affected the phosphorous removal in HSSF. This might be related to the increase in plant growth and microbial activity in the warm season (Elfanssi *et al.* 2018).

CONCLUSION

This study showed that horizontal subsurface flow CWs with a broken brick bed had an excellent removal potential for organic and nutrient pollutants from hospital wastewater. The removal of BOD5, COD, and TSS in the planted bed wetlands was not significantly different from the removal in the unplanted bed. Broken brick bed wetlands provide better removal of TKN, ammonia, nitrate, and phosphate from wastewater than gravel bed wetlands and they provide better adsorption sites for ammonium, nitrate, and phosphate. *Typha* with the broken brick bed significantly improved ($P < 0.05$) the treatment performance of the constructed wetland systems for the removal of ammonia, nitrate, and phosphate. No seasonal differences were observed in pollutant removal by the wetlands except in the case of nitrate and phosphate, which were more efficiently removed in the dry season. Use of locally available broken brick as a wetland substrate would increase the nutrient removal performance as well as decrease the cost of the medium when applied in full scale CWs.

REFERENCES

Abdul, J. M. & Ganapathyvenkatasubramanian, S. 2016 Comparison of nutrient and organic removal in constructed wetlands. *International Journal of Science Technology & Engineering* **2** (12), 164–171.

Albalawneh, A., Chang, T. K., Chou, C. S. & Naoum, S. 2016 Efficiency of a horizontal sub-surface flow constructed wetland treatment system in an arid area. *Water (Switzerland)* **8** (2), 1–14.

Almuktar, S. A. N., Abed, S. N. & Scholz, M. 2018 Wetlands for wastewater treatment and subsequent recycling of treated effluent : a review. *Environmental Science and Pollution Research* **25**, 23595–23623.

Andreo-Martínez, P., García-Martínez, N. & Almela, L. 2016 Domestic wastewater depuration using a horizontal subsurface flow constructed wetland and theoretical surface optimization: a case study under dry Mediterranean climate. *Water* **8** (10), 434.

APHA 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.

Avsar, Y., Tarabeah, H., Kimchie, S. & Ozturk, I. 2007 Rehabilitation by constructed wetlands of available wastewater treatment plant in Sakhnin. *Ecological Engineering* **29** (1), 27–32.

Bama, P., Thushyanthy, M., Alvappillai, P. & Pirabhaharan, M. 2013 Evaluation of lab scale constructed wetlands to treat the toddy distillery effluent with different aquatic plants. *Archives of Applied Science Research* **5** (5), 213–219.

Basker, G., Deeptha, V. T. & Annadurai, R. 2014 Comparison of treatment performance between constructed wetlands with different plants. *International Journal of Research in Engineering and Technology* **3** (4), 210–214.

Caselles-Osorio, A., Vega, H., Lancheros, J. C., Casierra-Martínez, H. A. & Mosquera, J. E. 2017 Horizontal subsurface-flow constructed wetland removal efficiency using *Cyperus articulatus* L. *Ecological Engineering* **99**, 479–485.

Cui, L., Li, W., Zhang, Y., Wei, J., Lei, Y., Zhang, M., Pan, X., Zhao, X., Li, K. & Ma, W. 2016 Nitrogen removal in a horizontal subsurface flow constructed wetland estimated using the first-order kinetic model. *Water* **8** (11), 514.

Elfanssi, S., Ouazzani, N., Latrach, L., Hejjaj, A. & Mandi, L. 2018 Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area. *International Journal of Phytoremediation* **20** (1), 75–87.

Gikas, G. D., Akratos, C. S. & Tsihrintzis, V. A. 2007 Performance monitoring of a vertical flow constructed wetland treating municipal wastewater. *Global NEST Journal* **9** (3), 277–285.

GIZ 2011 *Technology Review of Constructed Wetlands Subsurface Flow Constructed Wetlands for Greywater and Domestic Wastewater Treatment*. Sustainable Sanitation – Ecosan Program, Bonn, Germany.

Gupta, P., Ann, T. W. & Lee, S. M. 2016 Use of biochar to enhance constructed wetland performance in wastewater reclamation. *Environmental Engineering Research* **21** (1), 36–44.

Hussain, S. I., Blowes, D. W., Ptacek, C. J., Jamieson-Hanes, J. H., Wootton, B., Balch, G. & Higgins, J. 2015 Mechanisms of phosphorus removal in a pilot-scale constructed wetland/BOF slag wastewater treatment system. *Environmental Engineering Science* **32** (4), 340–352.

Keffala, C. & Ghrabi, A. 2005 Nitrogen and bacterial removal in constructed wetlands treating domestic waste water. *Desalination* **185** (1–3), 383–389.

Lee, C. Y., Lee, C. C., Lee, F. Y., Tseng, S. K. & Liao, C. J. 2004 Performance of subsurface flow constructed wetland taking pretreated swine effluent under heavy loads. *Bioresource Technology* **92** (2), 173–179.

Mairi, J. P., Lyimo, T. J. & Njau, K. N. 2012 Performance of subsurface flow constructed wetland for domestic wastewater treatment. *Tanz. J. Sci.* **38** (2), 587–596.

Mansing R, P. & Rout, P. D. 2013 Removal of phosphorus from sewage effluent by adsorption on laterite. *International Journal of Engineering Research & Technology* **2** (9), 551–559.

Martin, L., Théophile, F., Etienne, P. M. & Akoa, A. 2012 Removal of faecal bacteria and nutrients from domestic wastewater in a horizontal surface flow wetland vegetated with echinochloa pyramidalis. *African Journal of Environmental Science and Technology* **6** (9), 337–345.

Mateus, D. M. R., Vaz, M. M. N., Capela, I. & Pinho, H. J. O. 2016 The potential growth of sugarcane in constructed wetlands designed for tertiary treatment of wastewater. *Water (Switzerland)* **8** (3), 1–14.

Naik, K. S. & Stenstrom, M. K. 2012 Evidence of the influence of wastewater treatment on improved public health. *Water Science and Technology* **66** (3), 644–652.

Prost-Boucle, S., Garcia, O. & Molle, P. a. 2015 French vertical-flow constructed wetlands in mountain areas: how do cold temperatures impact performances? *Water Science and Technology* **71** (8), 1219–1228.

Qasaimeh, A., Alsharie, H. & Masoud, T. 2015 A review on constructed wetlands components and heavy metal removal from wastewater. *Journal of Environmental Protection* **6**, 710–718.

Rana, A. & Laura, J. S. 2014 Removal efficiency of horizontal constructed wetland for treating domestic wastewater using local plant species. *International Journal of Environmental Biology* **4** (1), 74–81.

Shi, W., Li, H. & Li, A. 2018 Mechanism and influencing factors of nitrogen removal in subsurface flow constructed wetland. *Applied Chemical Engineering* **1** (1), 9–14.

Sirianuntapiboon, S. & Jitvimolnimit, S. 2007 Effect of plantation pattern on the efficiency of subsurface flow constructed wetland (Sfcw) for sewage treatment. *African Journal of Agricultural Research* **2** (9), 447–454.

Skoczko, I., Struk-Sokołowska, J. & Ofman, P. 2017 Seasonal changes in nitrogen, phosphorus, BOD and COD removal in Bystre wastewater treatment plant. *Journal of Ecological Engineering* **18** (4), 185–191.

Skrzypiecbcef, K. & Gajewskaad, M. H. 2017 The use of constructed wetlands for the treatment of industrial wastewater. *Journal of Water and Land Development* **34** (1), 233–240.

Sun, G., Ma, Y. & Zhao, R. 2009 Study on purification efficiency of sewage in constructed wetlands with different plants. *World Rural Observations* **1** (2), 35–39.

UNWWDR 2017 *Wastewater The Untapped Resource. The United Nations World Water Development Report. FACTS and FIGURES*. World Water Assessment Program and UNESCO.

USEPA 2000 'Manual Constructed Wetlands Treatment of Municipal Wastewaters.' *National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio*, USA.

Villalobos, M. R., Zúñiga, J., Salgado, E., Schiappacasse, M. C. & Chamy Maggi, R. 2013 Constructed wetlands for domestic wastewater treatment in a Mediterranean climate region in Chile. *Electronic Journal of Biotechnology* **16** (4), 1–13.

Vymazal, J. 2007 Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment* **380** (1–3), 48–65.

Vymazal, J. 2011 Plants used in constructed wetlands with horizontal subsurface flow: a review. *Hydrobiologia* **674** (1), 133–156.

Wang, Z., Liu, C. X., Li, P. Y., Dong, J., Liu, L. & Zhu, G. F. 2012 Study on phosphorus removal capability of constructed wetlands filled with broken bricks. *Huan Jing Ke Xue* **33** (12), 4373–4379.

Wang, H., Wang, T., Zhang, B., Li, F., Toure, B., Omosa, I. B., Chiramba, T., Abdel-Monem, M. & Pradhan, M. 2014 Water and wastewater treatment in Africa – current practices and challenges. *Clean-Soil Air Water* **42** (8), 1029–1035.

Wang, M., Zhang, D. Q., Dong, J. W. & Tan, S. K. 2017 Constructed wetlands for wastewater treatment in cold climate – a review. *Journal of Environmental Sciences* **57**, 293–311.

Wu, H., Zhang, J., Wei, R., Liang, S., Li, C. & Xie, H. 2013 Nitrogen transformations and balance in constructed wetlands for slightly polluted river water treatment using different macrophytes. *Environmental Science and Pollution Research* **20** (1), 443–451.

Yang, Z., Wang, Q., Zhang, J., Xie, H. & Feng, S. 2016 Effect of plant harvesting on the performance of constructed wetlands during summer. *Water (Switzerland)* **8** (1), 24.

Yun, Y., Zhou, X., Li, Z., Uddin, S. M. N. & Bai, X. 2015 Comparative research on phosphorus removal by pilot-scale vertical flow constructed wetlands using steel slag and modified steel slag as substrates. *Water Science and Technology* **71** (7), 996–1003.

Zibiene, G., Dapkiene, M., Kazakeviciene, J. & Radzevicius, A. 2015 Phosphorus removal in a vertical flow constructed wetland using dolomite powder and chipping as filter media. *Journal of Water Security* **1** (1), 46–52.

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