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EFFECT OF LANDFILL LEACHATE SALINITY ON THE PERFORMANCE OF HYBRID VERTICAL FLOW TREATMENT WETLANDS UNDER EQUATORIAL CLIMATE

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ABSTRACT: *In this study, vertical flow treatment wetlands performances on landfill leachate operated under equatorial climate have been assayed during 2 years. Two pilots planted with Echinochoa Pyramidalys Lam have been operated. Effluent electrical conductivities (EC) measured at each of the four different seasons with the values of 2.5±0.5; 6±1; 7±2 and 9±1 mS/cm for long rain, short rain, short dry and long dry respectively; were used to determined COD and TN treatment performances. According to the experimental results, EC, pH, COD and TN decrease at different treatment stage. The evaluation of treatment system Removal Rate (RR) showed highest value of 66±6% for* RR_{COD} *and 79±6% for* RR_{TN} *both obtained during long rain season. The highest* RM_{COD} *(171±9* $gm^{-2}d^{-1}$*) and* RM_{TN} *(4±1*$gm^{-2}d^{-1}$*) was obtained during short rain season. This work will help to design a full scale TW for LL under equatorial climate in Africa.*

KEYWORDS: Hybrid vertical treatment wetland, equatorial climate, landfill leachate, salinity , *Echinochloa pyramidalis*.

INTRODUCTION

In Sub-Saharan Africa including Cameroon, 58% of the population is facing water scarcity (Fonjong and Fokum, 2017). This is mainly relied to surface water quality coming from continental rainfall, which is the primary source of freshwater in developing countries (Kivaisi, 2001). Both qualities and quantities of this constant water supply are decreasing rapidly because of human activities (Bruch et al., 2011). Building wastewater treatment facilities is necessary, however, constructing and managing sewage facilities in most developing countries cities represents a huge challenge due to technical and economical limits (Chirisa et al., 2017). Consequently, discharging large volumes of untreated wastewater into surface waters is a common practice, so that as much as 80%–90% of all wastewater generated in developing countries are discharged directly into surface water bodies (Zhang et al., 2015). This practice can be a source of pollution, a hazard to the health of human populations and the environment alike. It has been reported that 60% of global ecosystem services are being degraded or used unsustainably, and highlighted the inextricable links between ecosystem integrity and human health and wellbeing. (Zhang et al., 2015).

Landfilling is a widely applied disposal method for 95% of municipal solid waste (MSW) (Akinbile et al., 2012) and represents one of the major source of pollution in developing countries. As most landfills are not properly covered while receiving bioactive wastes (Rafizul and Alamgir; 2012; Butt et al., 2014) it represents large amount of landfill leachate (LL), especially under equatorial climate characterised by high pluviometry (1620 mm per year in Cameroon). LL contains high concentrations of organic matter, nutrients, metals and high salinity levels (Butt et al., 2014).

On the one hand, treatment wetlands (TWs) have been recognized as sustainable wastewater management options for tropical/equatorial developing countries (Stottmeister et al., 2003; Kadlec and Wallace, 2008; Zhang et al., 2015), on the other, TWs have been largely used to treat landfill leachate in Europe and America (Bruch et al., 2011). Several studies reported the treatment of LL using mostly horizontal surface/subsurface flow TWs with and without recirculation (Nivala et al., 2007; Białowiec et al., 2012 Białowiec et al., 2014). TWs performances observed under tropical climate for LL were always outperforming those observed under temperate region (Ogata et al., 2015; Akinbilé et al., 2012). Some studies reported the use of forced aeration or recirculation in HF system to reduce the footprint and improve the overall COD and TN efficiencies (Nivala et al., 2007; Butterworth et al., 2013). Combining vertical flow (drained) and HF and/or saturated flow also enabled to improve removal efficiency while decreasing the footprint especially for N removal (Yalcuk and Ugurlu, 2009; Justin and Zupancic 2009; Speer et al., 2012). Considering the high organic loadings, vertical flow based solutions were therefore considered as promising (Speer et al., 2012). In this context, the aim of our study was to develop and evaluate the performance of a compact hybrid TW system to treat landfill leachates under equatorial climate. The impact of effluent salinity on the performance efficiency was particularly studied. The choice of *Echinochloa pyramidalis* was made based on previous studies in Cameroon, as this plant specie has been successfully applied to treat septage sludge with very high salinity levels up to 9ms/cm (Kengné, 2008, Ngoutané et al., 2011). A treatment wetland pilot system has been implemented in an active landfill site in Cameroon (Yaopundé) and fed with LL under field conditions during one year including four different seasons.

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MATERIAL AND METHODS

In Yaoundé (750 m elevation) average yearly rainfall is of 1.500 mm. The climate is considered as a Tropical savanna climate that corresponds to the Köppen climate classification categories "Aw". The rain season last from March to November including two peaks in May and October and a relative break in June-August so that it is possible to distinguish 4 seasons of 3 months each (Figure 1).

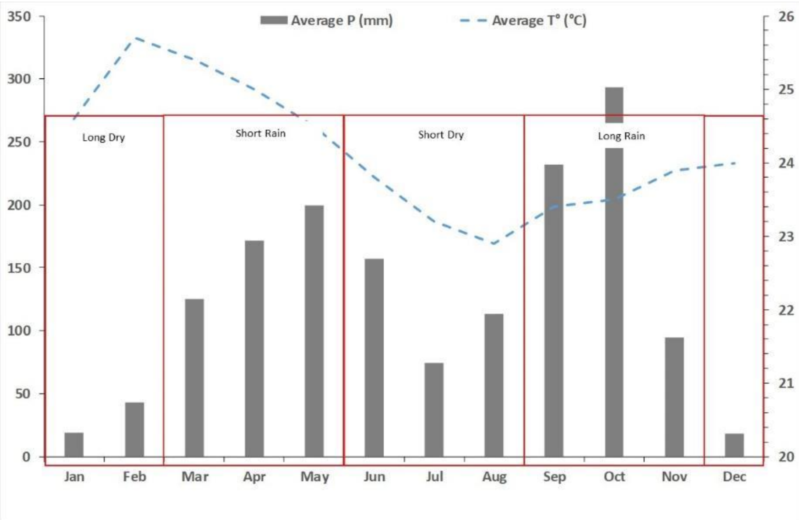

Figure 1. Seasons in Yaoundé (adapted from BBC weather)

Landfill site

Nkolfoulou landfill is located in the centre of Cameroon near the capital city of Yaounde. It receives 1200 tonnes of waste per day and was commissioned in 1990 on 56 ha area. It contains two closed cells (Cell 1 and Cell 2) and one cell in activity (Cell 3), so far, 4.6 million tons of waste have been stored (Figure 2). LL percolating through the different cells are collected in water channel and treated in a waste stabilisation pond system and finally discharged in the Foulou river (Figure 1). However, the majority of LL are not collected and reach streams and finally the Foulou river. The population generally use the water of the Foulou river for domestic and irrigation purposes.

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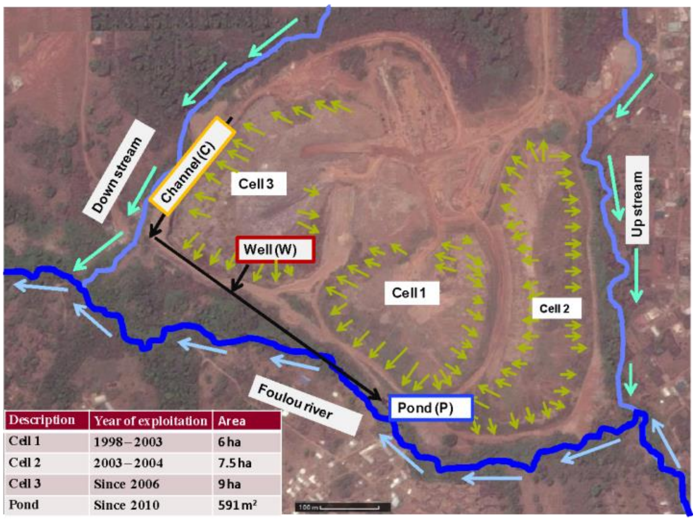

Figure 2. Modified Google map® top view of Nkolfoulou landfill site

This site is quite representative of very large landfilling site that can be implemented around large African cities and was chosen because it is monitored on a regular basis.

Treatment wetland pilot system: Tank 1 and 2

The treatment wetland pilot system consisted of two tanks in series (in m L:l:w : 1:1:1.). Each tank was filled with 3 layers of different granular sizes (Figure 3). Tank 1 was filled with 3 gravel layers and Tank 2 with 1 sand and 2 gravel layers. Tank 1 was designed to receive raw LL and favour soluble COD and NH4 oxidation. Tank 2 was designed to finalize NH4 oxidation and filtrate produced TSS. In both Tanks 1 and 2 a saturated layer was implemented with an overflow at 20 cm from the bottom to create a saturated anoxic zone to enhance denitrification and maintain plants health during dry periods. Tank 1 and 2 were planted in December 2015 with 12 rizhomes of *Echinochloa pyramidalis* each. After a commissioning period of 3 months during which tanks were fed with diluted LL (conductivity ≈ 0.2mS/cm), tanks were fed during 1 year (4 seasons) and samples were collected according to the following campaigns: 22 March – 10 May 2016 for short rain season; 26 July – 9 August 2016 for short dry season; 23 August to 4 October 2016 for long rain season and 6 December 2016 to 24 January 2017 for long dry season. Raw LL was taken either at the outlet of the waste stabilisation pond or inside the last pond (if no outflow).

Tank 1 was fed intermittently from Mondays to Tuesdays (3 days) with 10 batches of 20 L per day (using siphon feeding device), Tank 2 received outlet of Tank 1 by gravity; From Wednesdays to Sundays (4 days) the system remained unfed as resting period.

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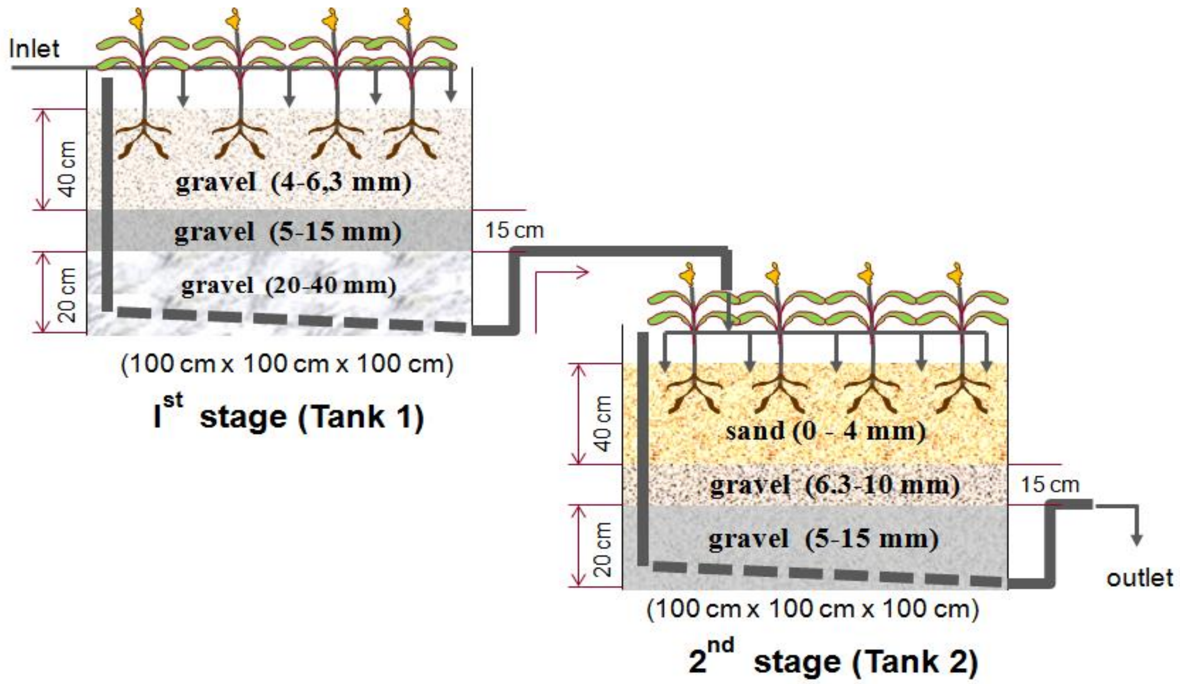

Figure 3. Schematic side view of the treatment wetland pilot system

Sampling and analysis

Daily temperature and precipitation were measured onsite on a weekly basis during the experiment. Evapotranspiration was measured using an unplanted lysimeter system and by measuring the difference between inlet and outlet of each tank.

Monitoring during each season was achieved by taking grab sample at outlet of Tank 1 and Tank 2 during at least 3 consecutive weeks. One litre of grab sample was collected in a bucket collecting at least 3 batches events every Tuesdays, the second feeding day of the week. Conductivity and pH were measured onsite. Collected samples were transported to the lab, stored at 4°C and analyzed within 24 to 48 hours. TSS, COD and TN were determined by Standard Methods (APHA, 1999). Since the largest amount of effluent was produced during the long rain season, complementary analysis including BOD (APHA, 1999) and ammonium (NH_4^+-N), nitrate (NO^{-3}-N) and the main ions have been performed on one week samples using ionic chromatography. Mass flows were estimated at inlet and outlet of the two Tanks over the seven days of the considered treatment week. At least three treatment weeks per season were realized.

The removal rate (RR), and loading rate (LR) and mass removal (MR) were calculated based on the following equations:

RR (%) = $100 \times \frac{(C_{in} - C_{out})}{C_{in}}$ (1) where C_{in} is inlet concentration (gL^{-1}) and C_{out} is outlet concentration (gL^{-1}) at the inlet and outlet of the considered system measured during the treatment

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MR (g.m^{-2}.d^{-1}) $= C_{in}\ x\ Q_{in}\ -\ C_{out}\ x\ Q_{out}$ (2)

$Q_{out} = Q_{in} + P\ - ET$ (3)

where Q_{in} (Lm^{-2}) and Q_{out} (Lm^{-2}) are the total water volumes entering and leaving the system during the treatment week (feeding days and resting period), P (Lm^{-2}) and ET (Lm^{-2}) are consequently total rainfalls and evapotranspirations

RESULTS

The average conditions recorded during our study showed a pronounced rainy season with an average rainfall accounting for more than 60% of the yearly cumulative amount. The average yearly temperature was quite constant and the evapotranspiration was intense during the long dry season with a net loss of water (Table 1).

Table 1. Average temperature and cumulative precipitations and evapotranspiration measured at Nkolfoulou landfill site during the study

Parameters	Unit	Long Rain	Short rain	Short dry	Long Dry
Temperature	°C	23.2	24.2	22.9	24.4
Rainfall	mm	1 205	487	182	53
Evaporation	mm	282	59	174	512

Treatment performances

The conductivity linearly increased from long rain season to long dry season as expected with values ranging from 2.5±0.5; to 9±1 mS/cm (Figure 4A). A decrease of the conductivity was observed from Tank 1 to Tank 2 during each season. The largest decrease of 40% was observed during the long rain season. The pH at inlet ranged from 8.5 to 9.5 with more variability observed during the rainy seasons. The highest pH was observed during dry season. A slight pH decreased was also observed after each treatment stage.

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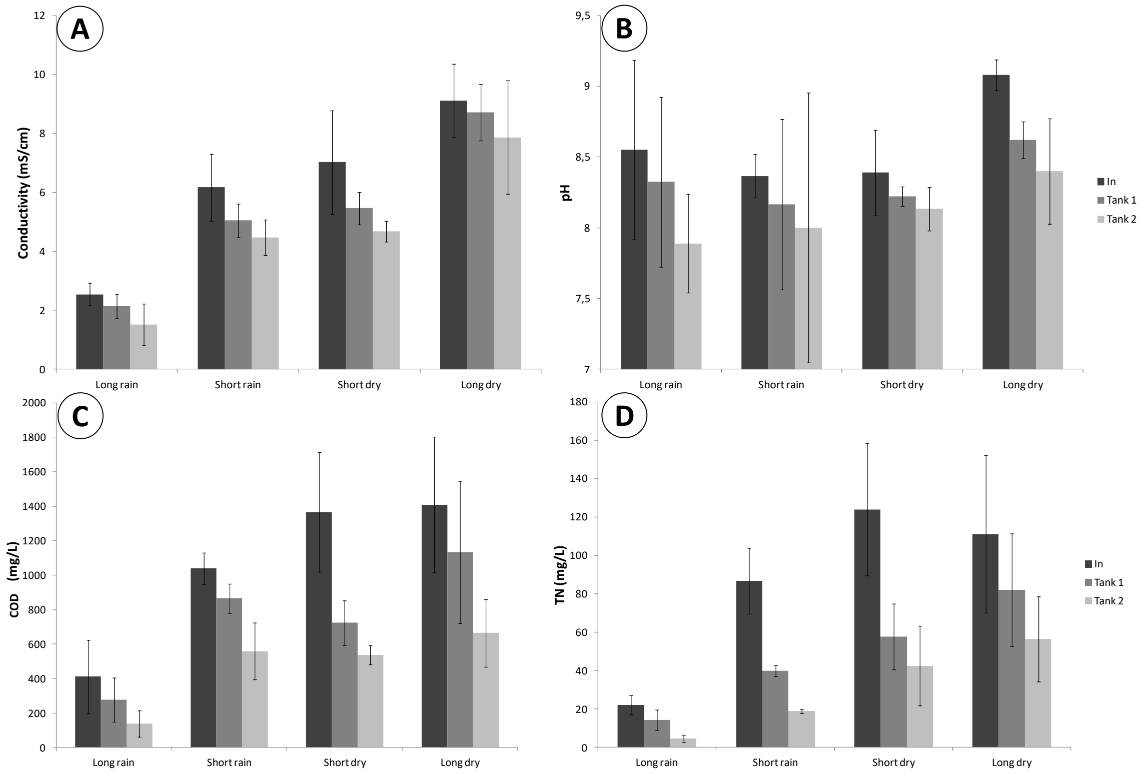

Figure 4. Evolution of conductivity (A), pH (B), COD (C) and TN (D) during each season

COD and TN gradually also increased from long rain season to long dry season, the dilution with precipitation can be observed (Figure 4 C and D). TSS at inlet varied between 5 and 500 mg/L (Table 2). A slight TSS removal was always observed but the values were quite low compared to COD and other pollutants as LL contained mostly soluble pollutants.

Table 2. Evolution of TSS with season and treatment level (min-max and mean in bracket)

mg/L	Long rain	Short rain	Sort dry	Long dry
In	27 – 500 (154)	75 – 155 (115)	43 – 27 (35)	35 – 125 (85)
Tank 1	22 – 115 (84)	34 – 64 (49)	37 – 49 (43)	35 – 63 (45)
Tank 2	18 – 200 (57)	36 – 76 (56)	24 – 31 (27)	27 – 84 (42)

Table 3. Evolution of RR and RM with season

		Long rain	Short rain	Sort dry	Long dry
RR (%)	COD	66±6	65±1	45 ±14	48±3
	TN	79±6	62±5	60±8	47±10
MR (g.m^{-2}.d^{-1})	COD	13±5	171±9	42.±14	14±3
	TN	1±0	4±1	2±0	1±0

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The best removal rates were obtained for the most diluted conditions (long rain / short rain) whereas the optimal mass removal were obtained during the short rain season were the best compromises between the dilution and the loading were reached.

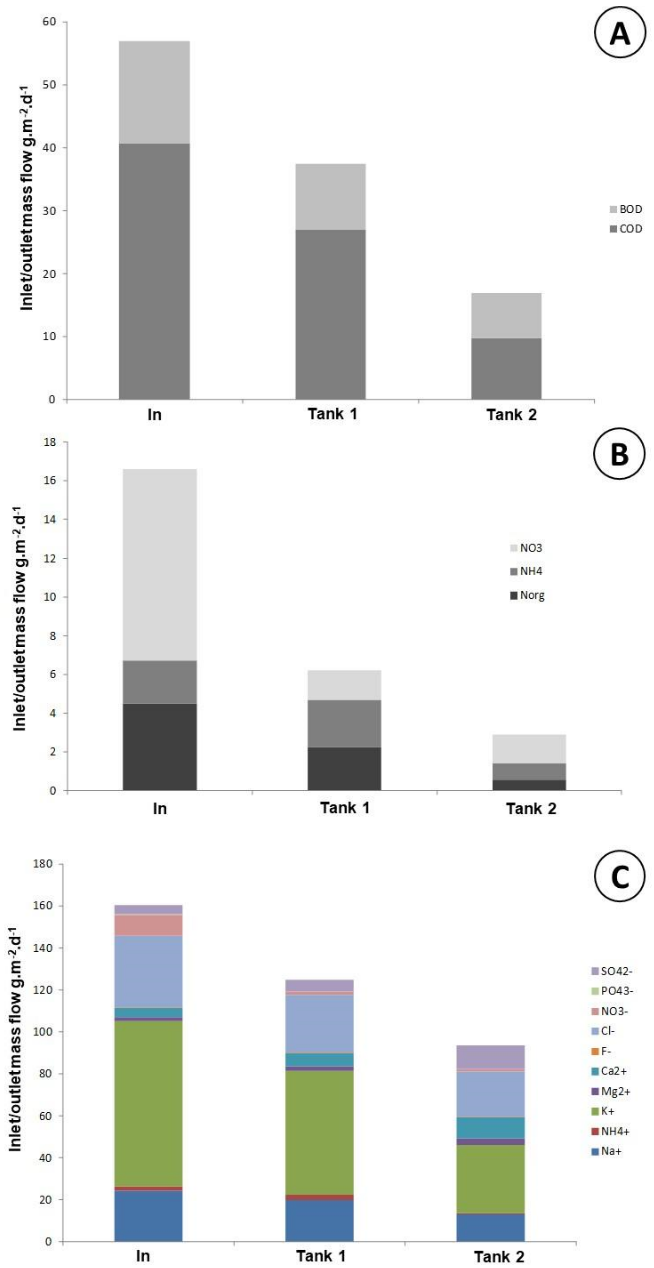

Figure 5. Focus on Inlet/Outlet mass flow of COD; BOD, main nitrogen forms and ions during one campaign of the long rain season

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DISCUSSION

As expected COD, and TN concentrations decrease with rainfall as previously observed in other studies (Mangimbulude et al., 2009). Consequently, LL salinity gradually increased from long rain (2.5±0.5 mS/cm) to long dry season (9±1 mS/cm) which affected both COD and TN removal performances, with a decreased with the diminution of rainfall.

At comparable organic loadings, the treatment wetland pilot system showed similar RR performance on TN and COD than those obtained in a smaller pilot with recirculation in Thailand (Akinbile et al., 2012). When applying a smaller loading rate (< 0.2 $g.m^{-2}.d^{-1}$) and using a HF with recirculation reactor better (more than 95%) RR_{COD} and RR_{TN} were observed in small pilot systems (Bialowiec et al., 2012).

COD and TN removal rate at lower salinity (66% and 79%) in this study was better than those observed using combine system in Slovenia (41% and 36%) (Justin and Zupancic, 2009) and hybrid system in Canada (60% et 36%) (Speer et al., 2012)

The lowest MR values were observed during the long rain season mainly due to the dilution. MR increased with precipitation decrease up to a critical point where biological processes were most likely hampered by increase of LL salinity and toxicity (hypothesis of presence of PAH, heavy metals etc.). This critical point gives the optimal MR that the system can reach. The gap between MR and RR in TW was already mentioned with increase of MR and decrease of RR when the organic loading is increased.

In our study, the largest MR_{COD} (173±9 $g.m^{-2}.d^{-1}$) and MR_{TN} (21±4 $g.m^{-2}.d^{-1}$) were obtained during the short rain season (EC of 6±1mS/cm). MR_{COD} was higher than the optimal value observed in Thailand (82.1 $g.m^{-2}.d^{-1}$) by Ogata et al., (2015), confirming that using a compact hybrid system enabled to increase the overall mass removal rates for LL treatment.

TSS range was quite similar at different season and was in the range obtained in Thailand (Ogata et al., 2015). A large variability was observed during the long rain season probably linked to the resuspension generated by high flow in the pond system. A decrease was recorded at the outlet of each tank.

BOD/COD measured during the long rain season showed a ratio of 0.3 at inlet and outlet of Tank 1 and up to 0.4 after Tank 2 which means that the biodegradability of LL increased in the system. Most of the organic compounds in the leachate are biodegradable as the LL was characterized by BOD/COD ratio > 0.1. Martin et al., (2013) observed a decrease of BOD/ COD ratio from 0.38 to 0.28 between inlet and outlet of the waste stabilization pond system in Nkolfoulou landfill site. This difference between the treatment wetland system and the pond system can be explained by the oxygenation conditions which are always high in the wetland compare to anoxic / anaerobic in the pond.

The pH was less impacted by the seasons and the value ranged between 8.3 and 8.6 except during the long dry season. The pH decrease can be linked to nitrification and/or denitrification occurring in each treatment tank as the optimal pH range for the activity of bacteria involves in nitrification and/or denitrifcation is between 7.5 and 8.5 (Bulc, 2006).

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In this study, raw LL entering the system in all season except long rain, showed a C:N ratio around 10 (optimal for organic matter treatment). At the outlet of tank 1 during short rain season, this ratio increased up to more than 20 but remained quite constant during the dry season. When C:N ratio > 20 there is not enough nitrogen to allow carbon degradation. This can also explain the inhibition of organic matter degradation during the dry season compared to rainy season.

During the long rain season case, at the inlet / outlet of thank 1 C:N ranged between 15 and 20. At this range, the nitrogen needs of bacteria involve in organic matter degradation are covered. At the outlet of thank 2 C:N ratio of 29 was registered showing nitrogen limitation at the outlet of the system.

Net organic nitrogen and NO_3-N decreases were observed at inlet /outlet of Tank1, associated with an increase of NH4, which means that both aerobic and anoxic conditions were met for ammonification and denitrification. In tank 2, organic nitrogen and NH_4-N decrease while NO_3-N increase which means that the ammonification and nitrification were still active while denitrification was limited, maybe by the lack of carbon. To a minor extend the decrease of NO_3-N in Tank 1 can be linked to plant uptake which has been estimated in Europe between 0.27 to 0.68 $g.m^{-2}.d^{-1}$(Molle and Prost-Boucle, 2009). This is confirmed by a study made in Thailand using HF planted with cattail in which 12% of the input nitrogen had been removed by plant uptake (Ogata et al., 2015). The use of forced aeration HF in USA (Nivala et al., 2006) enhanced NO_3-N production by a factor of 70.

This study showed that equatorial landfill leachate could be treated using hybrid treatment wetland. In nkolfoulou landfill site the salinity limit (6±1 mS/cm) to obtain optimal removal mass per feeding day of 171±9 g COD $m^{-2}d^{-1}$ and 4±1g TN $m^{-2}d^{-1}$was observed during short rain season. Nevertheless, during dry seasons, LL leachate dilution or desalination to obtained required salinity will be needed.

CONCLUSION

The conductivity decrease in the TW system was most likely a results of NO_3-N and NH_4-N elimination by nitrification / denitrification coupled to ion absorption onto media and metabolisation by the plants. The pH decrease observed in the system was due to nitrification / denitrification. The RR_{COD} and RR_{TN} exhibited highest values of 66±6% and 79±6% respectively during long rain where the salinity was the smallest (EC = 2.5±0.5 mS/cm). This study was conducted to assess the effect of seasonal salinity on the treatment performances of Nkolfoulou LL under equatorial climate. It revealed that highest mass removal of cabon and niotrogen were obtained during the short rain season (EC = 6±1 mS/cm). Nitrogen was never completely treated even if amonification, nitrification and denitrification processes have been observed, this could be overcom by the use of effluent recycling to enhance the treatment performance. The LL treatment feasibility in equatorial context using hybrid treatment wetland then showed, the scaling up of the system could now be consider. However, a prelinary desalination is necessary durin dry season.

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APPENDIX

Table A. Climate and efficiency comparison of different LL TW systems

Country	climate	Reactor Volume (m3)	Temperature / rainfall (monthly average)	System	Max Removal rate (%)	Reference
Thailand	Tropical	2	28 °C / 120 mm	HF	COD: 58; TKN: 84; NH_4–N: 94 COD: ; TKN: ; NH_4–N:	Ogata et al., 2015
Malaysia	Tropical	0,072	28.5°C / 196 mm	HF with recirculation	COD: 79; TN: 59; NH_3–N: 99.7	Akinbilé et al., 2012
USA	Temperate	42	8.2 °C / 75 mm	HF HF with aeration	COD: 53; NH_4–N: 43 COD: 60; NH_4–N: 98	Nivala et al., 2007
UK	Temperate	60 60	10°C / 63 mm	HF HF with aeration	NH_4–N: 59 NH_4–N: 99	Butterworth et al., 2013
Poland	Temperate	0.022 0,28	22.3°C / 44 mm 7.4°C / 44 mm	HF with recirculation VF	COD: 96; TN: 96 NH_4–N: 99.99 COD: 92.5	Białowiec et al., 2012 Białowiec et al., 2014

Turkey	Temperate	0.2	9.3°C / 66 mm	HF VF	COD: 61; NH_4–N: 49 COD: 36; NH_4–N: 67.4	Yalcuk and Ugurlu, 2009
Slovenia	Temperate	11.000	10.3°C / 83 mm	combined VF -HF	COD: 40.9; TN: 35.5; NH_4–N: 41.9	Justin and Zupancic (2009)
Canada	Temperate	178	4°C / 112 mm	FFR – HF-VF sand filter - VF-VF-HF-VF wetland	COD: 60; TN: 35.5; NH_3–N: 99	Speer et al., 2012

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