A Study of the Efficiency of a WSP during a Dry Season; The Case of Mikililand Estate, Addis Ababa, Ethiopia

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Abstract

A detailed analysis of the efficiency of Mikililand Estate Waste Stabilization Pond (WSP) in Addis Ababa was conducted during a dry season. Composite samples were taken across the pond from both influent and effluent for 6 sampling periods based on retention time intervals. The study revealed strong raw wastewater characteristics and high mean flow rate (1421.45 m^3/d), short retention time (13.20 days), high volumetric (525.24 g BOD_5/m^3/d) and surface loading rates (997.46 kg BOD_5/ha/d). Overall mean removal efficiencies were; 71.28% BOD_5, 58.82% TSS, 34.48% NH_4^+-N, 46.87% PO_4^{3-}, and 62.70% FC and these parameters had significantly different removal efficiencies ($P < 0.05$) across each sub-pond. BOD_5, FC and PO_4^{3-} removal efficiencies have correlation with retention time ($R = 0.500, 0.083, 0.390$, respectively). Mean removal efficiency of anaerobic, facultative and maturation ponds for BOD_5 were 37.18%, 43.44% and 19.17%, whereas FC removal efficiency was 7.07%, 18.23%, and 50.91%, respectively. Lack of monitoring and maintenance activities was observed. Treated effluent discharge to Little Akaki River did not meet Ethiopian permissible discharge limit standards excluding pH, temperature and NH_4^+-N. Reuse of effluents for unrestricted irrigation would not comply with WHO total coliform guidelines and other standards such as Oman for FC, BOD_5, TSS, NH_4^+-N and NO_3^--N. There was low removal efficiency across each sub-pond and overall pond of Mikililand Estate WSP. Hence, connecting parallel ponds and regular monitoring are recommended to increase the removal efficiency.

Index Terms - Dry Season, Efficiency, Treated Effluent, Wastewater, WSP

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1 INTRODUCTION

Discharging wastewater without proper treatment causes serious surface water pollution [1]. Hence, wastewater treatment methods like WSPs are neces sary for consistent and reasonably cost effective performance [2].

WSPs are the simplest technologies commonly used for domestic wastewater treatment in developing countries when there is availability of land [3]. WSPs have high potential of removing pollutants such as BOD_5, COD, TSS, TC and FC [3]. The first WSP in Addis Ababa was Kality WSP commissioned in 1981 [4]. However, In Ethiopia, WSPs were recognized and given attention as a first priority option for urban wastewater treatment in 2007 in order to ensure sus tainable environment and development [5].

Mikililand Estate WSP was commissioned in 2008 for 25,200 residents with the design flow rate of 1,814.4 m^3/d flowing into two series of anaerobic, facultative and maturation ponds (AP, FP and MP) [6]. Yet, these wastewater treatment plants cater for less than 10% of Addis Ababa residents' and more than 90% dispose their wastewater into storm water drainage network; this leads to major environmental pollution and create amenity problems [7]. As unmanaged growth of Addis Ababa is continuing rapidly, proper treatment of wastewater should be a major concern to prevent pollution of rivers nearby and inside the city [7, 8]. Hence, for proper treatment WSPs require high monitoring activities to obtain high efficiency through continuation of the physical and operational WSP design properties such as flow rate, retention time, depth, volume, volumetric and surface loading rates [9]. Above the standards and/or guidelines treated effluent parameters could arise when WSP become overloaded and lack of monitoring and maintenance activities occur [10].

2 MATERIALS AND METHODS

Mikililand Condominium Estate WSP is located between 466,541 m to 466,847 m E and 999,987 m to 1,000,214 m N in Addis Ababa. It started providing service in 2009 and comprised of 4,657 households (25,407 populations) during the study period.

The mean rainfall and temperature of Addis Ababa is 1,200 mm/year and 9.8 - 23.4^{o}C. The net evaporation (e) from Nov. – Jan. is 170 mm/d.

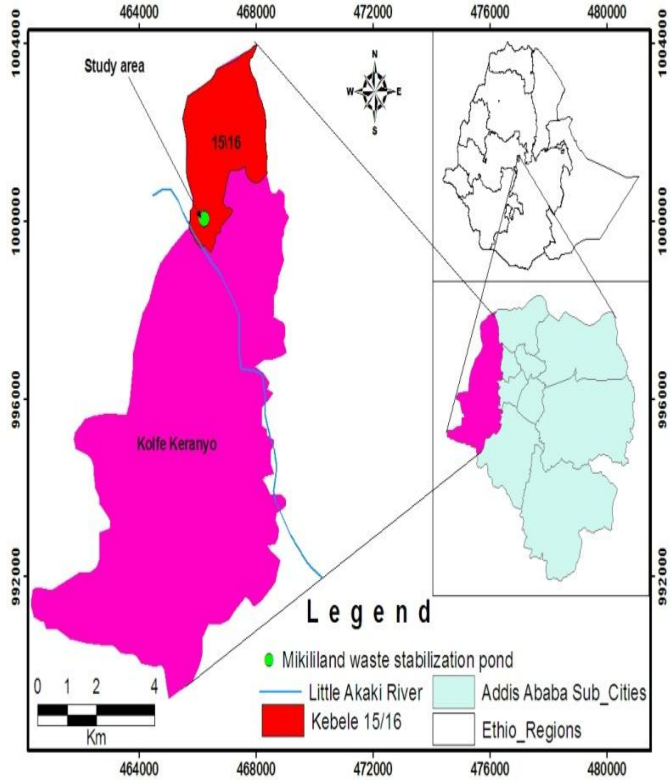

Fig.2.1. Location of the Mikililand WSP

2.1 Study design and sampling sites

Descriptive study design was used in order to assemble data through physico-chemical and biological parameter analysis, and measurement of Retention time (θ), Flow rate (Q), Volume (V), Depth (D), Volumetric and surface loading rates (VLR & SLR).

Four sampling sites were selected for data collection. These were influent of anaerobic pond (AP), influent of facultative pond (FP), influent and effluent of maturation pond (MP).

Depth of FP and MP was measured once before initial phase of data collection using white towel test techniques to measure the depth change due to sludge accumulation [11]. Flow rates were measure d using the design parshall flume flow measuring technique as follows:-

$$Q = 24 \times 60 \times 2.23 \times 10^{-2} \times W(\frac{H_a}{304.8})^{1.522(\frac{W}{304.8})^{0.026}}$$

Where H_a = The upstream depth of flow of wastewater

W = Width of the influent surface (W = 300 mm)

Q = Flow rate

Retention times of each sub-pond were determined as:

$$\theta_a = \frac{V_a}{Q_a} \quad [12]$$

$$\theta_f = \frac{2A_f D_f}{2Q_{inf} - 0.001A_f \times e}$$

$$\theta_m = \frac{2A_m D_m}{2Q_{inm} - 0.001 \times A_m \times e} \quad [9]$$

Whereas VLR and SLR were determined by

$$\lambda_{va} = \frac{inBOD_{5a}}{v_a} \times Q_a$$

$$\lambda_{sf} = \frac{10 \times in_f BOD_5}{A_f} \times Q_{in_f} \quad [13]$$

Temperature, pH, and DO were measured onsite during sampling using portable thermometer, pH meter, and DO meter, respectively from the influent of AP, influent of FP, influent and effluent of MP.

2.2 Sampling techniques and laboratory analysis

Composite flow weighted samples were collected using polyethylene bottles (1000 mL) at 08:00, 11:30 and 13:30 during 6 sampling periods (NF1, NF2, DF1, DF2, JF1 and JF2; N= November, D= December, J= January) at sampling sites within retention time intervals for both sampling periods and sampling sites. Samples were transferred to EPA laboratory using icebox within an hour. APHA [15] procedures were also adopted for TC BOD_5, and FC analysis whereas HACH [14] proc edures were also adopted for COD, TSS, NO_3^-N, NH_4^+N, and PO_4^{3-} analysis. During data analysis, SPSS version 16 was used for statistical analysis of descriptive statistics, one way ANOVA, Duncan's method and correlations. Significant difference was accepted at $P < 0.05$.

3 RESULTS AND DISCUSSION

3.1 Raw wastewater characteristics

Mikililand Estate WSP raw wastewater was classified as strong since its BOD_5 was > 400 mg/L and COD was > 700 mg/L based on [3] wastewater strength category. The ratio of BOD_5: COD showed a mean of 0.273 mg of COD can be degraded biologically out of 1 mg of COD within the retention time of 5 days. In contrast, the study of Oke *et al.* [16] revealed 0.351 - 0.789 mg COD can be degraded biologically out of 1 mg of COD. This is due to the presence of high ratio of COD: BOD_5 which indicates presence of non-biodegradable fraction. PO_4^{3-} concentrations (48 mg/L) was also strong using a guideline (strong if

PO_4^{3-} > 15 mg/L) [17]. This high concentration may be attributed to the presence of widespread use of detergents for washing activities.

3.2 Physical and operational Properties of Mikililand Estate WSP

3.2.1 Flow rate

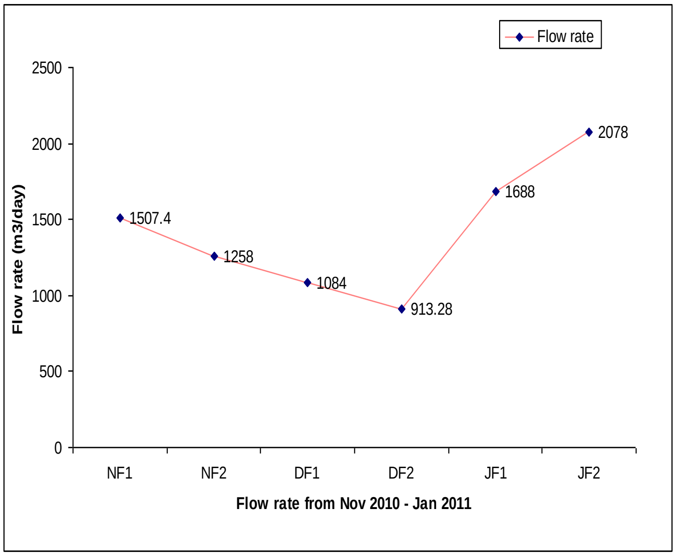

Fig.3.1. Flow rate trends of Mikililand WSP

Fluctuations of flow rates were attributed to variation in residents' water consumption.

3.2.2 Retention time

The mean retention time of AP, FP and MP as indicated in Table 3.3 and Fig.3.2 was short and less than the design retention time. This short retention time was due to a higher flow rate than the design flow rate.

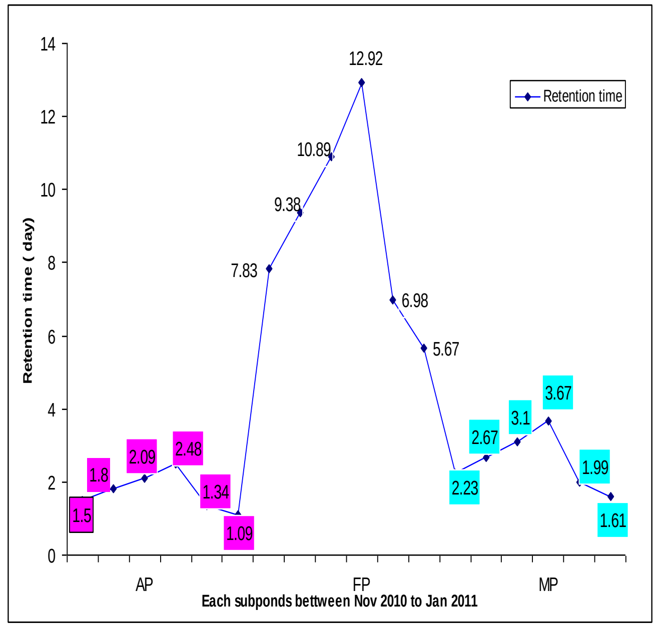

Fig.3.2. Retention time trends of anaerobic, facultative and maturation ponds

There was significant variation in retention time across each sub-pond (P = 0.000; Table 3.3) and it was negatively correlated with flow rate across the sub-ponds (R= - 0.327) even though the correlation was not significant (P = 0.185; N=18 Table 3.1).

3.2.3 Volumetric and Surface loading rates

VLR and SLR have significant correlation with flow rates (R = 0.968; P = 0.002: R = 0.843; P = 0.035, N= 18, respectively) (Table 3.1).

The different loading rate is due to variations of flow rate.

Table 3.1 Pearson correlations of retention time, volumetric and surface loading rates with flow rate.

	Pearson correlation (R)	Flow rate (Q)
Retention time	R	- 0.327
	P	0.185
	N	18
VLR	R	0.968
	P	0.002
	N	18
SLR	R	0.843
	P	0.035
	N	18

Occurrences of objectionable odors in AP and FPs occurred due to short retention time, high VLR and SLR. VLR > 400 g $BOD_5/m^3/d$ for AP cause odor problems [13]. Pearson *et al.* [18] point out that reduction of retention time causes odor, and low VLR of 17 - 26% from the design will not develop objectionable odor.

3.2.4 Depth and Volume

The average depth of FP and MP did not change much from the design. This contributed to no change in average volume of the Mikililand WSPs. However, slight variation of depth and volume occurred at different sides of the pond. The slight variation of depth may be attributed to very low sludge accumulation from different sides within the last 2 years of operating period. FP and MPs average temperature as indicated in Table 3.2 was appropriate for no significant sludge accumulations to occur. Mara [13] explained when temperature is greater than 15^oC sludge accumulation rate in FP and MPs are minimal and takes many years for significantly different average depth to occur. This result is in line with [11] where, slight variation of depth in FP and MP did occur at different sides during the years of operating period.

3.2.5 Temperature, pH and DO

The mean temperature of AP, FP and MP as indicated in Table 3.2 was greater than 20^oC which was more than the design temperature of Mikililand WSP (design temperature = 18.5^oC). Above 15^oC, pond function is normal if retention time, flow rate, depth, volume, VLR and SLRs are as per the design value [9, 13]. There is no significant difference in temperature (P = 0.576; Table 3.3) across the sub-ponds and this may be due to the study being carried out only during the dry season. The mean pH of AP, FP and MP as indicated in Table 3.2 had no significant difference across each sub-pond (P = 0.111; Table 3.3) due to high VLR and SLRs and no significant difference in temperature across each sub-pond (P = 0.576; Table 3.3) and also no significant difference in retention time between AP and MP by Duncan's method (P > 0.05; Table 3.2).

Table 3.2 Duncan's methods result for presence of physical and operational properties

	Flow rate (m^3/d)	Retention time (day)	pH	Temperature (°C)	DO (mg/L)
AP	1421.45 (913.28 - 2078)	1.72^b (1.09 - 2.48)	6.86^b (6.38 - 7.52)	20.91^a (18.4 - 23.2)	-
FP	-	8.94^a (5.67 - 12.92)	7.49^a (7.09 - 7.73)	21.91^a (18.9 - 24.3)	2.05^a (1.4 - 2.8)
MP	-	2.54^b (1.61 - 3.67)	7.18^{ab} (6.61 - 8)	21.8^a (19.6 - 23.20)	2.45^a (1.8 - 3.4)

Table 3.3 One way ANOVA for presence of significant differences in temperature, pH, DO and retention time

Physical and operational properties	P –Value
Temperature	0.576
pH	0.111
DO	0.000
Retention time	0.000

The mean DO of FP and MPs had no significant difference using Duncan's methods (P > 0.05, Table 3.2). This may be due to the short retention time for algae to release DO in FP and MPs. However, there is significant difference in DO across each sub-pond (P = 0.000; Table 3.3). This is attributed to AP having no DO. Therefore; the presence of DO in other ponds makes the variation significant.

3.3 Mean removal efficiency (%) of anaerobic, facultative, maturation and overall ponds

Table 3.4 One way ANOVA for removal efficiency across each sub-pond

Each sub-pond's removal efficiency	P – value
BOD_5	0.017
COD	0.123
TSS	0.000
NO_3^--N	0.327
NH_4^+-N	0.000
PO_4^{3-}	0.000
TC	0.000
FC	0.017

Table 3.5 Correlations for BOD_5, FC and PO_4^{3-} removal with retention time

Each sub-pond removal efficiency (%)	Pearson correlation (R)	Retention time
BOD_5	R	0.500
	P	0.035
	N	18
FC	R	0.083
	P	0.743
	N	18
PO_4^{3-}	R	0.390
	P	0.109
	N	18

Table 3.6 Mean removal efficiency of AP, FP and MP of Mikililand WSP

	Anaerobic pond	Facultative pond	Maturation pond
BOD_5	836.83 ± 78.89 (725 – 940) 525.67 ± 219.60 (280 – 825) 37.18%[a]	525.67 ± 219.60 (280 – 825) 297.33 ± 193.46 (107 – 595) 43.44%[a]	297.33 ± 193.46 (107 – 595) 240.33 ± 147.17 (98 – 459) 19.17%[b]
COD	3065.67 ± 556.36 (2270 – 3780) 2085.50 ± 582.69 (1502 – 2805) 47%[a]	2085.50 ± 582.69 (1502 – 2805) 1581.50 ± 593.12 (827 – 2291) 24.17%[a]	1581.50 ± 593.12 (827 – 2291) 1091 ± 458.17 (643 – 1913) 31.01%[a]
TSS	1584.17 ± 711.66 (871 – 2525) 609.67 ± 294 (230 – 980) 61.51%[a]	609.67 ± 294 (230 – 980) 795.67 ± 298.05 (410 – 1175) * [c]	795.67 ± 298.05 (410 – 1175) 652.33 ± 186.95 (435 – 879) 18.0%[b]
NO_3^--N	46.5 ± 10.59 (37 – 63) 36.83 ± 12.97 (19 – 57) 20.79%[a]	36.83 ± 12.97 (19 – 57) 31.33 ± 11.71 (18– 50) 14.93%[a]	31.33 ± 11.71 (18– 50) 24.17 ± 10.94 (14 – 43) 22.85%[a]
NH_4^+-N	34.67 ± 11.45 (21 – 52) 46.17 ± 14.48 (24 –67) * [c]	46.17 ± 14.48 (24 –67) 34 ± 10.18 (20 – 48) 26.36%[b]	34 ± 10.18 (20 – 48) 22.67 ± 7.97 (12 – 34) 33.32%[a]
PO_4^{3-}	48 ± 20.26 (24 – 29) 59.83 ± 22.87 (31 – 92) * [b]	59.83 ± 22.87 (31 – 92) 39.67 ± 14.8 (23 – 63) 33.69%[a]	39.67 ± 14.8 (23 – 63) 25.50 ± 13.82 (9 – 47) 35.72%[a]
TC	$6.95 \times 10^5 \pm 3.04 \times 10^5$ ($2.9 \times 10^5 – 9.8 \times 10^5$) $6.395 \times 10^5 \pm 2.87 \times 10^5$ ($2.74 \times 10^5 – 8.9 \times 10^5$) 7.98%[b]	$6.395 \times 10^5 \pm 2.87 \times 10^5$ ($2.74 \times 10^5 – 8.9 \times 10^5$) $5.3 \times 10^5 \pm 2.28 \times 10^5$ ($2.62 \times 10^5 – 7.8 \times 10^5$) 17.12%[b]	$5.3 \times 10^5 \pm 10^5 2.28 \times 10^5$ ($2.62 \times 10^5 – 7.81 \times 10^5$) $2.68 \times 10^5 \pm 1.08 \times 10^5$ ($1.8 \times 10^5 – 4.1 \times 10^5$) 49.43%[a]
FC	$5.725 \times 10^5 \pm 2.94 \times 10^5$ ($1.65 \times 10^5 – 8.1 \times 10^5$) $5.32 \times 10^5 \pm 2.87 \times 10^5$ ($1.6 \times 10^5 – 7.5 \times 10^5$) 7.07%[b]	$5.32 \times 10^5 \pm 2.87 \times 10^5$ ($1.6 \times 10^5 – 7.5 \times 10^5$) $4.35 \times 10^5 \pm 2.46 \times 10^5$ ($1.05 \times 10^5 – 6.8 \times 10^5$) 18.23%[ab]	$4.35 \times 10^5 \pm 2.46 \times 10^5$ ($1.05 \times 10^5 – 6.8 \times 10^5$) $2.135 \times 10^5 \pm 1.11 \times 10^5$ ($0.98 \times 10^5 – 3.7 \times 10^5$) 50.91%[a]

All units are in mg/L unless indicated otherwise except TC and FC (cfu/100 mL)

Percentage not followed by the same superscript letters (a, b, and c) in the same row has significant difference ($P < 0.05$) using Duncan's method * efficiency less than zero

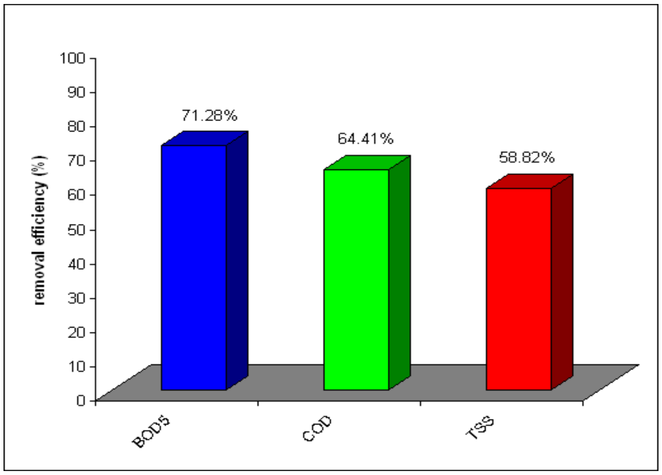

Fig.3.3. Overall removal efficiency of Mikililand WSP for BOD_5, COD, and TSS

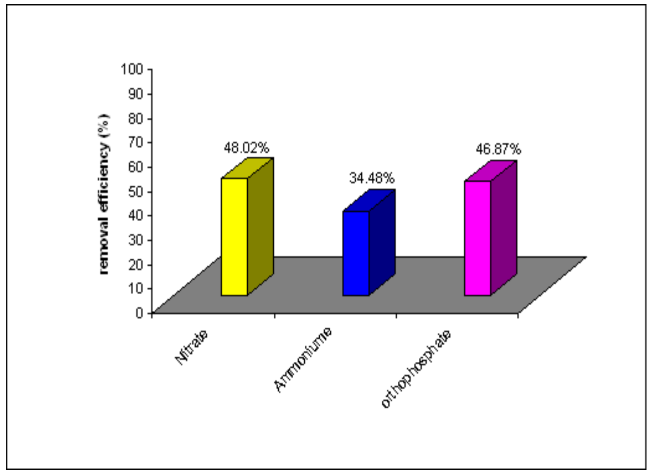

Fig.3.4. Overall removal efficiency of Mikililand WSP for NO_3^--N, NH_4^+-N, and PO_4^{3-}

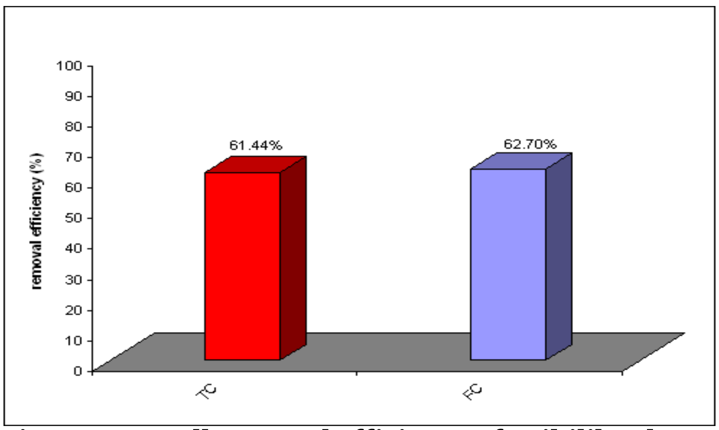

Fig.3.5. Overall removal efficiency of Mikililand WSP for TC and FC

3.3.1 BOD_5 and COD

Mean removal efficiency of AP for BOD_5 and COD as indicated in Table 3.7 is low and this is attributed to high VLR (525.24 g $BOD_5/m^3/d$) and short retention time (1.72 days; Table 3.3). This revealed that shorter time is required for anaerobic digestion of the resulting sludge solids in order to remove BOD_5. FP removal efficiency for BOD_5 and COD (Table 4.6) was also lower compared to its design removal of BOD_5 (76.3% at 13 days retention time, 1.5 m depth and 137.93 kg BOD_5/ha/d surface loading rate). This was caused by high SLR (997.46 kg BOD_5/ha/d) and short retention time of 8.94 days. The overall removal efficiency of Mikililand WSP for BOD_5 was 71.28% as indicated in Fig.3.3 which was low compared to the design removal efficiency (92.08%). This low efficiency is related to high flow rate, short retention time and high VLR and SLR. The removal of BOD_5 across each sub-pond has significant correlation (+ve) with retention time (R = 0.500; P = 0.035; Table 3.5). This is due to when there is an increasing retention time there will be sufficient time for bio-degradation of organic matter through biological process and removal of BOD_5 is enhanced. The removal of BOD_5 has significant difference across each sub-pond (P = 0.017; Table 3.4). This is attributed to significant different retention time across each sub-pond (P = 0.000; Table 3.5). In contrast, the Duncan's method indicated that BOD_5 removal was not significantly different between AP and FP (P > 0.05; Table 3.6). This is due to high volumetric loading rate of AP and high surface loading rate of FP with short retention time for both ponds, which contributed to overload conditions in both ponds. Removal of COD did not show significant difference across each sub-pond; ANOVA (P = 0.123) and Duncan's methods (P > 0.05) (Table 3.4; Table 3.6). This may be attributed to WSPs being not capable of removing significant nonbiodegradable organics [9]

3.3.2 TSS

AP removal of TSS (61.51%; Table 3.6) was a good performance within a short retention time (1.72 days) compared to BOD_5 and COD removal of AP and this was attributed to regular desludging; which helps to maintain actual depth free from sludge to enhance more gravity thickening of solids to occur. However, it is low compared to the expected design (removes most solids) and this is due to short retention time for anaerobic digestion of settled solids. The FP effluent of TSS (795.67 mg/L) was greater than influent (609.67 mg/L) and this might be due to the exposure of solid waste collection bins close to FP, from which wind action might have transferred solid matter and also the presence of algal growth. Algal growth produces additional suspended solids as high as 140 mg/L in influent of FP [19].

Overall removal efficiency of Mikililand WSP for TSS (58.82%; Fig. 3.3) was low due to short retention time reducing the removal of TSS especially, from AP by sedimentation.

A statistically significant different (P = 0.000; Table 3.4) removal of TSS through each sub-pond was also observed. The Duncan's methods also ind icated that there was significantly different removal across each sub-pond (P < 0.05; Table 3.6).

3.3.3 FC and TC

AP, FP and MP showed FC removal of 7.07% 18.23% and 50.91% whereas TC reduction of 7.98%, 17.12% and 49.43% (Table 3.6). The removal efficiency of TC and FC have significant difference across each sub-pond (P = 0.000; 0.017, respectively; Table 3.4). However, Duncan's methods revealed that there was no significant difference (P > 0.05) FC and TC removal between AP and FP (Table 3.6). This may be due to both ponds having no significantly different temperature (P > 0.05, Table 3.2). FC removal correlated (+ve) with retention time (R = 0.083, Table 3.5). Fecal bacteria die-off increased with retention time, temperature and pH increase simultaneously. MP removal of TC and FC as indicated in Table 3.7 was also low compared to [13] where 99.99% reduction of FC was reported. The overall efficiency of Mikililand WSP removal for FC and TC was 62.7% and 61.44%, respectively (Fig.3.4). This lower performance is due to short retention time.

3.3.4 NO_3^--N, NH_4^+-N and PO_4^{3-}

AP was not effectively removing NH_4^+-N and PO_4^{3-} since the effluent concentration was greater than influent and also removal of NO_3^--N was not high. The increment of effluent concentration for NH_4^+-N from influent may be associated with anaerobic conversion of organic nitrogen to nitrogen compounds like NO_3^--N and NH_4^+-N. A similar study by Pearson *et al*. [18] revealed that NH_4^+-N in effluent (53 mg/L) was greater than in influent (41 mg/L). However, Overall removal of NH_4^+-N has significant difference (P = 0.000; Table 3.4). PO_4^{3-} effluent also increased from influent of AP which may be related to poly-phosphate bacteria adding PO_4^{3-} from APs. Removal of NO_3^--N (20.79%) from AP was also low due to significant short retention time to utilize NO_3^--N as electron accepter. FP's low efficiency of nutrients removals (Table 3.6) might be attributed to short retention time for proper utilization of algae for algal biomass. The overall removal efficiency of Mikililand WSP for NO_3^--N, NH_4^+-N and PO_4^{3-} as indicated in Figure 3.5 was low and this is again due to short retention time. More removal of nutrients was achieved when more than one maturation pond existed and design retention time was applied without reduction [9]. The removal reduction of PO_4^{3-} across each sub-pond had significant difference but this did not occur for NO_3^--N (P = 0.000; 0.327, respectively) (Table 3.4). The removal of PO_4^{3-} has correlation (+ve) with retention time (R = 0.390) although not significant (P = 0.109) (Table 3.5).

3.4 Comparison of treated effluent with standards and/or guidelines

The treated effluent of Mikililand WSP did not meet Ethiopian Standards [20] discharge limit to rivers excluding pH, temperature and NH_4^+-N and Jordanian standards (2002) [cited in 23] except pH and DO (Table 3.8). Higher concentration of BOD_5 and COD from treated effluent is a result of low removal efficiency of the overall Mikililand

WSP. High BOD_5 and COD discharge to a river have an impact as deoxygenated water generate obnoxious odors [21, 22]. Beyond the standard limit treated effluent of NO_3^--N and PO_4^{3-} may also promote growth of unwanted aquatic plants. High TSS discharged to river causes turbidity in water and bottom deposits of solids. Discharging high effluent nutrients to a river causes toxic conditions to aquatic organisms and stimulates algal growth. FC and TCs did not comply with the microbiological quality guidelines of Oman (1993) [cited in 23] for reuse of unrestricted (vegetable) irrigation. BOD_5, COD, TSS and NO_3^--N also did not meet both Oman (1993) and Jordanian reuse standards (2002) standards [cited in 23] for unrestricted irrigation.

Table 3.7 Comparison of Mikililand WSP treated effluent with Ethiopian and other countries standards and guidelines of discharge to river and reuse for unrestricted irrigation

Parameter	Mikililand WSP effluent	[20][2]	Jordanian Standards $(2002)_2$[1]	Jordanian Standards $(2002)_3$[1]	[25][3] TC guidelines	Oman Standards $(1993)_3$[1]
pH	7.18	6 – 9	6 – 9	6 – 9	-	6 – 9
Temp.(°C)	21.8	40	-	-	-	-
DO	2.45	-	> 1.0	> 2.0	-	-
BOD_5	240.33	80	60	30	-	15
COD	1091	250	150	100	-	150
TSS	652.33	100	60	50	-	15
NH_4^+-N	22.67	30	-	-	-	5
NO_3^--N	24.17	20	45	30	-	50
PO_4^{3-}	25.5	5	-	-	-	-
TC (cfu/100 mL)	2.68×10^5	400	-	-	1000	-
FC (cfu/100 L)	2.135×10^5	-	-	-	-	200

All units are in mg/L unless indicated otherwise except pH
[1]cited in [23] [2] Discharge to river [3] Reuse for unrestricted irrigation.

4 CONCLUSION

Low removal efficiency of each sub-pond and the overall pond was recorded. In order to achieve high efficiencies of the overall pond and each sub-pond, connecting parallel pond is essential to maintain satisfactory retention time, flow rate and loading rates in addition to sufficient monitoring and maintenance activities.

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