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Original Article

Performance of Wastewater Stabilization Ponds: A Case Study of Nzoia Sugar Factory Wastewater Treatment Plant, Kenya

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Abstract - *Water pollution is one of the most common environmental problems encountered worldwide, especially in developing nations. To avert this, both domestic and industrial effluents should be treated by appropriate technologies to acceptable levels before disposal. Wastewater stabilization ponds are widely used for domestic and industrial wastewater treatment worldwide. This study aimed to determine the performance of wastewater stabilization ponds for industrial sugar effluent by evaluating the treatment plant's operational parameters and hydraulic characteristics. Key parameters were; biochemical oxygen demand, total suspended solids, chemical oxygen demand, total dissolved solids, and electrical conductivity. Wastewater samples were tested using the standard testing methods. The results showed the treatment plant did not meet the acceptable discharge standards for the key parameters. It was also established that all parameters varied significantly ($p<0.05$) across the different ponds except for BOD ($p>0.05$). Wrong positioning of the inlet and outlet structures, a smaller length to width ratio, and non-functional mechanical aerators were attributed to the poor effluent quality. Recommendations were to address the design aspects of the ponds and ensure proper maintenance of the mechanical aerators*

Keywords - *Aerated ponds, Biochemical oxygen demand, Hydraulic performance, Industrial effluent, Short-circuiting.*

1. Introduction

Waste stabilization ponds (WSPs) are large shallow basins surrounded by earth embankments in which domestic and industrial wastewater, septage, and sludge, as well as animal wastes, are treated specifically by natural processes involving both bacteria and algae [1]. [2, 3], describe them as chemical reactors applied to reduce solids, organic matter, and pathogenic organisms. They represent reliable, cost-effective, and easy-to-operate methods for treating domestic and industrial wastewater [4]. Thus, most preferred by developing countries because of their temperate and tropical climates where conventional wastewater treatment cannot be attained due to a lack of a reliable energy source Toumi et al. [5]. Some countries in tropical climates that utilize WSPs for wastewater treatment are Kenya, Uganda, Tanzania, Malawi, Zimbabwe, Botswana, and Zambia [6].

The performance of WSP systems depends on several factors, including the organic loading regime, type of wastewater, pond geometry, and physical arrangement of the pond system. Also, the environmental conditions such as air temperature, amount of wind, and the incident sunlight to which the pond is exposed affect the performance [7]. Other factors are the living organisms such as planktons and benthos, hydraulic pond behavior such as hydraulic retention time (HRT), wastewater flow rate, and the existence of dead waters or short-circuiting [1]. Short-circuiting occurs when wastewater enters and leaves the pond within a very short time, usually less than the designed hydraulic retention time.

Coggins, et al. [7] reported a decrease in performance efficiency of WSPs, which was attributed to organic overloading that was beyond the plant's design capacity, imprecise design parameters, and inadequate operation. It was further established that the generally poor performance of the system could be influenced by inefficient hydraulic performances, short-circuiting, sludge accumulation, and flow velocities. The choice of pond configuration during design should be such that short-circuiting is minimized; where possible, this can be done by introducing baffles [8]. Minimal short-circuiting is important since it improves hydraulic efficiency. The inlet and outlet should be carefully located to control the quantity of scum (Olukanni & Ducoste, 2011). For anaerobic and primary facultative, the inlet should discharge below the wastewater surface level and above for maturation and secondary facultative ponds. The outlet should be located to reduce the discharge of scum [9].

Disposal of untreated or partially treated industrial effluents from sugar processing factories, for instance, leads to serious pollution of the waterways. These effluents exhibit high contents of BOD, chemical oxygen demand (COD), total dissolved solids (TDS), and low dissolved oxygen (DO) content which is toxic to aquatic life as established by Siddiqui and Waseem [10]. According to et al. [11], untreated effluents from sugar mills degrade surface water bodies and fertile soils and pollute groundwater resources. Sugar processing factories form the biggest water consumers and simultaneously generate huge amounts of wastewater daily. The estimated per capita water demand for Nzoia Sugar Company (NSC) ranges from 2,000m^3 to 3,000m^3 as per the Company's records. Consequently, the factory's daily wastewater effluent generation varies from 1,500m^3 to 2,700m^3, as indicated by the pollution control section records.

NSC manages its industrial effluents by WSPs technology. The selection of this technology was based on the low cost of operation and maintenance, a favourable tropical climate, and the availability of land for construction and future expansion. Despite these factors, according to monitoring reports from Water Resources Management Authority, pollution control section, there has always been a challenge of consistently meeting effluent disposal standards set by the National Environment Management Authority (NEMA), thus, putting the receiving water body which in this case is R. Kuywa at risk of pollution. R. Kuywa is a tributary of R. Nzoia, the largest river in the Kenyan portion of the Lake Victoria basin; any change in the river's water quality can ultimately affect the lake. The water quality in this river is of great concern; thus, NSC is responsible for protecting it by discharging effluent of acceptable standards into the river.

A study by [12] on the physicochemical characteristics of R. Kuywa established high values of pH, turbidity, and TSS, among other parameters of the river, at different sampling locations which exceeded NEMA standards. Muchanga and Salim [13] reported high Chromium and Cadmium concentrations above the allowable in their study on the determination of heavy metals in the lower part of the R. Kuywa, thus indicating the poor water quality of river Kuywa, which could pose serious health problems. All these were attributed to anthropogenic activities, industrial effluents especially from sugar processing being among them.

This study, therefore, aimed at determining the performance of the wastewater treatment plant by evaluating the operational parameters of the treatment unit processes and operations for effective management of the wastewater for NSC.

2. Materials and Methods

2.1. Study Area

The research was conducted on the wastewater treatment plant of NSC, which is one of the key players in Kenya's Sugar Industry. It is located in Bungoma County, Bungoma South sub-county, 5Km from Bukembe, off the Webuye-Bungoma highway (Fig. 1). The Company serves over 67,000 farmers in Bungoma and Kakamega counties. It is situated at a latitude of 0˚35'N, a longitude of 34˚40'E, and an altitude of between 1420-1490 meters above sea level.

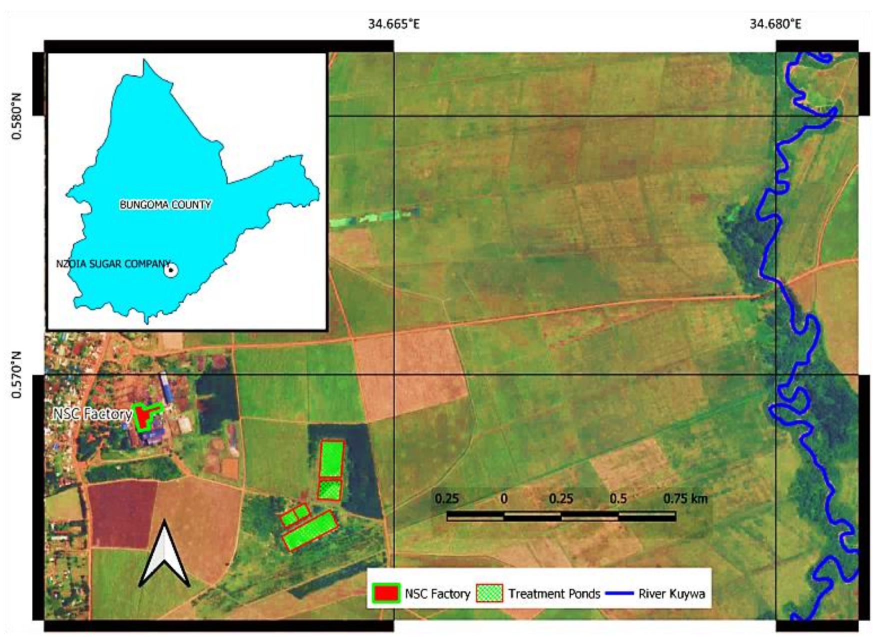

Fig. 1 Map of the study area

2.2. Data Collection and Analysis

The data collection involved field measurement of the ponds' hydraulic characteristics and wastewater sample collection. Raw and treated wastewater samples were collected at the inlet and outlet chambers of aerated, facultative, and maturation ponds and taken for physicochemical laboratory testing. Sampling was done fortnightly for six months, from April to September 2018. Temperature, pH, turbidity, EC, and TDS were measured in situ. Analysis for BOD, COD, and TSS has been carried out at the Kakamega Water Resources Management Authority (WRMA) laboratory. The samples were preserved by maintaining the sample container temperature at 4℃. All tests were carried out using the standard methods for water and wastewater analysis [14]. The equipment used for wastewater laboratory tests was; BOD oxitop box with accessories, a COD reactor with accessories, a filtration unit, a suction pump, desiccators, and an analytical weighing balance. The color was measured using the Lovibond color comparator 2000+. Other portable apparatus was from HACH; DO meter, TDS meter, pH and temperature meter, and turbidimeter accompanied by the relevant standard solutions for calibration and their respective reagents where applicable.

The wastewater plant's performance was determined using MS Excel, where descriptive and inferential statistics performed statistical analysis on the Physico-chemical data. The performance efficiency was obtained by computing the input (C_i) and output (C_e) concentrations for individual constituents at sampling events. The removal rates were attained by determining the input and output concentrations. The percentage removal per constituent was calculated as:

$$\text{Pond efficiency} = \frac{c_i - c_e}{c_i} \text{ x } 100\% \qquad (1)$$

Where C_i is the concentration of the influent and C_e is the concentration of the effluent.

The results for pond geometry, effluent, and influent quality, as well as pond efficiencies, were presented in Tables 1 and 2, respectively.

3. Results and Discussion

3.1. Nzoia Sugar Company Wastewater Treatment Plant Layout Description

The wastewater flows through bar screens located at the inlet chamber, which traps larger solid waste material from the wastewater, referred to as screenings that are removed manually, dried, and disposed of by burning. The next stage is the grit chamber, where inorganic solid particles are removed. There are two chambers equipped with sluice gates for flow control to facilitate the removal of grit. The wastewater then goes through the sedimentation process in a rectangular sedimentation basin for a retention period of two (2) days (Table 1 and Fig. 2). These allow settlement of the organic solids in the wastewater as it flows into a pair of aerated ponds, which are provided with mechanical aerators. These ponds are meant to maintain dissolved oxygen throughout the entire depth. The mechanical aerators are supposed to maintain continuous mixing keeping the solids in suspension, which prevents the settlement of algae that could result in an anaerobic bottom layer. The mixing is as well crucial in keeping the algae at the surface for sufficient oxygen production via the process of photosynthesis. However, the mechanical aerators were faulty and had not been in operation for a long time.

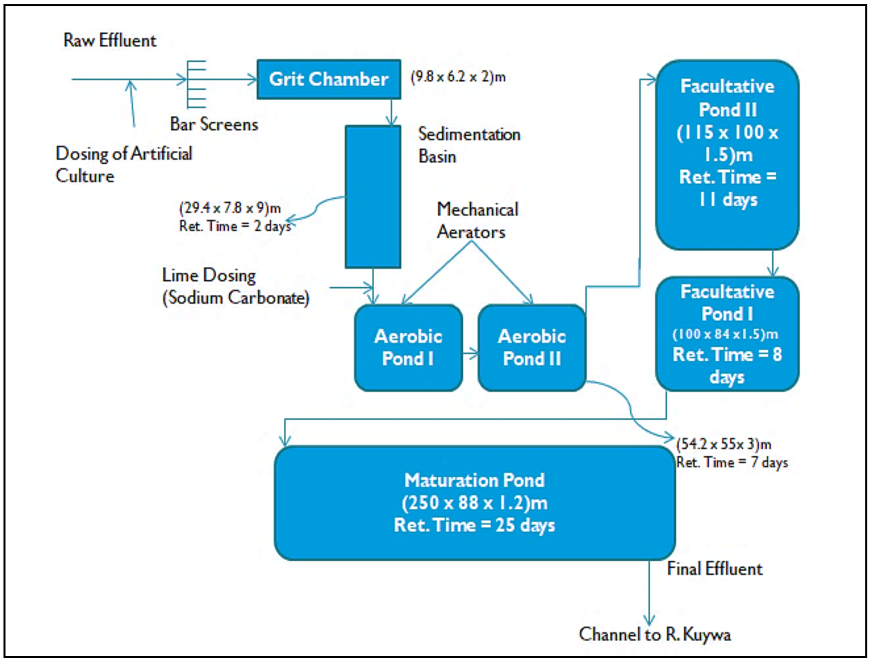

Fig. 2 Nzoia Sugar Company wastewater treatment plant layout plan

Table 1. Hydraulic characteristics of the ponds

Stage	L (m)	W (m)	D (m)	L : W	HRT (days)
Screens	0.2	1.4	2.0	N/A	N/A
Inlet Chamber	2.5	1.4	2.0	N/A	N/A
Grit Chamber	9.8	2.6	2.0	N/A	N/A
Lime Dosing Chamber	3.0	3.0	1.0	N/A	N/A
Sedimentation Basin	29.4	7.8	9.0	3.77:1	2
Aerated Pond I	54.2	52.0	3.0	1.04:1	7
Aerated Pond II	55.0	54.2	3.0	1.02:1	7
Facultative Pond I	100.0	84.0	1.5	1.19:1	8
Facultative Pond II	115.0	100.0	1.5	1.15:1	10
Maturation Pond	250.0	88.0	1.2	2.84:1	25

Key: L = Length, W =Width, D = Depth, HRT = Hydraulic Retention Time

Lime (sodium carbonate – Na_2CO_3) addition occurs just before the wastewater enters the aerated ponds for pH adjustment in a lime dosing chamber. This process of adjusting the pH is crucial as the pH of the raw industrial wastewater is usually very low (4.3-4.9); thus, it's necessary to raise it to allow optimum bacterial activity. The plant also has two secondary facultative ponds of different sizes in series; facultative I and facultative II, where BOD, COD, total solids, and turbidity are expected to be reduced by the processes of sedimentation and both aerobic and anaerobic digestion [15]. At this stage of treatment, the mutual relationship between algae and aerobic bacteria exists. Finally, there is a maturation pond for polishing up the treatment process, which discharges the final effluent into River Kuywa through an open channel about three kilometers long.

3.2. Performance Efficiency for the Aerobic, Facultative, and Maturation Ponds

The results for the performance of the waste stabilization ponds for NSC, indicating the removal efficiencies at every treatment stage, are shown in Table 2.

3.3. Performance of Aerated Ponds

The aerated ponds are the first treatment stage of the NSC WSPs. The removal rates for TSS, turbidity, and color were 58.8%, 39%, and 40%, respectively (Table 2). They were the highest reduction rates as compared to the other parameters. BOD registered a very low removal rate (2.5%), and statistical analysis revealed BOD did not differ significantly ($p>0.05$) in concentration. COD, however, varied significantly ($p<0.05$) by recording an increase of 47.1% in concentration. Mara [3] reported a significant negative relationship between pH with BOD and COD from the correlation analysis. Thus, the performance could be attributed to the very low pH of 4.11 and 4.26 for the influent and effluent in the aerated ponds, respectively. Albeit the presence of optimal temperature (25^{o}C) to support biochemical reactions within the ponds, the majority of microbes involved in the waste stabilization process could not have been active and survived due to the acidic (4.26) pH. Also, according to [16], the operational wastewater depths appear to impact the treatment performance in terms of BOD, COD, TSS, and un-ionized ammonia removal. Therefore the physical design is directly related to loading rates and impacts water temperatures, gas exchange, and incident solar radiation, all of which strongly influence the oxygen state and biogeochemical processes of a WSP. Considering the depth of the aerated ponds (3m), which were the deepest, this could also explain the low BOD and COD removal. Consequently, a higher removal rate was registered by TSS (58.8%), and turbidity in these ponds, the concentration varied significantly ($p<0.05$) across the ponds. This performance could have been due to the raw effluent's high sediment load, the ponds' depth (3m) as well as the low velocity of the wastewater [8].

Table 2. The percentage removal rate for Aerobic, Facultative, and Maturation Ponds

	Raw	**Aerobic pond**		**Facultative pond**		**Maturation pond**	
Item	**Effl**	**Effl**	**R (%)**	**Effl**	**R (%)**	**Effl**	**R (%)**
Temp	26.06	25.2	N/A	25.2	N/A	24.95	N/A
Colour (Pt.Co)	50	30	40	40	-33	27.5	31.3
pH	4.11	4.26	N/A	6.06	N/A	7.04	N/A
EC (µS/cm)	388.5	665.5	-71.3	523	21.4	478	8.6
Turbidity (NTU)	877	532	24.1	269	49.4	196.5	27
COD (mg/l)	1360	2000	-47.1	840	58	600	28.6
TSS (mg/l)	632.5	262.5	58.5	152.5	41.9	140	8.2
TDS (mg/l)	233.1	399.3	-71.3	313.8	21.4	286.8	8.6
BOD (mg/l)	875	853	2.5	275	67.8	240	12.7

Key: Temp = temperature, R = removal, Effl= Effluent

EC and TDS significantly differed ($p<0.05$), reporting a huge increase in concentration (71.3%). Conductivity measures the dissolved ionic component, thus the electrical characteristic. Consequently, there exists a strong positive relationship between the two. The observed increase could be attributed to the aerobic breakdown of the organic and inorganic material leading to the release of dissolved solids [17]. This increase could also be associated with the lime stabilization process where sodium carbonate (Na_2CO_3) was usually added to the effluent to stabilize the pH raising it towards the neutral (pH 7.0) before the effluent entered the aerated ponds [18]. It could contribute to the increase in EC and TDS due to the high concentration of the introduced Na^+ and CO_3^{2-} ions and chemical reactions between Na_2CO_3 and ions naturally present in the organic and inorganic loading of the wastewater. A high concentration level of EC can augment the corrosive nature of industrial wastewater, which can lead to an increased corrosion rate in wastewater pipelines and metallic tanks or containers [19].

3.4. Performance of Facultative Ponds

There was an improvement in performance in these ponds compared to the aerated ponds for most parameters. The removal rates for the various parameters were as follows; BOD (67.8%), COD (58%), TSS (41.9%), and 21.4% for both EC and TDS (Table 2). Naturally, this type of pond is designed for organic loading reduction, which is well designed and properly maintained, and could achieve up to 90% BOD reduction [26]. It could explain this study's significant rate of BOD and COD reduction. Another reason for the improved performance in BOD and COD could be attributed to the recorded temperature (25.5ºC) and pH (6.06) in these ponds. A temperature range of 20ºC to 27ºC promotes bacterial action for aerobic and anaerobic biochemical processes at a pH range near the neutral (7), which most microbes prefer [21]. The presence/absence of TSS in wastewater affects the turbidity of the wastewater. Solids are removed by sedimentation of the particles at the bottom/anaerobic zone of the pond. More solids settled in these ponds, which also improved the turbidity of the effluent from 39% to 49.4%. EC and TDS recorded a great improvement from the aerated ponds. The 21.4% reduction for both parameters in the facultative ponds could have been due to the removal of nitrates by the denitrification process, where nitrates are reduced to nitrous oxide and then into nitrogen gas which is less soluble in water, thus escaping into the atmosphere [22]. On the flip side, there was an increase in colour (33%) which could be attributed to the production of new green algae and bacterial cells through the mutual relationship in facultative ponds [15].

3.5. Performance of the Maturation Ponds

It is the last stage of WSPs wastewater treatment. Maturation ponds, also known as polishing ponds, are designed for pathogen removal but also polishing regarding the other parameters. The removal rates were COD (28.6%), BOD (12.7%), colour (31.3%), TSS (8.2%), turbidity (27%), EC and TDS (8.6%). This pond's average temperature and pH were 25.94ºC and 7.04, respectively. Optimally, the two favor biochemical activities [21]. It was also observed that there was no increase in loading of any parameters as recorded in the previous types of ponds. This pond performed better than the aerated ponds in removing COD and BOD. The operational temperature and pH could have been the cause of the improved performance. However, the level of BOD and COD were still higher than the acceptable levels, which pointed to a decline in DO since the available oxygen in the wastewater was being consumed by the bacteria, which could lead to an inability of fish and other aquatic organisms to survive in the effluent receiving river [19].

Comparing the performance of the three types of ponds in organic and inorganic loading, it was established that facultative ponds performed better than maturation ponds, whose performance was better than the aerated ponds. Therefore, the aerated ponds were poor performers and could have been the main cause why NSC WSPs could not meet the permissible effluent standards.

3.6. The Hydraulic Efficiency of the WSPs

The mode by which the wastewater distributes within the pond expresses the hydraulic efficiency of WSPs [23]. In this study, hydraulic efficiency was measured by investigating some design aspects of the ponds. The pond geometry in terms of the length-to-width ratio and the position of the inlet and outlet structures were investigated (Table 1).

3.7. Length to Width Ratio (L: W)

Length-to-width (L: W) ratio is considered the main factor which influences the hydraulic performance of WSPs. The L: W ratios were 1.04:1, 1.02:1, 1.19:1, 1.15:1, and 2.84:1 for the aerated I & II, facultative I & II, and maturation ponds, respectively (Table 1). Normally, wastewater in WSPs moves in eddies and recirculation, thus rarely homogeneous. A uniform velocity profile is preferred for WSPs, which characterizes plug flow conditions. This velocity profile occurs when the L: W ratio is large [23]. L: W ratio greatly affects the amount of mixing. For facultative and maturation ponds to achieve plug flow, they must have an L: W ratio of 10 to 20. On the other hand, large L: W ratios increase the construction cost. Optimally, L: W ratios of 2:1 have been recommended, reducing sludge accumulation at the inlet. The maturation pond was the only pond with an L: W ratio within the recommended 2:1. The two pairs of aerated and facultative recorded lower L: W ratios which could have hampered plug flow conditions and promoted short-circuiting in the system. The poor performance of the aerated ponds could be attributed to the lower L: W ratios.

3.8. Inlet and Outlet Positions

The inlet and outlet of the ponds were provided with a single pipe and an overflow weir, respectively. To prevent channeling and short-circuiting in the WSPs, [24] recommended the inlet and outlet chambers not to positioned on opposite sides. From the pond layout in Figure 2, it was established that the aerated pond I, facultative pond I & II had their inlet and outlet structures positioned correctly according to design recommendation [25]. However, for the aerated pond II and maturation pond, the inlet and outlet were located on the opposite sides. Considering the large L: W ratio (2.84:1) for the maturation pond, the wrong positioning of the inlet and outlet could have had minimal effect on its performance because of the long HRT. The poor performance of the aerated ponds could be attributed to short circuiting and the formation of dead water zones that could have reduced hydraulic retention time due to the wrong positioning of the inlet and outlet. These results agree with Gopolang and Letshwenyo [8], who reported poor hydraulic efficiency of WSPs due to the wrong positioning of the inlet and outlet.

4. Conclusion and Recommendations

Based on the study results, it was concluded that NSC WSPs' performance was generally considered unsatisfactory. The performance efficiency of each treatment unit was low for most parameters; thus, the final effluent had a high potential of polluting the receiving water of R.Kuywa. Regarding organic loading reduction, facultative ponds were better performers, followed by the maturation pond and finally aerated ponds, which recorded the least performance.

The poor performance of the aerated ponds could be attributed to the reduced HRT and short-circuiting and a lack of consistency in the operation of mechanical aerators caused by occasional breakdowns, as was evident at the time of the study. This poor performance of the aerated ponds could be associated with the unsatisfactory general performance of the entire wastewater treatment process, as was established by the study.

It was recommended that the mechanical aerators for the two aerobic ponds be well maintained to consistently be in operation to boost microbial action and reduce BOD and COD loading to acceptable levels. Second, NSC should consider relocating the aerated pond I outlet to minimize issues related to short-circuiting, dead water zones, and reduced HRT. Lastly, NSC to improve the frequency of routine sampling alongside routine follow-up sampling for monitoring to ensure compliance of all the parameters and any deviation from the permissible to be resolved within the shortest time possible to safeguard the environment as well as human and aquatic lives.

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