Water Benchmark and Performance Assessment of an Agro-food Wastewater Treatment Plant Using Biophysicochemical Characterization Approach

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Abstract

The hazard posed by poorly treated effluent from agro-food treatment plant has been a growing concern to environmentalists and regulatory bodies. This study is aimed at benchmarking fresh water utilization and assessing the treatment efficiency of an agro-food wastewater treatment plant in Lagos, Nigeria based on biophysicochemical characterization. Water utilization analysis and benchmarking were initially conducted to determine areas with significant water saving potentials. Influent and effluent samples were collected daily for six months (September 2016 to February 2017) and analyzed for 25 biophysicochemical pollution indicators. Results were compared with Lagos State Environmental Protection Agency (LASEPA) guidelines for industrial effluent. Significant improvements were recorded for all the assessed biophysicochemical parameters. The treatment plant was adjudged satisfactory with all assessed parameters falling within permissible limits and average removal efficiencies ranged from 4.78% to 96.9%. However, plant overloading resulting from high water intensity and inadequate plant monitoring accounted for the low removal efficiencies recorded for some parameters. Given the current performance, significant improvements in areas such as freshwater management, routine plant monitoring and adjustment of hydraulic loading rates are necessary to optimize the plants' operation in line with standard practice.

***Keywords**:* agro-food, wastewater, biophysicochemical, treatment plant

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1. Introduction

Agro-food industries are crucial for Nigeria's economic growth, contributing about 10% to the nation's gross domestic product (GDP). The industry has evolved into a diversified industry involved in the production of varied products ranging from beverages to animal products. The beverage industry alone currently produces about 1.1 billion liters which is about 1% of nominal GDP (Olaoye, 2014). The industry consumes huge amount of fresh water and exerts significant pressure on the environment by discharging poorly managed hazardous wastes. This negative environmental impact requires quick intervention. Poor wastewater handling had resulted in the spread of infectious waterborne diseases with adverse socio-economic effects collaborating the United Nations Development Programme's statement that only 30% of wastewater treatment plant in Sub-Saharan African cities were satisfactorily operating. The importance of efficiently treating industrial and domestic wastewater before disposal as a means of preserving the environment and public health have not been fully harnessed in Africa. (UNESCO IHP, 1996; UNEP, 2000).

Disposal of poorly managed waste by agro-industries and related activities have been identified as a major source of industrial pollution worldwide (Rajinikanth *et al*., 2013; Fang *et al*., 2016). This practice is attracting strict environmental laws and costly penalties that have propelled the development of improved treatment technologies. Biological treatment methods involving aerobic and high rate anaerobic treatment systems, chemical treatments and industrial wetlands are among the methods developed (Agyemang, 2010; Jabile and Ibarra, 2017).

Wastewater generated from agro-food industrial operations have distinct characteristics that differ from other industrial effluents. It is highly biodegradable, nontoxic with high concentrations of biological oxygen demand (BOD) and suspended solids (SS) depending on raw material, processing technique, unit operations and plant clean-up techniques (Amuda and Amoo, 2007; Rajagopal, 2008; Satyawali, *et al*., 2009; Arienzo *et al*., 2009; Ganesh *et al.*, 2010; Alkaya and Demirer, 2015). The most harmful constituent of this wastewater is generated during equipment and facility clean-up and contains residues of detergents and other cleaning products. Therefore, agro-food industrial wastewater treatment plants (AWWTP) are designed with individual specificity different from conventional sewage treatment plants, however, effluent fluctuations and quality deterioration are the major limitations of these plant (Capodaglio *et al*., 2016; Boguniewicz-Zabłocka *et al*., 2017). Treatment efficiency must be consistently monitored to check these limitations. Since most agro-food processing plant is closely integrated with wastewater treatment facilities, a comprehensive assessment of the whole system starting from the processing plant is a logical approach. This study is therefore aimed at benchmarking fresh water utilization and assessing the treatment efficiency of an agro-food wastewater treatment plant under irregular flow and varied biophysicochemical composition conditions. The treatment plant performance was assessed based on the reduction efficiency of key biophysicochemical pollution indicators.

2. Methodology

2.1 Characteristics of the AWWTP

The treatment plant receives raw effluent from a processing factory that primarily produces high-quality fruit drinks and a wide variety of dairy products. The plant was designed to treat 1200 m^3/day of wastewater and has a peak flow of 130 m^3/hour generating about 1100 m^3/day of effluent. The processing factory is integrated with the wastewater treatment plant generating wastewater from process operations such as washing, failed batch draining, flushing of the production line and product spillage/leakages. Stainless screens and grit chambers were installed as preliminary treatment structures closely followed by secondary treatment structures aimed at reducing the residual organic loads from the primary treatment stage. About 25-40 % of the wastewater BOD is reduced at this stage (Tchobanoglous *et al.*, 2004). The tertiary process is the last stage that reduces effluent biophysicochemical parameters using a combination of biological and physical processes. Table 1 gives the capacity of the different treatment units while Figure 1 shows the treatment flow diagram from the inlet channel to the final stage after which the treated wastewater is discharged.

Table 1. Wastewater treatment units with capabilities

S/No.	Treatment Unit	Capacity (m^3)
1	Screen Chamber	3
2	Equalization Tank	355
3	Buffer Tank	126
4	Up-flow Anaerobic Sludge Blanket (UASB)	1210
5	Hopper Bottom Settling Tank	109
6	Aeration Tank	476
7	Lamella Clarifier	50
8	Holding Sump	202
9	Pressure Sand Filter (PSF)	0.45
10	Activated Carbon Filter (ACF)	0.45
11	Sludge Sump	107
12	Decanter Centrifuge	100

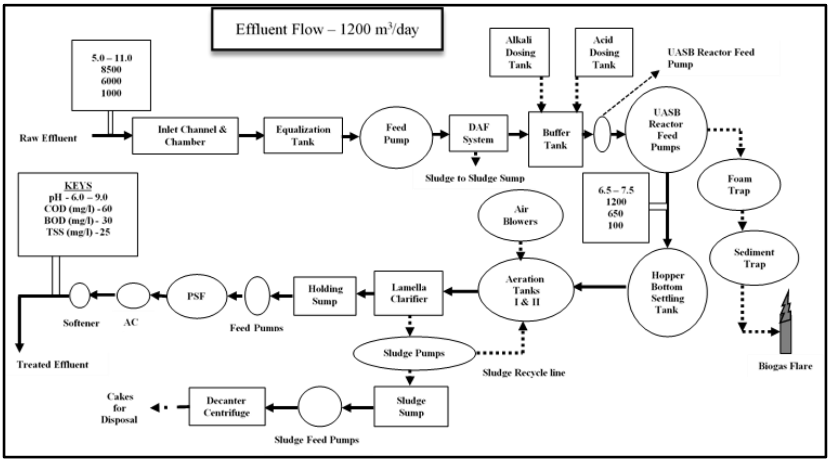

Figure 1. Process flow diagram for the wastewater treatment plant

Figure 2 shows the dissolved air flotation (DAF) unit. It is incorporated into the treatment stage as shown in Figure 1. It helps to clarify the wastewater by removing suspended matter such as solids, fat, oil etc. It is a combination of several individual units performing different functions. This unit is extensively used to treat wastewater generated in food processing plants, oil and gas, mining, pulp and paper and many major industries and municipal wastewater plants.

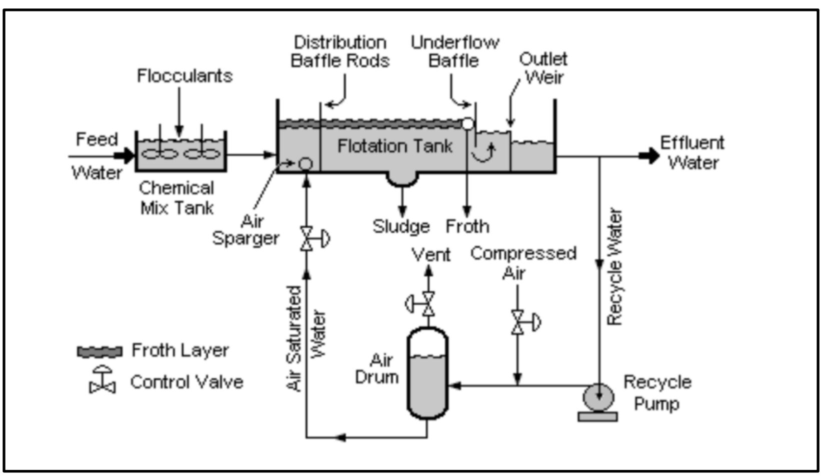

Figure 2. Schematic description of wastewater circulation in the DAF unit

2.2 Biophysicochemical Characterizations and Analysis

Transparent 500 ml sterilized pet bottles were used to collect effluent and influent samples from the plant inlet and outlet chambers twice daily for 6 months (September 2016 to February 2017) between 9.00 a.m. and 3.00 p.m. at temperatures ranging from 27 to 30°C. The samples were transported to the laboratory in plastic coolers maintained at 4°C to inhibit biodegradation. Wastewater samples were analyzed in triplicates for physicochemical and microbial properties using standard methods (American Public Health Association, 1985). Atomic absorption spectrophotometer was used to determine the amount of heavy metal in the samples. The treatment plant performance was assessed based on the removal efficiency of the various pollution indicators using Equation 1.

$$E_R(\%) = \frac{I_o - I_f}{I_o} \tag{1}$$

where:

I_f = The final values of the tested parameter
I_o = The initial values of the tested parameter

3. Results and Discussion

3.1 Freshwater Source and Utilization Pattern

The production plant uses fresh water at the rate of 29,700 m^3/month. The six major areas where fresh water is extensively used include plant clean up, fruits and product washing, utilities and plant operations, packaging preparations, product cooling and others (Figure 3). Freshwater is mainly from boreholes except in fruit mixing where it is further treated before use. The processing plant processes fresh fruits majorly harvested during the rainy season, March to October, and dairy products. This implies an increase in processing activity and fresh water utilization. The wastewater organic load is usually low due to the availability of fresh water during this period. Plant efficiency is best determined when the effluent organic load is high mostly due to low freshwater consumption pattern (Mijinyawa and Lawal, 2010).

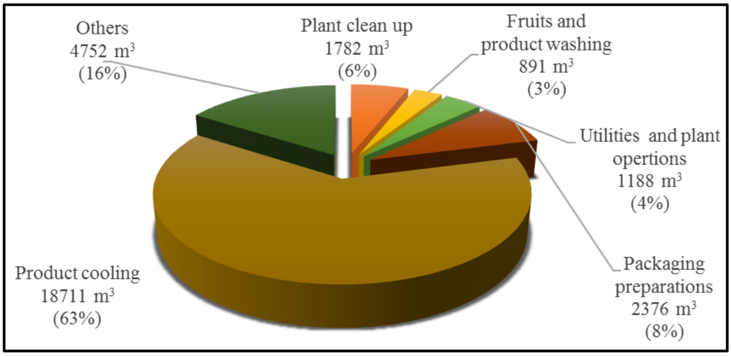

Figure 3. Breakdown of monthly freshwater utilization pattern in the processing plant (Adopted from Alkaya and Demirer, 2015)

As shown in Figure 3, product cooling accounts for the highest freshwater consumption with 18711 m^3/month which is about 61%. About 16% (4752 m^3) of the plant water requirement could not be accounted for and can be regarded as water lost through pipe leakages, evaporation losses etc. Half (8%) of this water is used during packaging preparations while about 6% (1782 m^3) is used during plant clean-up. Utilities and plant operations account for 4% (1188 m^3). Fruits and products washing account for the lowest (3%) water utilization operation. The processing plant water utilization pattern was compared with those reported from similar agro-food factories and presented in Table 2.

Table 2. Benchmarking fresh water utilization pattern

Treatment Unit	This study (%)	Pagan *et al.*, (2004) (%)	Gec¸ er, (2007) (%)	Alkaya and Demirer, 2015 (%)
Plant clean-up	6	25	36.1	9.8
Fruits and product washing	3	60	35.1	9.3
Utilities/plant operations	4	8	17.0	1.6
Packaging preparations	8	-	-	-
Product cooling	63	2	8.1	61.0
Others	16	5	3.7	18.3

The amount of fresh water reported for product cooling in this study was comparable with values reported by Alkaya and Demirer, (2015) (63 and 61%) while Pagan *et al*. (2004) and Gec¸ er (2007) reported fruits and product washing and plant clean-up as the highest freshwater consuming activities (60 and 36.1%). They further reported 5 and 3.7% as the amount of water consumed that was unaccounted for as against 16 and 18.3% recorded in this study and Alkaya and Demirer (2015) respectively. Fruits and product washing recorded the lowest water consumed (3%). Huge water saving potential, therefore, exists in the amount utilized for product cooling and unaccounted losses. This amount can be reduced to decrease overall water intensity of the processing and treatment plants. The high-water intensity accounts for treatment plant overloading beyond its design capacity. Closed-circuit cooling practice among others was suggested to replace the once-through cooling currently practiced in this processing plant as was also suggested by Casani and Knøchel (2002) and Oktay *et al*. (2007). Water saved or used from other processing activities can be also be reused in other processes like fruit washing and plant clean-up.

3.1 Preliminary Observations and Wastewater Characterization

The generated wastewater quality was low with all monitored parameters falling above the maximum permissible limit set by the local regulatory body (LASEPA). Performance of the wastewater treatment was assessed based on the reduction of biophysicochemical parameters as presented in Table 3 and Figures 4-9. Fluctuations in the intensity water consumed due to seasonal fluctuations and poor plant maintenance may account for the wide variations observed in the standard deviation of some parameters.

3.2 Microbial Parameters (Aerobic Mesophilic Organic Load)

The highest mesophilic organic load of 912 CFUs/ml was recorded in January 2017 with a corresponding reduction efficiency of 92.1% while the lowest (470 CFUs/ml) with a corresponding reduction efficiency 92.3%. The fluctuating water consumption pattern may account for the generation of varied organic load wastewater. The removal efficiency lies between 75.8% - 96.1% with an average removal efficiency of 91.19% as shown in Table 3. The final effluent quality falls below LASEPA permissible limit. The graphical representation of the mesophilic organic load and the percentage reduction after treatment are presented in Figure 4 and Figure 5.

3.3 Physical Parameters

The effects of treatment on the effluent color and suspended solids are presented in Figures 6 and 7. The highest color reduction and the corresponding removal efficiency (587 co-pt. and 98%) was obtained in September 2016 while the lowest (122 co-pt. and 85.2%) was recorded in February 2017. This can also be attributed to the amount of fresh water available to the processing plant. With a permissible limit of 250 co-pt., the treatment plant was adjudged effective.

Table 3. Wastewater characterization and treatment efficiency between September 2016 and February 2017

S/N	Wastewater Parameters	Raw Wastewater		Treated Wastewater		Percentage Reduction (%)	Max. Permissible Limit (LASEPA)
		Range	Mean Value	Range	Mean Value		
1	Colour (co-pt.)	122-587	279.17 ± 167.99	7-18.1	10.38 ± 3.91	96.28	250
2	pH at 25°C	3.71-5.12	4.50 ± 0.61	7.32-8.02	7.86 ± 0.38	-74.64	6.5-8.8
3	Conductivity (μs/cm)	841-1345	1149.17 ± 222.08	1304-3176	2395.00 ± 829.40	-108.41	4000
4	Free Carbon dioxide	114-930	444.00 ± 328.64	38-48.8	29.60 ± 23.30	93.33	100
5	Total Solid	472-832	663.17 ± 130.31	465-516	493.17 ± 19.04	25.63	525
6	TDS	590-812	669.17 ± 88.64	428-496	475.50 ± 601.43	28.94	500
7	Suspended Solids	20-40	30.50 ± 12.82	6-17	13.83 ± 6.74	54.64	25
8	Turbidity (FTU)	18-26	21.67 ± 3.20	2-5	4.48 ± 1.22	79.32	5
9	Oil/Grease	2.64-4.2	3.30 ± 0.65	0.72-1.02	0.74 ± 0.38	77.58	10
10	Total Alkalinity	695-300	449.83 ± 134.38	132-148	141.77 ± 5.54	68.48	150
11	Total Hardness (mg/l as $CaCO_3$)	120-440	312.33 ± 111.47	298-460	366.67±64.30	-17.40	500
12	Calcium Hardness	92-158	109.67 ± 30.71	68-92	83.33 ± 9.61	24.01	100
13	Chloride	110-320	204.33 ± 67.40	106-162	129.50±22.03	36.62	250
14	Sulphate	22.4-92	71.07 ± 25.07	54-84	67.67 ± 10.84	4.78	250
15	Nitrite (NO_2)	0.06-0.09	0.08 ± 0.01	0.01-0.04	0.02 ± 0.01	71.43	-
16	Nitrate (NO_3)	1.74-3.84	2.44 ± 0.79	0.74-1.38	1.00 ± 0.25	58.96	≤10.0
17	Silica (SiO_2)	29.42-38.1	33.54 ± 3.27	11.86-21.8	16.01 ± 4.50	52.26	≤40.0
18	Dissolved Oxygen	0.26-0.92	0.63 ± 0.27	2.08-2.35	2.17 ± 0.12	-243.27	2.00≥
19	BOD	188.6-506	335.1 ± 113.60	20.2-27.76	22.37 ± 2.74	93.33	≤30
20	COD	724-1724	1181.67 ± 400.44	36-51.02	44.09 ± 6.32	96.27	≤60
21	Iron	1.94-7.36	3.49 ± 2.00	0.06-0.16	0.11 ± 0.03	96.90	≤10
22	Copper	0.07-0.68	0.29 ± 0.23	0.01-0.08	0.04 ± 0.03	86.71	0.5
23	Zinc	1.02-1.92	1.42 ± 0.42	0.22-1.08	0.83 ± 0.33	41.58	2
24	Lead	0.02-0.36	0.17 ± 0.13	0.05-0.12	0.06 ± 0.04	65.69	0.5
25	Aerobic Mesophilic Organism	470-912	646.67 ± 167.23	28-132	57 ± 40.23	91.19	402

*TDS - Total dissolved solids, BOD – Biochemical oxygen demand, COD – Chemical oxygen demand. All parameters are in mg/l except Color: (co-pt.); Conductivity: (μs/cm) and Turbidity: FTU; Aerobic mesophilic organism (CFU/ml).

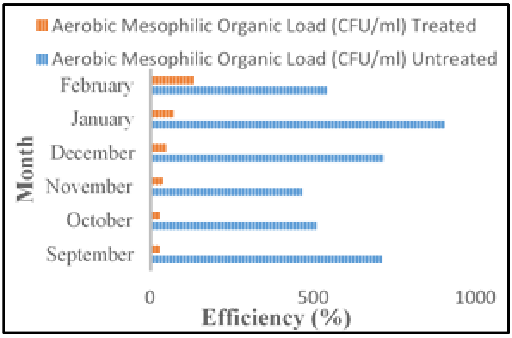

Figure 4. Reduction of mesophilic organic load

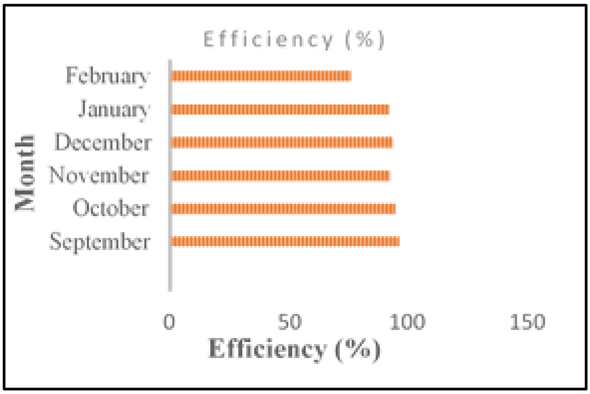

Figure 5. Reduction of efficiency of mesophilic organic load

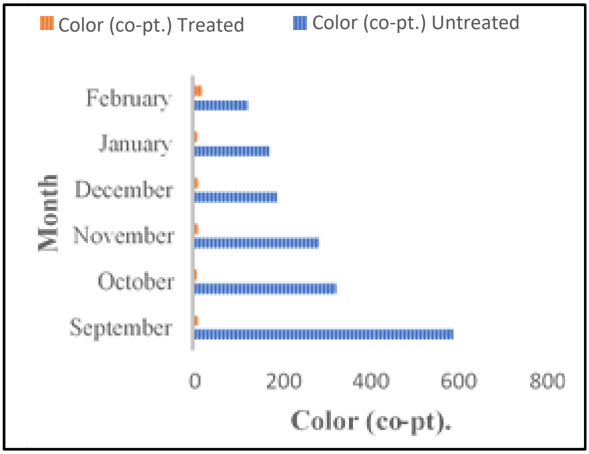

Figure 6. Effect of treatment on effluent color

The raw wastewater suspended solids (SS) load fluctuated between 20 and 51 mg/l while the treated wastewater value ranged between 7 and 18.1 mg/l over the assessment period as shown in Figure 7 and 8. The SS was consistently kept below the permissible value of 25 mg/l except for the month of December 2016 when a marginal value of 24 mg/l was obtained. This can be attributed to ineffective monitoring and poor routine maintenance during the observed period. The wastewater turbidity ranged from 18 to 26 formazin turbidity unit (FTU) while the reduction efficiency ranged from 72 to 91.7% with the highest recorded in October 2016 while the lowest in February 2017. This parameter also falls below the local permissible limit of 5 FTU. The untreated effluent

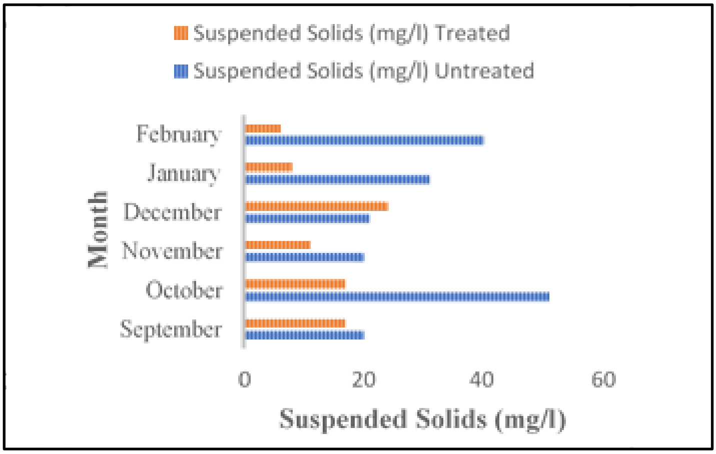

Figure 7. Effect of treatment on effluent suspended solid load

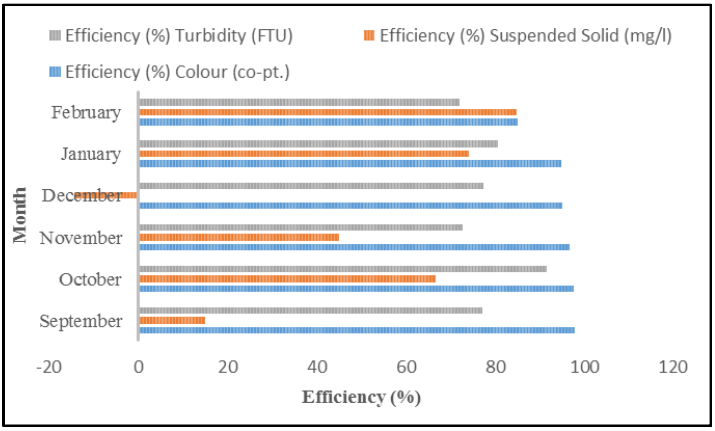

Figure 8. Removal efficiency of effluent color, suspended solid and turbidity

was characterized by objectionable odor. Hydrogen sulfide gas produced during the decomposition of the organic matter in the raw wastewater by anaerobic bacteria especially when the wastewater is in the UASB reactor accounts for the obnoxious odor produced at this treatment stage. The effluent odor was completely removed from the treated wastewater from September 2016 – November 2016, while the treated effluent was considered unobjectionable from December 2016 to February 2017. This is partly due to blockage or constant loading of the UASB beyond its design capacity which affected its performance to reduce the organic load during this period.

3.4 Biological Parameters

The biological parameters investigated include BOD and dissolved oxygen (DO). Concentrations of these parameters ranged between 188.6 to 506 mg/l for BOD and 0.26 to 0.92 mg/l for DO respectively. The BOD values fall above the permissible limit (≤ 30 mg/l) while the DO values fall below the permissible limit (≥ 2 mg/l). The BOD concentration was significantly reduced to 20.2-27.76 mg/l (Figure 9) corresponding to a reduction efficiency range of 88.7-95.3% while DO concentration was significantly increased from 26-0.92 mg/l to a permissible range of 2.08-2.35 mg/l respectively. The most significant percentage reduction (95.3%) for BOD was obtained in September 2016 while the lowest (88.7%) was recorded in February 2017. Average concentrations for untreated wastewater recorded in similar treatment facilities mostly ranged between 0.2-0.4 mg/l (Raboni, *et al*., 2013). These low levels of DO usually reported in biological reactors adversely affects the kinetics of nitrogen removal and eventually inhibits denitrification performance (Capodaglio *et al*., 2016).

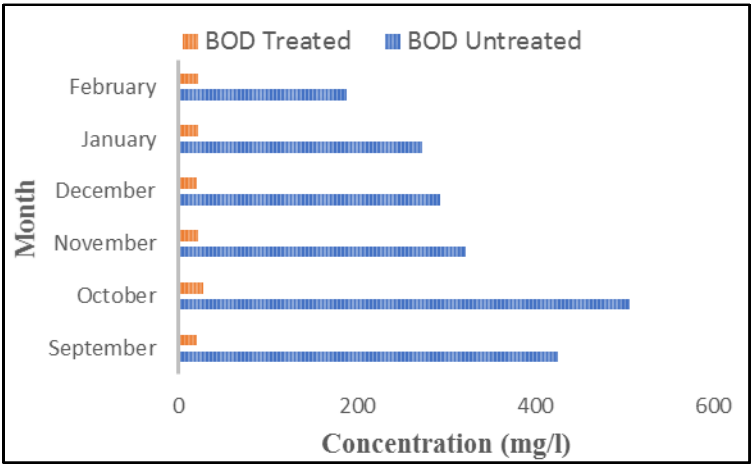

Figure 9. Variation of BOD concentration in the effluent

3.5 Chemical Parameters

The chemical pollution indicators assessed are presented in Table 3. Significant variation was observed in the wastewater pH. It ranged from an acidic value of 3.7 to 5.1 while the pH of the treated effluent ranges from a near neutral value of 7.3 to a slightly alkaline value of 8.2 which is within the permissible limit of 6.5 to 8.8. This compares well with a range of 7.23-8.67

reported in a similar study of Ajim *et al*. (2015). The most significant removal efficiency was recorded for free carbon dioxide and COD. The free carbon dioxide content in the wastewater varied from 114 to 930 mg/l before treatment. After treatment, the values obtained varied from 38 to 48.8 mg/l, corresponding to an average removal efficiency of 93.33%. Effluent COD dropped from an average value of 1181.67 to 44.09 mg/l corresponding to a removal efficiency of 96.27%. This significant reduction was also reported by Boguniewicz-Zabłocka *et al*. (2017). The BOD and COD removal efficiency varies from 88 to 97%. Electrical conductivity significantly improved from an average range of 841-1345 mg/l to an improved range of 1304-3176 mg/l. This value falls below the 4000 mg/l permissible limit of LASEPA. Total solids (TS) and TDS that gives a measure of the organic and inorganic solids present in the effluent have high average values ranging from 472-832 mg/l and 590-812 mg/l. These values were reduced to 465-516 mg/l and 428-496 mg/l respectively corresponding to average removal efficiencies of 25 and 28%. The low removal efficiency suggests poor system performance for TS and TDS removal. This can be traced to the performance of the DAF unit that helps to clarify the wastewater by removing excess suspended matter. Alkalinity is responsible for water hardness. It is caused by the presence of calcium and magnesium salts associated with carbonates. Significant treatment performance (77.58%) was recorded for oil/grease and total alkalinity (68.48%), thus, bringing them below permissible limits. Total hardness was slightly improved from an average value of 312.33 to 366.67 mg/l. In a conventional biological treatment process, ammonium nitrogen is first oxidized to nitrite (NO_2-N) and then to nitrate (NO_3-N) by autotrophic bacteria. Nitrate is then biologically reduced to nitrogen gas by heterotrophic bacteria during denitrification. Organic substrate is usually utilized during this process. Aerobic biological nitrification is accomplished by Nitroso-bacteria (*Nitrosomonas*) for ammonium nitrogen to nitrite and by Nitro-bacteria (*Nitrobacter*) for nitrite oxidation to nitrate (Capodaglio *et al*., 2016). The treatment plant was adjudged effective in reducing ammonium nitrogen to nitrite (NO_2-N). An average reduction efficiency of 71.43% was recorded while a lower removal efficiency of 58.96% was recorded in reducing nitrite to nitrate (NO_3-N). As previously observed, the low levels of DO observed in this study adversely affected the kinetics of nitrogen removal and eventually inhibits the reduction of nitrate. Furthermore, the level of DO strongly influences denitrification rate, therefore, the DO level should be consistently maintained below 0.2 mg/l to achieve high denitrification efficiency (Capodaglio *et al*. 2016). Calcium hardness in the raw wastewater ranged between 192 to 158 mg/l. This was slightly reduced from 83.33 to 9.61 mg/l resulting in a low average reduction efficiency of 24.01%. The average reduction efficiency recorded for chloride, sulphate and silica (SiO_2) were 36.62%, 4.78% and 52.26% respectively. Although these efficiencies are low, their final concentrations fall below the state permissible limits.

3.6 Metallic Parameters

The average reduction efficiency of the metallic parameters assessed was varied. The highest average removal efficiency of 96.90% was recorded for iron, closely followed by copper (86.71%) as shown in Table 3. An average value of 41.58% was recorded for zinc while 65.69% was recorded for lead which is very hazardous to plant and aquatic life. The concentration of these metals still falls below the permissible limits making the treated wastewater safe for disposal.

4. Conclusion and Recommendations

Product cooling and miscellaneous uses were identified as the major areas with huge water saving potential. Closed-circuit cooling and water reuse practice were suggested to minimize the water demand of the processing factory thereby reducing the water intensity of the wastewater treatment plant. The removal efficiencies of all the parameters fell below the maximum permissible limit by LASEPA of Nigeria. The wastewater treatment plant was adjudged efficient; however, technical factors and operational lapses account for the low efficiencies recorded for some parameters (TS, TDS, calcium hardness, sulphate and zinc). This renders the treated wastewater unsafe for ingestible re-use. However, it can be used as hydrant fluid and at the factory car wash while the solid and gaseous by-products can be used for animal feed and gaseous fuel for the processing plant. The treatment plant has the capacity to further reduce the concentration of key pollutants if properly managed and optimized. Adequate monitoring measures with periodical equipment upgrade should be established to optimize treatment performance. To further improve the effluent quality, a slow sand filter should be installed after the sequential batch reactor and the use of plastic tanks in which breeding of algae within the treatment units should be stopped. Furthermore, treated effluent should be disinfected before disposal.

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