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Wetland system: a cheaper and efficient treatment option for food processing waste in Africa

J.A. Adelegan & O.A. Agbede, Nigeria

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The study investigates an alternative wastewater treatment system for the food and beverage industry in Africa. A subsurface flow wetland system was designed and compared with a combination of anaerobic and aerobic bioreactor installed for a brewery in Nigeria. The cost of the designed wetland system is 33% of the cost of installed bioreactor. The waste characteristics for the designed subsurface flow constructed wetland after treatment falls within the USEPA threshold while that of the installed Bioreactor, are above. In addition, the treatment efficiency of the designed subsurface flow constructed wetland for controlling parameters; BOD, TSS and Faecal Coliform are 96.83%, 88.42% and 96.29% respectively while that of the UASB reactor, are 62.94%, 15.36% and 63.81%. Hence, the designed subsurface flow constructed wetland is more efficient in the removal of BOD, TSS and Faecal Coliform and could be an excellent alternative for the food and beverage industry in Africa.

Introduction

Industry has been reckoned to contribute to environmental pollution in developed countries and much research has been done to proffer technological solutions. However, little is known appropriate adoption that are “Best Available Technology (BAT)” or “Best Practicable Technology (BPT)” and “Locally Adaptable and not Entailing Excessive Costs (NEEC)” to curb external diseconomies of production among industrial firms in developing countries, especially in Africa. In this regard, this research investigated the technology adopted (advanced wastewater treatment plant) for a brewery industry in West Africa. The cost and treatment efficiencies among other indicators were examined. In spite of the prohibitive investments costs, the effluent characteristics are far higher than the international threshold for wastewater discharged into river bodies. Hence, an alternative low-cost and efficient wastewater treatment technology (Subsurface Flow Constructed Wetland System) was recommended and designed for adoption by food processing industry in Africa.

Technology adoption by the brewery industry in West Africa

The technology adopted is an advanced wastewater treatment plant for the food processing industry in West Africa. The treatment process is made up of secondary treatment including both anaerobic and aerobic treatment. Secondary treatment could be a biological treatment directed at the removal of soluble biodegradable organic matter through biological degradation. Such treatment processes can be aerobic or anaerobic or a combination of the two. Aerobic processes use bacteria and other organisms that feed on waste products and break them down, using oxygen from their surroundings; anaerobic processes use bacteria that obtain the oxygen they require from the materials on which they are feeding.

The influent is composed of the wastewater from the brewing house and the packaging unit. The raw wastewater is channelled into an influent pump pit where the raw water is pumped into an equalization tank. The equalization tank prevents shock and pH correction also takes place. Hydrochloric acid or caustic soda is added depending on the pH of the raw wastewater.

After the PH correction in the equalization tank, the wastewater is piped to the Upflow anaerobic sludge blanket (UASB) reactor where anaerobic organisms digest the organic matter in the wastewater. Upflow anaerobic sludge blanket (UASB) technology, normally referred to as UASB reactor, is a form of anaerobic digester that is used in the treatment of wastewater. The UASB reactor is a methanogenic (methane-producing) digester that evolved from the anaerobic clarigester. UASB uses an anaerobic process whilst forming a blanket of granular sludge which suspends in the tank. Wastewater flows upwards through the blanket and is processed (degraded) by the anaerobic microorganisms. The upward flow combined with the settling action of gravity suspends the blanket with the aid of flocculants. Biogas with a high concentration of methane is produced as a by-product, and this is captured and used as an energy source. The biogas is captured and used for factory heating purpose. The biogas plant has a capacity of about 3000 m^3.

The treated wastewater is piped to an aerobic reactor. With UASB, the aeration and the whole process of settlement and digestion occurs in one or more large tank(s). Only the post UASB liquids, with a much reduced BOD needs to be aerated. The aerobic reactor is made up of three channels. The capacity of the aerobic reactor is also about 3000 m^3. Chlorination subsequently takes place after treatment with calcium hypochlorite. The sludge is collected into a sludge tank for final disposal.

The effluent is channelled to an open drain for discharge into river bodies that is about 2.5 km away from the treatment plant. However, the effluent mixed up with an existing oxidation pond at about 2.0 km before the discharge point. The industry monthly wastewater volume is 124,000 m^3 and that the cost of installation of the plant is USD 5 million.

The emission surveillance data revealed that the efficiency of the treatment plant in BOD_5 removal, COD removal and TSS removal are 72.9%, 72.69% and 42.68% respectively. Despite the huge technology investment towards pollution control, the effluent at discharge point has BOD_5, COD and TSS values of 256.5 mg/l, 562.58 mg/l and 74.33 mg/l respectively which all exceed the Federal Ministry of Environment threshold of 30 mg/l, 80 mg/l and 30 mg/l for BOD_5, COD and TSS discharged into river bodies for food processing industry.

Subsurface flow constructed wetland as alternate low-cost and efficient technology

Previous work indicates the need for a locally adaptable technology for waste treatment in the food processing industry in Africa. The cost of bioreactor is prohibitive and a survey of wetland technology indicates an adaptable technology. Wetlands are defined as ecosystems where the water surface is at or near the ground surface for long enough each year to maintain saturated soil conditions and related vegetation (Crites, *et al,* 2006). The major wetland types with potential for water quality improvement are swamps that are dominated by trees, bogs that are characterized by mosses and peat, and marshes that contain grasses and emergent macrophytes. The majority of wetlands used for wastewater treatment are in the marsh category. The capacity of these ecosystems to improve water quality has been recognized for at least 30 years (USEPA, 2003). There are two basic wetland systems used in the treatment of polluted water which includes natural wetlands and constructed wetlands. There are three types of natural wetlands which have been known to treat urban wastewater and storm water. These include swamps, bogs and marshes. There are also three types of constructed wetlands which includes Free Water Surface (FWS) constructed wetland or Surface Flow (SF) wetlands, Sub Surface Flow (SSF) constructed wetlands and engineered wetlands.

However, a Subsurface flow constructed wetland is recommended over Free Water Surface wetland for the brewery industry because subsurface flow wetlands are often used where the wastewater being treated in noxious or odorous and where the attraction of wildlife may be undesirable [Crites, *et al* (2006)]. The Subsurface flow wetland is generally more costly to construct than a Free Water Surface wetland (FWS) of equivalent size. In some cases, this may be compensated for by the better SSF treatment efficiency (higher rate constants) and other advantages. The Table below shows rate (areal k values at 20°C) and cost comparison for FWS and SSF wetlands (Higgins, 2003).

When the reduction of BOD is the controlling parameter, selection of the more costly SSF variety might be desirable, as the difference in cost is not that great and, on average, the table indicates that a SSF wetland will cost only 37% more than FWS, but the advantage in treatment efficiency is very large (a ratio of 5.29 times). However, where the reduction of suspended solids or phosphorus is controlling, selection of less costly FWS variety (less than one-seventh the cost of the SSF alternative) might be indicated. This is because for these two contaminants, the dominant pollutant reduction processes are not biological ones, but instead are settling/filtration (gravitational/inertial) and adsorption (geochemical) for the TSS (suspended solids) and TP (total phosphorus) cases respectively. One might opt for a FWS wetland for pathogens removal (FC) where, on average, it would cost almost six times as much to achieve the same removal levels in a SSF one. But where the removal of one or other of the nitrogen compounds are controlling, the relatively small increases in treatment efficiency (*i.e.* rate constant ratios from 1.43 to 2.06 times) would not normally seem to justify the higher average SSF wetland costs (cost ratios of 3.57 to 5.0 times). For the brewery industry, the controlling parameter is the BOD, however the pathogens and suspended solid are also key parameters to be considered. Hence, the subsurface and vertical flow constructed wetland is considered to more appropriate.

Table 1. Areal k values at 20◦C and cost comparison for FWS and SSF wetlands

	TSS	**BOD**	**TP**	**NH^4-N**	**Org-N**	**NO^3-N**	**FC**
FWS k value, m/yr	>1000	34	12	18	17	35	75
SSF k value, m/yr	>1000	180	12	34	35	50	95
SSF k/FWS k	~1.00	5.29	1.00	1.89	2.06	1.43	1.27
SSF cost/FWS cost	7.14	1.37	7.14	3.85	3.57	5.00	5.88

Source: Higgens, *et al (*1993)

Controlling parameters for design

For the brewery industry, the controlling parameter is the BOD, however the pathogens and suspended solid are also key parameters to be considered. Hence, the subsurface and vertical flow constructed wetland is considered to be more appropriate. All constructed wetland systems are considered to be an attached-growth biological reactors, and their performance can be estimated with first-order plug-flow model.

The BOD_5, COD and TOC range from 946.8 mg/l, 2059.9 mg/l and 0.036% before treatment respectively to 350.92 mg/l, 751.75 mgl and 0.024% after treatment. The BOD_5 and COD values are much higher than the FME threshold of 30 mg/l and 80 mg/l respectively despite the efficiency of the treatment plant. The total suspended solids value range from 129.67 mg/l before treatment to 109.75 mg/l after treatment and subsequently to 74.33 mg/l at point of discharge which indicates the presence of organic and inorganic solids. The reduction in the values after treatment is an indication of the efficiency of the treatment plant. However, these values are much higher than the limit of 30 mg/l stipulated by the Nigerian Federal Ministry of Environment. The total dissolved solids also ranges from 834.42mg/l before treatment to 429.92 mg/l at point of discharge. This however falls within the maximum limit of 2000 mg/l allowable by FME.

The nutrients value range from 114.06 mgl, 6.95 mg/l, 7.09 mg/l, 36.74 mg/l to 3.61% for phosphates, nitrates, ammonia, total phosphorus and total nitrogen before treatment respectively to 39.41 mg/l, 2.55 mg/l, 3.43 mg/l, 12.6 mg/l to 2.98% after treatment. The nitrates values after treatment are within the permissible limits for food processing industry. The major ions range from 14.9 mg/l to 7.64 mg/l for sulphates and chloride before treatment to 7.56 mg/l to 17.86 mg/l after treatment respectively. However, the sulphate and chloride ions are within FME permissible limits of 500 mg/l and 600 mg/l respectively. The viable count indicates high bacterial load with value ranging from 4.27×10^{14} cfu/ml, 1.29×10^4 cfu/ml, 0.7×10^4 cfu/ml and 8.23×10^{14} cfu/ml before treatment and after treatment. However, the values are much higher than the threshold of 400 MPN/100ml stipulated by FME for food processing industry.

The basic relationship for plug-flow reactors is given by equation 1:

$C_e/C_0 = \exp[-K_T t]$ (Crites et al, 2006) (1)

Where

C_e = Effluent constituent concentration (mg/L)

C_0 = Influent constituent concentration (mg/L)

K_T= Temperature-dependent, first-order reaction rate constant (d^{-1})

t = Hydraulic residence time (d)

Table 2. Influent concentration and FME threshold for food processing industry

Parameters	Unit	Influent concentration	FME threshold
BOD	mg/L	946.8	30
COD	mg/L	2059.9	80
TOC	mg/L	0.036	N/S
TSS	mg/L	129.67	30
TDS	mg/L	834.32	2000
Total N	/L	3.61	N/S
SO4	mg/L	14.6	500
PO4	mg/L	114.06	5
Cl	mg/L	7.64	600
NO3	mg/L	6.95	20
NH3	mg/L	7.09	N/S
Total P	mg/L	36.74	N/S
Cu	mg/L	0.129	1
Fe	mg/L	0.441	20
Zn	mg/L	0.635	<1
Mn	mg/L	0.064	20
Faecal Coliform	mg/L	2.1 x 103	400

*** N/S = Threshold have not been set by the Federal Ministry of Environment**

The hydraulic residence time in the wetland can be calculated with Equation (2) below:

$t = LWyn/Q$ (Crites et al, 2006) (2)

where;
L = Length of the wetland cell (m)
W = Width of the wetland cell (m)
y = Depth of water in the wetland cell (m)
n = Porosity, or the space available for water to flow through the wetland. Porosity is a percent (expressed as a decimal)
Q = The average flow through the wetland (m^3/d)

The surface area of the wetland can be obtained by combining equation 1 and 2:
$A_s = (LW)$

$$A_s = \frac{Q \ln (C_0/C_e)}{K_T yn} \qquad \text{(Crites et al, 2006)} \qquad (3)$$

Where A_s is the surface area of wetland (ft^2; m^2). The value used for K_T in equation (3) depends on the pollutant that must be removed and on the temperature. The subsurface flow wetlands are designed based on hydraulic detention time and average design flow. The shortest detention times are usually necessary for BOD, nitrate nitrogen, and TSS removal from food processing wastewater, while ammonia and metals usually requires longer detention times.

Wetland sizing

The parameter (BOD, etc) that requires the largest treatment are for removal is the limiting design factor, and that area should be selected for the intended project. The wetland should then provide acceptable treatment for all other parameters of concern.

$$A_s = \frac{Q \ln (C_0/C_e)}{K_T(y)(n)} \qquad \text{(Crites et al, 2006)}$$

The influent concentration is obtained from the waste characterization study for the brewery industry. The effluent concentration could be obtained from the Federal Ministry of Environment effluent threshold for food processing industry effluent. The values are as shown in Table 1.

From the waste characteristics and the effluent threshold below, the design of the wetland system would be carried out for the BOD, TSS, Pathogens and Phosphate because they are the parameters with characteristics above the threshold for the brewery industry under consideration. The COD and TOC are closely linked with the BOD. In addition, the design is also carried out for total nitrogen, total phosphorus and ammonia because the effluent threshold are not stipulated by the Federal Ministry of Environment. However, the BOD, TSS and the Pathogens are the controlling parameters for the food processing industry. All other parameters not designed for are within the Federal Ministry of Environment threshold for food processing industry.

Table 3. Wetland sizing using the first order plug flow model

Parameters	Q	C_o	C_e	T	K_{20}	K_T	y	n	As
BOD	4153	946.8	30	28	1.1	1.753	0.6	0.38	44829
TSS	4153	129.7	30	28	1.1	1.753	0.6	0.38	19010
FC	4153	2100	400	28	1.1	1.753	0.6	0.38	21535
COD	4153	2060	80	28	1.1	1.753	0.6	0.38	42186
PO_4	4153	114.1	5	28	1.1	1.753	0.6	0.38	40613

From the table above, $A_s = 44{,}829 m^2$

(The area was computed with a safety factor of 25%)

The aspect ratio (length-to-width) selected for a SSF wetland strongly influences the hydraulic regime as the resistance to flow increases as the length increases. The minimum width of the SSF wetland cell can be estimated using a model developed by Reed et al (1995):

$W = (1/y)[(Q_A)(As)/(m)(k_s)]^{0.5}$ Crites et al (2006) (4)

Where

W= Width of the SSF wetland cell (m)

y = Average depth of water in the wetland (m)

Q_A = Average flow through the wetland (m^3/d)

As = Design surface area of the wetland (m^2)

m = Portion of the hydraulic gradient used to provide the necessary head, as a decimal

Ks = Hydraulic conductivity of the media used (m3/m2/d)

m = 0.15 and Ks = 30,000 m3/day (Crites et al, 2006)

Hence W = 352.3m and L = 127.4m

Design of the SSF wetland system for BOD removal

The approach for the design for the BOD removal is the volume-based detention model, as expressed in the equation below:

$$A_s = \frac{Q \ln (C_0 - \ln C_e)}{K_T(y)(n)}$$ (Crites et al, 2006)

Where

A_s = Wetland surface area (m^2)

Q = Average design flow (m^3/d)

C_0 = Influent BOD concentration (mg/L)

C_e = Effluent BOD concentration (mg/L)

K_T= Rate constant = 1.1 (d^{-1}) at 20°C shown in Table 3

y = Design depth (m)

n = Porosity of media

The temperature of the wastewater will affect the rate constant according to the following equation:

$$K_T = K_{20}(1.06)^{(T-20)}$$

Where
K_T = Rate constant at temperature T
K_{20} = 1.1 d^{-1}
T= Wastewater temperature (°C)

However, because the BOD removal requires the largest treatment area, A_s = 44,829m^2 which constitute the limiting design factor. Hence for the BOD removal, the effluent concentration would be 30 mg/L.

The hydraulic residence time is given by

t = LWyn/Q

= 2.5 days

Design of the wetland system for TSS removal

The removal of TSS in SSF wetlands is correlated to the hydraulic loading rate (HLR) as shown in the equation below:

$C_e=C_o[0.1058+0.0011(HLR)]$ (Crites et al, 2006) (5)
Where
C_e =Effluent TSS (mg/L)
C_o =Influent TSS (mg/L)
HLR=Hydraulic loading rate (cm/d)

The hydraulic loading rate is the flow rate divided by the surface area. The equation is valid for hydraulic loading rate values between 0.4 and 75 cm/d. Hence, HLR= 9.26cm/d, the influent TSS, C_o =129.67mg/L, then C_e = 15.01 mg/L. Hence, the effluent TSS is within the Federal Ministry of Environment threshold of 30mg/L and the designed wetland treatment efficiency is 88.43%.

Design of the wetland system for faecal coliform removal

The estimating model for faecal coliform removal is given by

$C_e/C_0 = [1/(1+K_T(t)]$ (Crites et al, 2006)
Where t is the hydraulic residence time (HRT) in the system, K_{20}=2.6 and Θ= 1.19
Hence K_T = 10.45. This model was developed for facultative ponds and it gives conservative estimate for faecal coliform removal in both FWS and SSF wetland system. C_0, the influent concentration is 2.1 x 10^3 MPN/100ml, Hence C_e=78 MPN/100ml indicating a high treatment efficiency of 96%. It shows that the subsurface flow wetland system is very efficient in the removal of pathogens. The effluent concentration for the faecal coliform is also far below the Federal Ministry of Environment threshold of 400 MPN/100ml.

Design elements of the subsurface flow wetland for the brewery industry

Treatment media and vegetation

The initial rooting medium for the vegetation would be fine gravel which would 150mm deep. However, the mail treatment layer would be a relatively small gravel(<20mm). The total SSF wetland depth would be 0.6m. Vegetation in SFF wetlands should be perennial emergent plants. The recommended vegetation for the SSF wetlands for the brewery industry is Reeds and a typical variety is *Phragmites Australis (common reed).* The distribution is worldwide and optimum PH is 2 to 8. Growth is very rapid via rhizomes and lateral spread is approximately 1m/year, providing very dense cover in 1 year with plants spaced at 0.6m.

Comparison of land requirements for the wetland system and the bioreactor

This section present the relative land take of the two systems. The constructed wetland requires about 44,829m^2 while the land take of the bioreactor as measured from the brewery treatment plant is about 6,675m^2 . The land for the constructed wetland is available and cheap relative to the cost of the bioreactor.

Table 4. Comparison of waste characteristics of designed wetland system and the installed UASB bioreactor

Parameter	Unit	Before treatment	UASB bioreactor after treatment	SSF constructed wetland after treatment	FME threshold
BOD_5	(mg/L)	946.8	350.92	30	30
TSS	(mg/L)	129.67	109.75	15.01	30
Total N	(%)	3.61	2.98	0.58	N/S
PO_4	(mg/L)	114.06	39.41	16.9	N/S
NO_3	(mg/L)	6.95	2.55	5.1	20
NH_3	(mg/L)	7.09	3.43	3.98	N/S
Total P	(mg/L)	36.74	12.6	27.55	N/S
FC	MPN/100ml	2100	760	78	400

The cost of the installed 3000m^3 bioreactor for the brewery industry is USD 5 million however the cost of the constructed subsurface flow wetland system with a capacity of 5,200m^3 is costing USD 1.65 million. The designed capacity of the wetland system is to accommodate a daily wastewater generation volume of 4,153 m^3 with an additional capacity of 25% as factor of safety to accommodate excess production. Hence, the designed capacity of the wetland system is bigger than that of the installed bioreactor. In addition, the cost of the designed wetland system is 33% of the cost of installed bioreactor. The cost of operation and maintenance of the designed wetland system is much lower than that of the installed bioreactor. The comparative treatment efficiency of the designed wetland system and the installed bioreactor is shown in Table 5: As shown in the table above, the waste characteristics for the designed subsurface flow constructed wetland falls within the Federal Ministry of Environment threshold for food processing industry

However, for the installed Bioreactor, most of the waste characteristics are above the stipulated threshold. In addition to the waste characteristics threshold, the treatment efficiency of the designed subsurface flow constructed wetland for the controlling parameters, BOD, TSS and Faecal Coliform are 96.83%, 88.42% and 96.29% respectively. For the installed UASB reactor, the treatment efficiency for the same controlling parameters, BOD, TSS and Faecal Coliform are 62.94%, 15.36% and 63.81% respectively. Hence, the designed subsurface flow constructed wetland is more efficient in the removal of BOD, TSS and Faecal Coliform.

*** N/S = Threshold have not been set by the Federal Ministry of Environment**

Conclusion

The cost of the installed 3000m^3 bioreactor for the brewery industry is USD 5 million however the cost of the constructed subsurface flow wetland system with a capacity of 5,200m^3 is costing USD 1.65 million. The wetland system is designed to accommodate a daily wastewater generation volume of 4,153 m^3 with an additional capacity of 25% as factor of safety to accommodate excess production. Hence, the designed capacity of the wetland system is bigger than that of the installed bioreactor. In addition, the cost of the designed wetland system is 33% of the cost of installed bioreactor.

Table 5. Comparison of treatment efficiency of designed wetland system and the installed UASB bioreactor

Parameters		UASB bioreactor after treatment	SSF constructed wetland after treatment
BOD_5	(mg/L)	62.94%	96.83%
TSS	(mg/L)	15.36%	88.42%
Total N	(%)	17.45%	83.93%
PO_4	(mg/L)	65.45%	85.18%
NO_3	(mg/L)	63.31%	26.62%
NH_3	(mg/L)	51.62%	51.62%
Total P	(mg/L)	65.71%	25.01%
FC	MPN/100ml	63.81%	96.29%

The waste characteristics of the designed subsurface flow constructed wetland falls within the Federal Ministry of Environment threshold for food processing industry. However, for the installed Bioreactor, most of the waste characteristics are above the stipulated threshold. In addition to the waste characteristics threshold, the treatment efficiency of the designed subsurface flow constructed wetland for the controlling parameters, BOD, TSS and Faecal Coliform are 96.83%, 88.42% and 96.29% respectively. For the installed UASB reactor, the treatment efficiency for the same controlling parameters, BOD, TSS and Faecal Coliform are 62.94%, 15.36% and 63.81% respectively. Hence, the designed subsurface flow constructed wetland is more efficient in the removal of BOD, TSS and Faecal Coliform.

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Contact details

Name of Principal Author: Dr. Joseph Adelegan
Address: Global Network for Environment and Econ
Development Research, Ibadan, Nigeria
Tel: +234 8062843428
Fax: +234 2 8106202
Email: dr_joseph_adelegan@yahoo.com
www: www.gneeder.org

Name of Second Author: Professor O.A. Agbede
Address: Department of Civil Engineering
University of Ibadan, Nigeria
Tel: +234 8033847722
Fax: +234 2 8106202
Email: oluwoleagbede@yahoo.com
www: www.ui.edu.ng