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Performance Evaluation of Constructed Wetlands and Conventional Wastewater Treatment Systems in Selected Kenyan Tea Factories

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Abstract:
Environmental pollution due to discharge of untreated or poorly treated industrial waste waters has become a major source of concern with respect to the safety of our environment. An assessment of the performance of wastewater treatment systems in treating tea factory effluent was carried out on selected tea factory treatment plants which use constructed wetlands and conventional treatment systems. Selected factories were Eberege tea factory and Chinga tea factory using conventional and constructed wetlands systems respectively. A conventional treatment plant consists of chemical, biological and physical processes combined which aid in removal of contaminants while a constructed wetland is a natural biological system comprised of various methods which utilize natural biological processes for effluent treatment. In Kenya, the National Environmental Management Authority (NEMA) regulates discharge to the environment and therefore every industry is required to obtain a license for releasing their waste water in to the environment upon satisfaction of specified requirements. As per NEMA guidelines, parameters of interest in tea factory effluent include; Biological Oxygen Demand, Total Suspended Solids, pH, fecal coliform, Chemical Oxygen Demand, color, organic nitrogen, flow, copper, zinc and surfactants. These parameters were therefore analyzed in both treated and untreated wastewater from the two factories using approved US/EPA testing methods for wastewater. The results obtained from the untreated effluent in both factories had high levels of >48.6mg/L BOD, >150.3mg/L COD and >29.3mg/L TSS while the treated effluent registered a major decrease of pollutants levels with readings of <25.5mg/L BOD, <70.4mg/L COD and <30.2mg/L TSS. Color in the untreated effluent gave readings of >15 hazen units while the treated effluent recorded <12 hazen units with the conventional treatment plant giving the clearest effluent of <6 hazen units. Organic nitrogen levels in the untreated effluent were >7.8 mg/L while the treated effluent levels were <2.8 mg/L with the constructed wetland registering the lowest values. Copper and zinc levels were below the detection limit in all untreated effluent samples with an exception of one sample which recorded zinc levels of 0.543mg/L but was effectively treated since the result of the treated effluent was <0.001mg/L. Surfactants were found to be below detection level in both untreated and treated effluent samples. Fecal coliform bacteria were also absent in all samples. Both systems of treatment were effective in treating the factory effluent since the values obtained were below the permissible NEMA limits even though the degree of treatment varied with the conventional plant giving the least toxic treated effluent. Conventional wastewater treatment plants are more expensive to install and maintain compared to constructed wetlands hence not highly recommended for treating less toxic effluent.

Keywords: *Conventional, constructed wetland, tea, pollution, wastewater treatment*

1. Introduction

1.1. Wastewater Treatment

The chief objective of treating wastewater is to avoid possible danger to human health or intolerable damage to the natural environment by disposing toxic domestic and industrial effluents. Effluent released to the environment usually finds its way in surface waters which are mostly used for agricultural purposes. Treatment plants are designed with an aim of reducing or eliminating suspended solids and organic loads hence limiting pollution to the environment(Akali *et al.*, 2011).

Waste water treatment plants (WWTP) use either of the two major systems: conventional treatment and natural biological treatment. A conventional wastewater treatment system refers to a system consisting of chemical, biological and physical processes combined which aid in removal of contaminants from waste water. The various stages involved include; preliminary, primary, secondary and tertiary(Okoh *et al.*, 2007). In preliminary treatment, the incoming raw effluent from the factory is barred to get rid of all big objects that make their way into the treatment system. Bar screens of different sizes are incorporated to get rid of these items. At the primary stage, inorganic and organic loads which can settle via sedimentation are removed. Large sedimentation tanks known as clarifiers are used for that purpose. The clarified water then proceeds to the next treatment step which is secondary treatment. This step involves use of biological treatment processes which remove organic matter in waste water up to 90%. Aerobic treatment processes which use microorganism in the presence of oxygen to break down organic matter are performed. The proceeding stage is the tertiary treatment step which involves generation of a higher quality effluent through use of advanced treatment processes. Disinfection is the final stage whose main aim is to eliminate or reduce the number of microorganism's present in the wastewater.Advantages ofthe conventional wastewater treatment system include; minimal land requirement, high efficiency and applicability to small scale water treatment. The disadvantages are; reliability on heavy machinery and chemicals, high energy requirement and technical knowledge required for operation(Rodriguez *et al.*, 2017).

On the other hand, constructed wetland is a low rate natural system which uses biological processes to treat organic wastewater. It's an artificial swamp which uses aquatic plants (Phragmites karka) to treat wastewater. The treatment process takes place at the root system of the wetland plants where by disease causing bacteria and nutrients from wastewater are degraded(Kivaisi, 2001).Advantages of this system include; easy maintenance, cheaper to construct and less energy requirements.

Previous studies done in tea factories with respect to waste management highlighted the ineffectiveness of the stabilization ponds used by then due to overloading hence introduction of better systems of wastewater treatment(Oirere *et al.*, 2004). Conventional treatment plants and constructed wetlands were therefore constructed in several tea factories for treating their wastewaters.

1.2. Wastewater Regulations

In Kenya, the ministry of environment is tasked with all issues related to the protection of the environment including effluent discharge(EMCA, 2006). The National Environment and Management Authority (NEMA) have established regulations meant to forbid release of effluent to the environment or public sewer against the set standards. Test parameters of interest for testing in tea factory effluent as per NEMA are; Biological Oxygen Demand, Total Suspended solids, pH, fecal Coliform Bacteria Chemical oxygen demand, color, organic nitrogen, copper, zinc and surfactants. The permissible limits are as shown in table 1.

Parameter	**Maximum allowable (Limits)**
BOD (5 days at 20^{o}C) (mg/l)	30
TSS (mg/l)	30
pH (hydrogen ion activity-non-marine)	6.5 – 8.5
Fecal coliforms (counts /100 ml)	Nil
COD (mg/l)	50
Color/dye/pigment	15 hazen units
Organic nitrogen as N (mg/l)	100
Flow	Not defined
Copper (mg/l)	1.0
Zinc (mg/l)	0.5
Surfactants (mg/l)	Nil

Table 1: NEMA permissible limits for effluent discharge

2. Materials and Methods

2.1. Study Sites

Treated and untreated effluent samples were drawn from Eberege and Chinga tea factories wastewater treatment plants. Eberege tea factory is located in Kanyenya sub county, Kisii County, Kenya. It lies at 34.7^{0}E and 0.9^{0}S with an altitude of 1735 meters. Below is a satellite picture of Eberege tea factory.

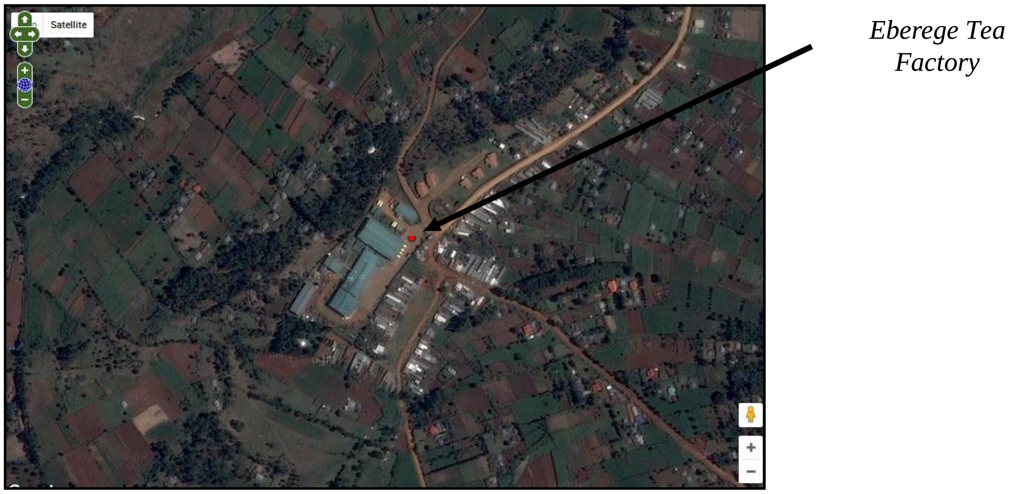
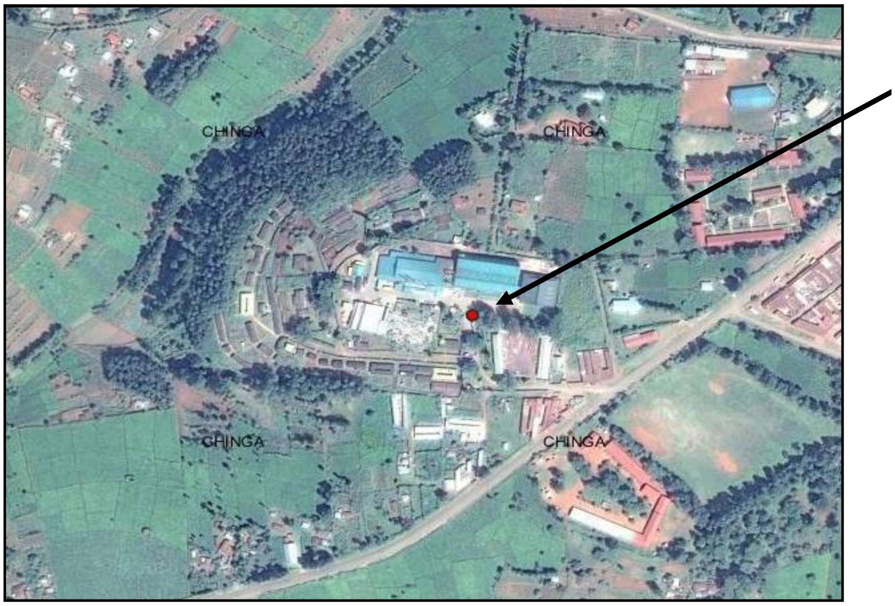


Figure 1: Eberege Tea Factory

On the other hand, Chinga tea factoryis situated 170 km north of Nairobi and 12 km south of Othaya in Kirinyanga County, Kenya. It lies at 36.9^{o}E and 0.61^{o}S with an attitude of 2,061 meters. Below is a satellite picture of Chinga tea factory.



Chinga tea factory

Figure 2: Chinga Tea Factory

2.2. Sampling and Analysis

Composite samples were collected in 500ml sterile polyethylene bottles, stored in a cooler box and thereafter transported to the lab for analysis within the following 12 hours. The Standard operating procedures used were in line with (USEPA, 2002) and (APHA/AWWA/WEF, 2012). The refrigerated sample was mixed thoroughly each time, and a sample drawn for analysis of the following parameters;

2.2.1. Biochemical Oxygen Demand (BOD)

An airtight container containing the sample was incubated for 5 days at 20^{o}C. The value of dissolved oxygen was determined both before and after the 5 days of incubation. Thereafter, BOD calculation was done from the difference between final dissolved oxygen and initial dissolved oxygen. The difference gave the amount of oxygen utilized by the microorganisms during the 5 incubation days. Initial dissolved oxygen was determined immediately after dilution was made.

$CH_2O + O_2 = CO_2 + H_2O$

The BOD was thereafter calculated as follows;

$$BOD\ (\frac{mg}{l}) = \frac{(\text{Do} - \text{D5} - \text{BC}) \times \text{ Volume of diluted sample}}{\text{Volume of sample}}$$

Whereby Do was diluted sample initial dissolved oxygen, D5 was the diluted sample dissolved oxygen at day 5 while BC was the blank correction

2.2.2. Chemical Oxygen demand (COD)

COD is the amount of oxygen identical to the amount of dichromate oxidant used up by suspended and dissolved matter in a water sample which has been treated with the oxidant at defined conditions. Reflux of a test portion in the presence of mercury sulfate with a silver catalyst and potassium dichromate in concentrated sulfuric acid was carried out for a given time period, during which the oxidizable material present reduced part of the dichromate. The remaining dichromate was titrated with ammonium iron (ii) sulfate. Calculation of the COD value was done from the amount of dichromate reduced. COD was calculated as follows;

$$COD, mgO_2/ll = \frac{(\text{A} - \text{B}) \times 8000}{\text{ml of sample}}$$

Whereby A was ammonium (ii)sulfate blank volume, B was the ammonium (ii)sulfate sample volume, M was the molarity of ammonium(ii)sulfate while 8000 was the milliequivalent oxygen weight ×1000ml/L.

2.2.3. Surfactants

Most common occurring surfactants are the anionic surfactants. They react with the cationic dye methylene blue which is water soluble but insoluble in chloroform. A blue salt is formed upon reacting which can be measured spectrophotometrically at 652 nm. Therefore, the methylene blue method-spectrophotometric method was used.

2.2.4. Organic Nitrogen

Amino nitrogen of various organic materials was converted to ammonium sulfate in the presence of potassium sulfate, sulfuric acid and a catalyst. A mercury ammonium salt was formed during digestion, which was decomposed by sodium thiosulfate. Ammonia was distilled into boric acid from an alkaline medium after decomposition which was later determined by titration with a standard mineral acid. Ammonia nitrogen and organic nitrogen make up total nitrogen. Therefore, to do away with the interference of the ammonia nitrogen, distillation was done prior to digestion of the sample to get rid of the ammonia which was contained in the distillate. The residue was then used for organic nitrogen determination as per the following formula;

$$\frac{Mg}{l}\,organicnitrogen = \frac{(\mathrm{A} - \mathrm{B}) \times 280}{\mathrm{V}}$$

Where A - Volume of sulfuric acid used in sample
B – Volume of sulfuric acid used in blank
V – Volume of test sample

2.2.5. Zinc and Copper

In a flame atomic absorption spectrophotometer, the sample to be analyzed was sucked up in a nozzle, atomized and mixed in the nebulizer with fuel. The molecules and ions were combusted forming atoms. A flame originating from a cathode lamp containing similar metal to the one being analyzed excited the atoms to a higher energy level. This energy was given off in photons as they returned to the ground state. A monochromator isolated the light wavelength whose current was magnified by a photomultiplier in order to allow detection by a computer.

2.2.6. Total Suspended Solids

A glass fiber filter filtered the well-mixed test sample and thereafter dried at 105°C to a constant weight. TSS was represented by the weight increase of the filter. TSS was calculated as shown;

$$TSSinmg/l = \frac{\mathrm{W}_2 - \mathrm{W}_1}{\mathrm{V}}$$

Whereby, W_2 was the mass of the residue and filter paper, W_1 was the mass of the clean filter paper while V was the volume of sample.

2.2.7. pH

pH measurement uses a pH electrode system which is a combined glass electrode made up of reference cell and sensing half cell. Two solutions were separated by the sensing half-cell which was a semi permeable pH sensitive membrane whereby the internal solution was of known pH value while the outer one was the test sample. The difference in electrical potential developed between the two sections gave the sample pH.

2.2.8. Fecal Coliform

Membrane filtration technique was used for fecal coliform analysis. When bacteria are subjected to the right conditions for growth, they reproduce rapidly increasing in numbers. Incubation of solid media with a water sample which contains coliform bacteria leads to growth and multiplication of colonies since the bacteria are subjected to favorable growth conditions. The bacteria originally present in the water sample can be determined by counting the growth colonies. Calculation of coliform density was done as follows;

$$\frac{coliforms}{100\,ml} = \frac{\text{coliform colonies} \times 100}{\text{ml of sample filtered}}$$

2.2.9. Color

APHA (American Public Health Association) color/hazen scale suitably known as the platinum cobalt scale is a color standard defined by the American Society for Testing and Materials. The APHA scale ranges between 0-500 in parts per million units of cobalt in water. Distilled water is represented by zero in the scale. Both instrumental measurements and visual comparison can be used in APHA standards. Visual comparison method was used in this study. The standard closest to the sample was determined and color standard number reported in hazen units.

$$Colourinhazenunits = \frac{\mathrm{A} \times 50}{\mathrm{B}}$$

Whereby, A was the estimated color of the diluted sample while B was the volume of sample taken for dilution.

3. Results and Discussion

The results obtained as tabulated in tables 2, 3 and 4 clearly shows that the untreated wastewater from the two factories was polluted. On the other hand, the treated effluent from both factories was characterized with a substantial decrease of pollutant concentration since the values of the test parameters greatly reduced even though the extent of pollutant reduction differed in the two factories.

Variables	Eberege tea factory		Chinga tea factory	
	Influent	**Effluent**	**Influent**	**Effluent**
Biochemical oxygen demand (mg/L)	60.8 ± 9.2	20.2 ± 2.3	57.3 ± 5.2	22.6 ± 6.3
Total Suspended Solids (mg/L)	29.6 ± 1.1	27.4 ± 0.5	30.3 ± 0.6	28.5 ± 0.9
pH	6.3 ± 0.2	6.5 ± 0.3	6.4 ± 0.1	6.5 ± 0.2
Fecal coliforms (counts/100 ml)	Absent	Absent	Absent	Absent
Chemical Oxygen Demand (mg/L)	164.8 ± 10.2	50.4 ± 2.3	179.2 ± 6.5	60.6 ± 3.2
Color in Hazen units (H.U)	20	5	15	10
Organic Nitrogen (mg/L)	11.2 ± 0.2	2.8 ± 0.1	8.5 ± 0.1	0.5 ± 0.1
Copper (mg/L)	<0.001	<0.001	<0.001	<0.001
Zinc (mg/L)	0.543 ± 0.002	<0.001	<0.001	<0.001
Surfactants (mg/L)	Nil	Nil	Nil	Nil

Table 2: Influent and effluent pollutant levels in Eberege and Chinga factories treatment plants obtained during the 1st sampling

Variables	Eberege tea factory		Chinga tea factory	
	Influent	**Effluent**	**Influent**	**Effluent**
Biochemical oxygen demand (mg/L)	75.8 ± 5.3	18.1 ± 2.1	80.2 ± 3.2	26.5 ± 0.4
Total Suspended Solids (mg/L)	31.5 ± 1.2	26.3 ± 0.7	32.2 ± 0.5	30.2 ± 0.2
pH	6.5 ± 0.1	6.8 ± 0.1	6.3 ± 0.2	6.3 ± 0.1
Fecal coliforms (counts/100 ml)	Absent	Absent	Absent	Absent
Chemical Oxygen Demand (mg/L)	161.4 ± 15.1	55.63 ± 5.3	150.26 ± 10.9	45.8 ± 4.4
Color in Hazen units (H.U)	18	6	16	12
Organic Nitrogen (mg/L)	12.8 ± 0.3	3.1 ± 0.1	7.8 ± 0.2	0.2 ± 0.1
Copper (mg/L)	<0.001	<0.001	<0.001	<0.001
Zinc (mg/L)	<0.001	<0.001	<0.001	<0.001
Surfactants (mg/L)	Nil	Nil	Nil	Nil

Table 3: Influent and effluent pollutant levels in Eberege and Chinga factories treatment plants obtained during the 2nd sampling

Variables	Eberege tea factory		Chinga tea factory	
	Influent	**Effluent**	**Influent**	**Effluent**
Biochemical oxygen demand (mg/L)	75.8 ± 5.3	18.1 ± 2.1	80.2 ± 3.2	26.5 ± 0.4
Total Suspended Solids (mg/L)	31.5 ± 1.2	26.3 ± 0.7	32.2 ± 0.5	30.2 ± 0.2
pH	6.5 ± 0.1	6.8 ± 0.1	6.3 ± 0.2	6.3 ± 0.1
Fecal coliform (counts/100 ml)	Absent	Absent	Absent	Absent
Chemical Oxygen Demand (mg/L)	161.4 ± 15.1	55.63 ± 5.3	150.26 ± 10.9	45.8 ± 4.4
Color in Hazen units (H.U)	18	6	16	12
Organic Nitrogen (mg/L)	12.8 ± 0.3	3.1 ± 0.1	7.8 ± 0.2	0.2 ± 0.1
Copper (mg/L)	<0.001	<0.001	<0.001	<0.001
Zinc (mg/L)	<0.001	<0.001	<0.001	<0.001
Surfactants (mg/L)	Nil	Nil	Nil	Nil

Table 4: Influent and effluent pollutant levels in Eberege and Chinga factories treatment plants obtained during the 3rd sampling

3.1. Pollutant Removal Efficiency by Conventional and Constructed Wetland Systems

Both systems of treatment were able to treat the effluents even though the degree of treatment varied between the two systems as seen in table 5. In overall, the conventional treatment plant in Eberege tea factory was more effective in treating the tea factory effluent. BOD, TSS, COD and color percentage reduction was higher in Eberege conventional plant with percentage contaminant removal of 59.3-76.1, 7.4-17.3, 59.3-69.4 and 66.7-75 respectively. Moreover, Chinga constructed wetland recorded percentage contaminant removal values of 49.4-60.6 BOD, 5.5-6.2 TSS, 58.3-70.9 COD and 25-35.3 color.

Variables		**Eberege tea factory - conventional WWTP**			**Chinga tea factory - Constructed wetland WWTP**		
		Before treatment	**After treatment**	**% removal of pollutant**	**Before treatment**	**After treatment**	**% removal of pollutant**
BOD (mg/L)	1st Batch	60.8	20.2	66.8	57.3	22.6	60.6
	2nd batch	75.8	18.1	76.1	80.2	26.5	67
	3rd batch	50.4	20.5	59.3	48.6	24.6	49.4
TSS (mg/L)	1st Batch	29.6	27.4	7.4	30.3	28.5	5.9
	2nd batch	31.5	26.3	16.5	32.2	30.2	6.2
	3rd batch	30.7	25.4	17.3	29.3	27.7	5.5
pH	1st Batch	6.3	6.5	N/A	6.4	6.5	N/A
	2nd batch	6.5	6.8	N/A	6.3	6.3	N/A
	3rd batch	6.5	6.7	N/A	6.5	6.5	N/A
Fecal coliform (counts/100 mL)	1st Batch	Absent	Absent	N/A	Absent	Absent	N/A
	2nd batch	Absent	Absent	N/A	Absent	Absent	N/A
	3rd batch	Absent	Absent	N/A	Absent	Absent	N/A
COD (mg/L)	1st Batch	164.8	50.4	69.4	179.2	60.6	66.2
	2nd batch	161.4	65.63	59.3	150.26	45.8	58.3
	3rd batch	170.8	58.57	65.7	168.62	49.1	70.9
Color (H.U)	1st Batch	20	5	75	15	10	33.3
	2nd batch	18	6	66.7	16	12	25
	3rd batch	17	5	70.6	17	11	35.3
Organic nitrogen (mg/L)	1st Batch	11.2	2.8	75	8.5	0.5	94.1
	2nd batch	12.8	3.1	75.8	7.8	0.2	97.4
	3rd batch	13.2	2.3	82.6	12.4	0.4	96.7
Copper (mg/L)	1st Batch	<0.001	<0.001	N/A	<0.001	<0.001	N/A
	2nd batch	<0.001	<0.001	N/A	<0.001	<0.001	N/A
	3rd batch	<0.001	<0.001	N/A	<0.001	<0.001	N/A
Zinc (mg/L)	1st Batch	0.543±0.002	<0.001	100	<0.001	<0.001	N/A
	2nd batch	<0.001	<0.001	N/A	<0.001	<0.001	N/A
	3rd batch	<0.001	<0.001	N/A	<0.001	<0.001	N/A
Surfactants (mg/L)	1st Batch	Nil	Nil	N/A	Nil	Nil	N/A
	2nd batch	Nil	Nil	N/A	Nil	Nil	N/A
	3rd batch	Nil	Nil	N/A	Nil	Nil	N/A

Table 5: Comparison of contaminants removal efficiency between conventional and constructed wetlands wastewater treatment systems

The major difference in the contaminants removal efficiency between the two systems can be attributed to the incorporation of activated sludge processes and coagulants in the conventional wastewater treatment plant which greatly reduces the organic load as well as fine particles, hence reducing the values of BOD, COD, TSS, and trace metals by a big margin. Color reduction was more in Eberege conventional plant due to the use of coagulant $Ca(OH)_2$ which removed particles in colloid form hence most of the color was removed since its usually associated with the particles. In addition, the lime water also made the water basic hence increasing the treated effluent pH. Nevertheless, organic nitrogen percentage removal was higher in Chinga constructed wetland plant compared to Eberege. Organic nitrogen was removed via nitrification and denitrification processes whereby ammonium was oxidized to nitrite by the bacterium *Nitrosomonas* while the nitrite was oxidized to nitrate by the bacterium *Nitrobacter*. Nitrate was thereafter reduced to harmless nitrogen which entered the atmosphere.

4. Conclusion and Recommendation

In summary, conventional wastewater treatment plant was more efficient in treating the effluent since the common biological process incorporated which is the activated sludge process has a high efficiency in removing suspended solids, BOD_5, and nutrients while the resulting slurry can be used as compost. Conventional waste water treatment plants are very efficient in removing contaminants from effluent, for they use less space and their operations are independent of weather conditions. However, conventional waste water treatment plants have several disadvantages which include; a constant and high demand of electricity, high cost of construction and maintenance and qualified personnel for operating. These disadvantages make it challenging to construct and run a conventional waste water treatment plant regardless of its high efficiency in treating waste water.

On the other hand, natural biological systems of waste water treatment which include constructed wetlands use biological processes to treat organic waste water hence making them less complicated, lower in cost and easy in operation. Constructed wetlands are artificial wetlands which use aquatic plants to treat waste water. Advantages of constructed wetlands include; easy maintenance, they're natural systems, cheaper to construct and operate as compared to a conventional plant. Their disadvantages are; they require large space, highly experimental and increased sensitivity to nutrients, toxic and heavy metals

An effective waste water treatment system is of great importance in protecting the environment. Methods of treatment range from conventional to natural biological as discussed earlier.

With respect to tea factory waste waters, both systems were able to treat the effluent effectively despite the fact that the conventional treatment plant performed betterin overall. Considering the manageable amounts of wastewater released by tea factories in addition to their less toxicity nature, a well-designed constructed wetland is recommended for treating the factory wastewater. This will help in cutting down the cost of setting up and operating a conventional plant as well as promoting a healthy ecosystem

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