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Modelling Efficiency of On-Farm Sand Filter System in Microbial Contaminant Removal in Wastewater, Ghana

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Abstract: **Wastewater irrigation without adequate safeguards has been noted to have serious drawbacks for human health and the environment. This study modelled the levels of microbial contaminants in wastewater used for peri-urban vegetable crop production and also assessed the efficiency of an on-farm sand filter system on the contaminants in the Zagyuri community of the Tamale Metropolis of Ghana. The study considered widely the selection of a very good filter material and sizing of the filter column. Varying lengths of filter columns and depths of filter material were used in the design of the on-farm sand filter columns. With average dry bulk density and particle density of the filter media being 1.58 gcm^{-3} and 2.66 gcm^{-3} the porosity was 39.4 %. Considering the environmental conditions and the results obtained, mathematical models were developed for selection of the filter size. The results indicated that longer filter columns were more efficient in the removal of microbial contaminants contained in the wastewater. The concentration of faecal and total coliforms as well as helminth eggs was 24,444 MPN/l, 56,930 MPN/l and 56 eggs/l for the wet season respectively. In the dry season however, faecal coliform recorded a mean concentration of 13,780 MPN/l, total coliform had 41,113 MPN/l whilst helminth eggs were 74 eggs/l. Sizing of filter column in the design of wastewater treatment system using mathematical models have been realized to be very important in the achievement of good results.**

Keywords: **Wastewater, On-Farm Sand Filter, Microbial Contaminant, Efficiency.**

1. INTRODUCTION

Sand-filters remove pathogenic micro-organisms from polluted water by first retaining them in the filtration media before they are eliminated [18]. According to [11], retention is achieved mainly through straining in which larger micro-organisms (protozoans and helminths) are physically blocked as they move through the well-packed filter media, and adsorption, in which smaller ones like bacteria get attached to the filtration media. They added that elimination of pathogenic micro-organisms is achieved mainly by exposing them to unfavourable environmental conditions such as high temperature and also through predation by other organisms like protozoan's.

[19]reported that, typical pathogenic removal range for slow sand-filters is 0 - 3 log units and 1-3 log units for bacteria and helminths respectively. [11]reported that when wastewater is allowed to pass through sand-filter trenches, sand embankments, column sand-filters and simple sandbags as farmers channel irrigation water to collection storage ponds greatly affect protozoa and helminths.

2. MATERIALS AND METHODS

2.1 Study Area

Tamale Metropolitan area is located at the centre of the Northern Region of Ghana. It occupies 750 km^2 which is 13 % of the total area of the Northern Region. The population of Tamale Metropolis is reported as 371,351 with 185,995 (50.09 %) being males and 185, 356 (49.91 %) being females [5]. The Metropolis experiences one rainy season starting from April/May to September/October with a peak season in July/August. The dry season is usually from November to March. The mean annual rainfall is 1100 mm within 95 days of intense rainfall. The mean day temperatures range from 33-39 ^{o}C while mean night temperature range from 20-22 ^{o}C. The mean annual day sunshine is approximately 7.5 hours.

In the Metropolis there are several sites where wastewater vegetable farming takes place and the crops cultivated include cabbage, lettuce, *Amaranthus*and*Chochorus*etc. Figure 1 shows the map of Ghana and the Tamale Metropolitan Area. The study area according to [14] is 8 km from the city centre and covers according to different sources in total about 7-12 ha. The experimental field was located on latitude 09^{o}47'388'' N, longitude 00^{o}84' 776'' W and at an altitude of 167 m above sea level.

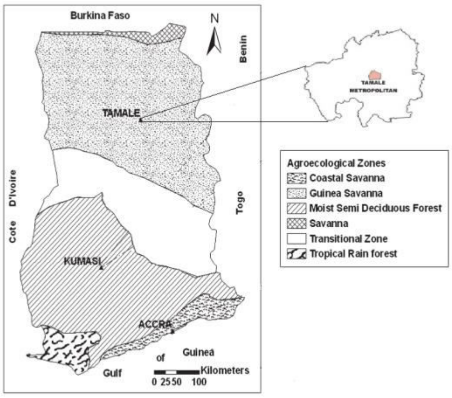

Fig.1. Map of Ghana Showing the Tamale Metropolitan Area *(Adopted and Modified from [1].*

2.2 Filter Design and Wastewater Sampling

On-farm sand filter units were designed using cylindrical containers with 6.5 cm diameter and varying lengths of 8.5, 17 and 25.5 cm. Filter gauze and mosquito net were used to cover both inlet and outlet units whilst the filter columns were filled with six (6) different grades of filter media. Staircase channels were designed to convey the filtered wastewater from the outlet point of the filter units to stabilization ponds. Plates 1a and 1b show the filter media used for the various filtration layers and the three (3) different sizes of filters respectively.

Plate 1a: Six (6) Grades of Filter Media

Plate 1b: Different Sizes of Filter Containers

The staircase design was aimed at cascading the water to improve the oxygen levels contained in the wastewater to promote the activity of micro-organisms. Construction in the field was done using concrete blocks, sand and cement as shown in Plate 2.

Plate 2: Construction Process of Experimental Set-up in the Field

2.3 Experimental Design

The experiment had three (3) treatments: treatment one (T_1) had length of the filtering container of 8.5 cm, treatment two (T_2) was 17 cm, treatment three (T_3) was 25.5 cm, and a control (main Source - MS) which is the raw wastewater. Each treatment had three (3) replications and each filtering unit was filled with six (6) different sizes of the filter media as presented in Table 1. Stabilization ponds of dimensions 2 m x 7 m were created to harvest the filtered wastewater from the various treatment set-ups. Wastewater from the Kamina Barracks sewage system was directed to the designed treatment system. Wastewater samples were taken from each of the ponds and main source to the laboratory for microbial and chemical quality analysis.

Table 1: Filter Media Sizes

Layer	Filter Media Size(mm)
Topmost	2.00
First	4.75
Second	8.00
Third	19.0
Fourth	37.5
Lowest	45.0

Filtered wastewater sampling was done at weekly (7 days) intervals for a period of sixteen (16) weeks that is eight (8) weeks for the rainy season and eight (8) weeks for the dry season in each sampling year (2011 and 2012). A total number of ten (10) filtered wastewater samples were collected at each sampling time.

During the sampling and laboratory analysis periods, sterile sampling containers, hand gloves, water and standard chemical reagents were used. Samples were stored over ice in cool box for transportation to the laboratory for analysis.

2.4 Methods

The following methods were used for the determination of the physical characteristics of the filter media as well as the various microbial and chemical parameters:

2.4.1 Helminth Eggs and Coliform Level Determination

Helminth eggs were enumerated using the concentration method as described by [17] whilst the Heterotrophic Plate Count (HPC) method was used for the determination of faecal and total coliforms.

2.4.2 Physical Properties of Filter Media

The filter media was obtained from igneous rock material. The bulk densities of the various filter media were determined using a weight and volume relations as in relation (1):

$$\rho_b = \frac{m_{fm}}{v_{fm}} \qquad (1)$$

Where:

$\rho_b -$ average bulk density in $\mathrm{g.cm^{-3}}$
$v_{fm} -$ volume of the filter media in $\mathrm{cm^{-3}}$
$m_{fm} -$ mass of the dried filter media in g

According to [15] average particle density is obtained using liquid immersion as in relation (2):

$$\rho_p = \frac{m_{fm}}{v_{fp}} \qquad (2)$$

Where:

$\rho_p -$ average particle density in $\mathrm{g.cm^{-3}}$
$v_{fp} -$ volume of the filter media excluding pore space in $\mathrm{cm^{-3}}$
$m_{fm} -$ mass of the dried filter material in g

Porosity of the filter media was determined by relating the average particle and bulk densities of the various media used (relation 3).

$$\eta = \left(\frac{\rho_b}{\rho_p}\right) \times 100\ \% \qquad (3)$$

where:

$\eta$is the porosity of the filter media in %

2.4.3 Modelling the Decay of Thermotolerant Coliform and Helminth Eggs

A multivariate linear regression model was developed

For each season for the three (3) microbial contaminants (faecal coliform, total coliform and helminth eggs) taking into consideration the environmental factors which have high level of influence on the occurrence and concentrations. The environmental factors considered were temperature, rainfall, solar radiation (duration), relative humidity, pH as well as the design length of the filter system.

The model was developed following the generalized linear model (4) as below;

$$Y_i = \beta_1 + \beta_{11}X_{11} + \beta_{12}X_{12} + \ldots\ldots\ldots\ldots.\beta_{ij}X_{ij} + \varepsilon_i \quad (4)$$

$$\beta_{ij} \geq 1\,; i = 1, \ldots\ldots\ldots\ldots..m$$

$$\beta_{ij} \geq 1; j = 1, \ldots\ldots\ldots..n$$

Where:

Y_i=*Natural* log *of daily microbial contaminant concentration*$\left(\frac{MNP}{100ml}\right)$ *on day j*

β_{ij}= *slope cooeficient explanatory variable* X_i: X_{ij} *is the* j^{th} *explanatory variable on day j*ε_i =*model error or residual on day j*

The dependent variables were considered as faecal coliform, total coliform and helminth eggs whilst the independent variables were the design parameters of the system, pH and the environmental factors.

3. RESULTS AND DISCUSSIONS

3.1 Characteristics of Filter Media and Design of On-Farm Sand Filter System

The six (6) filter media used had different void spaces or porosity thus translating to different efficiencies in the removal of various contaminants. Table 2 presents the physical characteristics of the filter media used for the design of the experiment. The average dry bulk density and particle density of the filter media were 1.58 gcm^{-3} and 2.66 gcm^{-3} respectively. Combining the individual filter media porosities (ranging from a low porosity of 16.5 % to 52.5 %) gives total average filter porosity of 39.4 %. A positive relation between filter media size and porosity was observed for the media used in the experiment. In a study in Uganda by [10] using two step filtration for grey water, the media size ranged from 2.56 - 5 mm for the first step and 1.18 - 2.56 mm for the second step with 65.6 % and 62 % porosity respectively. [16] reported that the permeability and durability of filters always is reciprocal to its treatment efficiency.

Table 2: Physical Characteristics of Filter Media Used in Filter Columns

Diameter (mm)	Dry Bulk Density	Particle Density (g/cm^3)	Porosity
	(g/cm^3)		(%)
2	1.66	1.99	16.5
4.75	1.79	2.95	39.3
8	1.69	2.9	41.7
19	1.48	2.57	42.5
37.5	1.47	2.62	43.8
45	1.39	2.93	52.5
Average	1.58	2.66	39.4

The filter material were filled into the nine (9) cylindrical filter units of the three (3) dimensions as shown in Figure 2.

The smallest diameter of filter media of 2 mm served as the first layer of each column whilst the biggest size filter media of 45 mm was at the bottom of the filter column. Rapid sand filtration has been reported to remove 90-99 % of helminth ova from coagulated primary effluent [9]. This is considered under specific media size of sand medium of 0.8 - 1.2 mm and minimum filter depth of 1 m with filtration rates of 7 - 10 m^3/m^{2}h and filtration cycles of 20 - 35 hours. [6]and[12] observed that under these conditions, the effluent consistently contains < 0.1 helminth egg per litre.

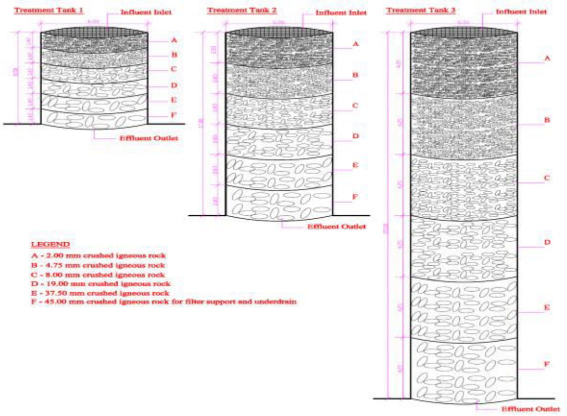

Fig.2. Designed Experimental Filters Indicating the Various Layers

3.2 Microbial Levels in Wastewater and their Reduction Using On-Farm Sand Filter

The concentration of faecal and total coliforms as well as helminth eggs was 24,444 MPN/l, 56,930 MPN/l and 56 eggs/l respectively for the wet season. In the dry season, faecal coliform recorded a mean concentration of 13,780 MPN/l, total coliform had 41,113 MPN/l whilst helminth eggs were 74 eggs/l. These mean concentrations were noted to be higher than the recommended levels of less than 1000/100 ml of coliforms and < 1 egg/l for unrestricted irrigation [19]. Except helminth eggs which experienced low number of eggs per litre in the wet season, coliform bacteria was observed to be generally high in the wet season as compared to the dry season (Tables 3, 4 and 5). In a study by [14] in Kumasi Ghana, a general increase in levels of faecal coliforms was observed after the first rains. Similarly, [4] observed in Dakar Senegal the effects of “laundry days” and “Friday prayers” on stream water quality.

Table 3: Mean Concentration and Removal Level of Faecal Coliform by Season

Treatment	Wet Season		Dry Season	
	Mean Concentration (MPN/l)	% Removal	Mean Concentration (MPN/l)	% Removal
T$_1$	24,444	68	13,780	62.6

T_2	24,444	75.7	13,780	67.2
T_3	24,444	80.9	13,780	69.7

It is clear in Table 3 that filter column length has a great influence on the reduction level of faecal coliform bacteria in wastewater. T_3 recorded higher levels of reduction in faecal coliform levels of 80.9 % and 69.7 % for the wet and dry season respectively. T_1 with the least filter material length recorded the lowest removal rate of coliform bacteria for both seasons (68.0 % for wet season and 62.6 % for the dry season).

Table 4: Mean Concentration and Removal Level of Total Coliform by Season

Treatment	Wet Season		Dry Season	
	Mean Concentration (MPN/l)	% Removal	Mean Concentration (MPN/l)	% Removal
T_1	56,930	62.2	41,113	50.3
T_2	56,930	64.9	41,113	54
T_3	56,930	73.8	41,113	59.6

The effect of the on-farm sand filter system on total coliform bacteria was observed to be higher in T_3 with percentage removal of 73.8 % and 59.6 % for the wet and the dry seasons respectively. T_1 with a container length of 8.5 cm recorded the least removal efficiency of total coliform contained in the wastewater with percentage removal rate of 62.2 % for the wet season and 50.3 % for the dry season.

For coliform bacteria it can be seen clearly in Tables 3 and 4 that container length which translates to the amount of filter material contained in the filter column had a positive linear effect on the removal rate of total coliform bacteria in wastewater.

Also, the effect of the on-sand filter was largely efficient in coliform bacteria removal in the wet season as compared to the dry season. This can be attributed to the favourable environmental conditions which led to the growth and optimal maturation of the surface microbiological layer (the *'schmutzdecke'*) thus improving the efficiency of bacteria removal.

Table 5: Mean Concentration and Removal Level of Helminth Eggs by Season

Treatment	Wet Season		Dry Season	
	Mean Concentration (eggs/litre)	% Removal	Mean Concentration (eggs/litre)	% Removal
T_1	56	70.2	74	57.6
T_2	56	71	74	72.6
T_3	56	73.9	74	74.1

The concentrations of helminth eggs per litre of wastewater was observed to be lower in the wet season (56 eggs/l) compared to the levels in the dry season with 74 eggs/l (Table 5). The results of the treatment effect on the removal of helminth eggs indicated that, the longer the filter material the more efficient the system. T_3 with total length of 25.5 cm recorded the highest level of helminth egg removal of 73.9 % and 74.1 % for the wet and dry seasons respectively. T_1 with a filter length of 8.5 cm however, recorded the lowest level of removal of helminths with percentages of 70.2 % and 57.6 % for the wet and dry seasons respectively.

[3]Noted that very good performance of farm-based options of wastewater treatment is normally achieved in the dry season compared to the wet season due to rainfall, shorter duration of sunshine and generally low temperatures.

Helminth eggs have been reported to be very resistant and behave quite differently from bacteria and viruses during treatment [7].

According to [8] during filtration, pathogens and other particulate matter are removed as they pass through sand or other porous granular media.

3.3 Prediction Models for Faecal Coliform Removal

From the multivariate regression analysis on the performance of the designed sand filter system, six (6) factors were considered in the evaluation of the system. These were the length of the container (L), the relative humidity (RH), temperature (T), solar radiation (hours) or the UV rays, rainfall (P) and pH of the wastewater. [3] noted that very good performance of farm-based options of wastewater treatment is normally achieved in the dry season compared to the wet season due to rainfall, shorter duration of sunshine and generally low temperatures.

The model equation for the design of the on-farm sand filter system for the removal of faecal coliform (FC) during the study was obtained as Equation 5. This prediction model was developed as a multivariate linear regression model using the output data from the treatment systems in SPSS version 16.00.

$$FC = 13.715 - 0.039L - 0.074RH - 0.017\,T + 0.180\,Ra + 0.044\,P - 0.584\,pH \text{ .... } 5$$

The R^2 suggests that about 46 % of the variables explain the FC levels contained in wastewater during the dry season after treatment. This indicates that other factors account for or influenced the reduction in concentration of faecal coliform levels in the wastewater during the dry season. The results show that an increase in the length of the treatment filters by a unit decrease the FC concentration level by 3.9 % in the dry season. An increase in the RH, T and pH by a unit results in the reduction of FC by 7.4 %, 1.7 % and 58.4 % respectively. However, in the dry season as observed from the prediction Equation 5, an inverse linear relationship existed between the variables Ra and P. This is because an increase by a unit of Ra and P results in a corresponding increase in the FC levels by 18 % and 4.4 % respectively of the factors. The results indicate statistical significance at the 0.05 level for L, RH, Ra and pH.

In the wet season of the study, the multivariate linear regression model that can be adopted for the reduction of the faecal coliform contained in wastewater is Equation 6.

$$FC = -\,0.587 - 0.082L + 0.003RH + 0.329T - 0.056Ra + 0.17P + 0.22pH \text{ .... } 6$$

$R^2 = 0.411$From Equation 6, 41.1 % of the reduction

Levels of FC are explained by the regression line. L and Ra are seen to contribute to the reduction in the concentration of the faecal coliform contained in the wastewater. A unit increase in L and Ra results in a corresponding reduction in FC concentration by 8.2 % and 5.6 %. The other environmental factors influencing the survival of faecal coliform were RH, T, P and pH and it is clear from Equation 6 that a unit increase in these parameters leads to a corresponding unit increase in the FC contained in the treated wastewater. 0.3 %, 32.9 %, 17 % and 22 % increase in FC concentration corresponds to a unit increase in RH, T, P and pH respectively as observed from the equation. Unlike the dry season, an increase in Ra during the wet season results in a unit decrease in FC concentration.

It has been reported that the higher the temperature, the higher the rate at which the degrading bacteria that are responsible for purification multiply. At the same time, the intake of oxygen via surface and oxygen solubility drops with increasing temperature. The most important factors considered to be controlling the rate of decay of faecal coliform are temperature, solar intensity and pH [2, 13].

3.4 Prediction Models for Total Coliform Removal

The results of the dry season showed that about 48 % of the removal of total coliform (TC) using the designed treatment system is explained by the factors influencing TC as in the model. The results of the model indicated that the parameters L, RH, T, P and pH have an inverse relationship with TC concentration in wastewater (Equation 7).

$$TC = 11.088 - 0.037L - 0.021RH - 0.037T + 0.039Ra - 0.297P - 0.004pH \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 7$$

$R^2 = 0.478$

From the model (Equation 7) a unit increase in L, RH, T, P and pH results in the reduction of TC concentration in the raw wastewater by 3.7 %, 2.1 %, 3.7 %, 29.7 % and 0.4 % respectively. Also, the Ra is realized to have direct impact or positive linear relationship on TC levels as a unit increase in Ra results in a 3.9 % increase in TC. Except P which is not statistically significant (p value > 0.05), L, RH and Ra are significant at 0.05 level whilst T and pH are significant at 0.10 level.

TC reduction in the wet season was characterized by a unit increase in L, Ra, and P. Equation 8 shows that with a unit increase in L, Ra and P, a respective 5.8 %, 4.8 % and 0.6 % reduction levels can be achieved. The effect of increase in RH, T and pH on the reduction was however, seen to be directly related.

$$TC = 2.593 - 0.058L + 0.017RH + 0.185T - 0.048Ra - 0.006P + 0.186pH \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 8$$

$R^2 = 0.325$

An increase in RH, T and pH rather provided favourable environmental conditions for the survival and multiplication of the TC as in Equation 8. From the model (Equation 8), only 32.5 % of the variables are explained by the regression equation with 67.5 % factors that have not been accounted for. According to [16] pathogen removal rates increase with long retention times, but all high rate plants work proudly on short retention times.

[19]guidelines and other independent surveys describe

transmission of worm infections as the greatest risk in relation to wastewater. Worm eggs, helminths, are well removed from effluent by sedimentation but accumulate in the bottom sludge. The long retention times of 1 to 3 years in septic tanks and anaerobic filters provide sufficient protection against helminths infection in practice. High pathogen removal rates are reported from constructed wetlands and shallow aerobic ponds. This effect is attributed to longer retention times, exposure to UV rays in ponds, and various bio-chemical interactions in constructed wetlands [16]. Also, exposure to UV rays has a substantial hygienic effect. The highest rate of pathogen removal can be expected from shallow ponds with long retention times, e.g. 3 ponds in a row with HRT of 8 to 10 days each. Effluents from aerobic ponds or constructed wetlands is suitable for surface irrigation, even in domestic gardens. However, the better the treatment effect of the system, the lower is the fertilizer value of the effluent [16].

3.5 Prediction Models for Helminth Egg Removal

The prediction model for helminth (H) eggs recorded a 55 % (R^2 value) as shown by Equation 9. The results show that L, RH, T, Ra and pH are inversely related to the concentration of H. This indicates that, a unit increase in L, RH, T, Ra and pH results in the reduction of H concentration by 6.1 %, 11.0 %, 8.0 %, 10.0 % and 13.3 % respectively whilst a unit increase in P results in 8.0 % increase in helminth egg concentration. Equation 9 presents the model parameters and the effect of variation in levels of these parameters on the concentration of helminth eggs in wastewater used by the resource poor farmers. However, except L which is found to be significant at 0.05 level, the other parameters were not statistically significant.

$$H = 4.959 - 0.061L - 0.11RH - 0.08T - 0.010Ra + 0.08P - 0.133pH \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 9$$

$R^2 = 0.545$

In the wet season the R^2 value of 43.4 % was obtained and slightly lower than the dry season as per the model equations 9 and 10 for the removal of helminth eggs. It is also clear as in Equation 10 that aside the length of the container which indicates that the more filter material contained in it, the higher the filtering efficiency, the rest of the factors did not positively reduce the concentration of the helminth eggs in the wastewater during treatment.

$$H = -1.283 - 0.054L + 0.028RH + 0.061T + 0.07Ra + 0.009P + 0.01pH \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 10$$

$R^2 = 0.434$

A unit increase in the length of container was observed to reduce the concentration of helminth eggs by 5.4 %. RH, T, Ra, P and pH were observed as per equation 10 to rather provide conducive environment for the growth and multiplication of helminth eggs during the wet season.

4. CONCLUSIONS

The results of the study indicated the level to which microbial contaminants in wastewater can be removed. Designing a wastewater treatment system involves selection of a very good filter material and sizing the filter column rightly.

Varying lengths of filter columns and depths of filter material were used in the design of the on-farm sand filter columns.

Mathematical models are very important and can be employed in the determination of the right size of filter container needed for the efficient removal of microbial (faecal and total coliforms, helminth eggs) contaminants contained in wastewater. These models considered the prevailing environmental conditions in the locality for the installation of the filter columns. Longer filter columns were more efficient in the removal of microbial contaminants contained in the wastewater. Efficient reduction in biological contaminants of wastewater used for dry season vegetable crop production therefore depends on accurate sizing of the filter column and selection of good filter media.

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AUTHOR'S PROFILE

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