EXPERIMENTAL STUDY AND DATA ANALYSIS OF WATER TRANSPORT AND THEIR INITIAL FATE IN THROUGH UNSATURATED OR DRY BIOREACTOR COLUMNS FILLED WITH DIFFERENT POROUS MEDIA

A Thesis
Submitted in Partial Fulfilment of the Requirements for the
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IN THE CENTER OF EXCELLENCE IN ENERGY

BY

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M. Tech. Thesis Presentation - Final Evaluation

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- Project title: Experimental Study and Data Analysis of Water Transport And Their Fate In Through Columns Filled With Different Media
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Outcome of the MTech Thesis Presentation

- Comments by Supervisors and Examiners

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* Take a note of all comments from all Examiners & incorporate in future research

- MTech Thesis copies submitted as below? [✓ Yes] / No

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Report of M.Tech Oral Examination

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Declaration by the student/thesis supervisors about the interdisciplinarity nature of the work:
Explain the interdisciplinarity nature of the work in few lines. This work involves porous media flow, electro-kinetics of water & Regression Analysis for modelling.

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The student has completed/not-completed the M.Tech. program.

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Note: Please make at least three signed hard copies of the oral examination report in a sealed envelope. Submit one copy to the Academic Section, and the other copy to the Academic coordinator. Other copies will stay with the thesis supervisor(s) for record.

DEDICATION

To

My Parents,
Shri Surender Singh Yadav and Smt. Sanil Lata
and
My Brother,
Aditya Yadav

DECLARATION

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included. I have adequately cited and reference the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea, data, fact or source in my submission. I understand that any violation of the above will cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been cited or from whom proper permission has not been taken when needed.

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Abstract

The electro-kinetic characteristics of different material bioreactor columns for treating water and waste water are experimentally studied. Separate columns of unsaturated gravels (~6mm) and ball clay were assessed for electro-kinetic characteristics by dosing water at a hydraulic loading rate of 50ml/min and 10ml/min. Similarly locally available organic materials such as sawdust, Moringa oleifera sheets and textile clothe pieces were also empirically analyzed. Size effects of the bio-reactor columns were also studied.

The effluent from textile clothe and gravel reactor respectively showed an increase in pH while a depreciation in pH in the effluent was observed in the Moringa Oleifera reactor and sawdust reactor. This may be due to leaching of acidic organic components for sawdust and Moringa Oleifera . In gravels effluent pH depreciated with increase in flow rate but the general trend of the effluent pH curve showed an initial improvement before it slowed down to an asymptote for a specific constant dosage and height. A multi-parameter stochastic linear model for change in pH as a function of column height, dosage rate, time for specific volume discharge and change in electrical conductivity between influent and effluent was derived. A general stochastic model was also developed to characterize pH change in any bioreactor irrespective of the material media.

Thirty centimeters of gravel exhibited an increase in conductivity with increase in flow rate while conductivity dipped with increasing flow rate when the gravel column height was halved. The measure of organic compounds in water decreased with increasing percolation rate through gravel. The chemical oxygen demand ratio within the gravel improved to unity showing increased containment of organic compounds with time. Organic textile clothes reactor also illustrated increased conductivity with increasing flow but conductivity dipped with increase in column height. For Moringa Oleifera reactors, a dosage of water at 10ml/min showed a significant improvement in conductivity with increase in column height.

An initial depreciation in temperature curve was observed within clay and gravel reactor. With increase in depth there was an increase in temperature within the gravel as the saturation by water improved. In sawdust reactors this was not the trend. A birth process model is proposed to simulated temperature within a bioreactor as a function of time irrespective of any specific material used as bioreactor media.

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Chapter 1

Introduction

In India rural villages are very much disconnected from the cities. Cities in India, on the whole, discharge 15 billion L^3 of waste water daily [Shah 2013]. This is equal to 80% of total water supplied that goes into sewages [CSE 2013].Jawaharlal Nehru National Urban Renewal Mission started by India in 2005 looks into sanitation and waste management in cities as well as development of technologies to serve economically backward [CSE 2013]. It aims at carbon neutral, energy efficient smart cities. More than 73% of major projects within this mission have not been completed on time. This represents neglect from the Government as well as communities towards water infrastructure development in India [Shah 2013].

The very basic shortcoming of water infrastructure is poor planning in centralized supply, buildings, infrastructure and distribution, less research, neglecting rural community and failure by public to adopt the service rules as well as inability to revise the rules laid down several decades ago [Jacob 2012, Rohilla, 2013].

Further to the above discussions the premise derived is either to impose and enforce better water/waste water management laws for people to abide or the other way round is to device point of use technologies. This will help to find a pathway to help our rural communities without much water infrastructure to dispose of their sewage at the source itself.

Large quantities of water are necessary to solve water scarcity issues. Therefore more efficient use proper reuse of waste water is also necessary. Added advantage of recycle and reuse, is that it is much energy efficient and cost effective compared to regular water treatment [Plappally and Lienhard 2013]. Moving forward in this regard this thesis discusses bioreactors. Bioreactors are known for decentralized wastewater treatment in rural areas far away from municipal sewage distribution systems of metropolitan cities [Jing 2008]. The major advantage of bioreactor is high treatment efficiency with relatively low cost and maintenance [Jing 2008]. It is important to study the transport phenomena and the electro kinetic physics that helps this treatment -technology to be energy efficient and cost effective.

Water coming out to our house has characteristics, low and varying pollutant concentrations, and low frequency of events because of inefficient treatment at municipal level. Containment of pollution from such systems is most challenging areas in the environmental engineering. Further, this study tries to find out the application of this fixed media bioreactor technology by testing its feasibility in the treatment of such water by using different media in bioreactor dosed with water at various flow rates. Effect of media size also is taken into consideration while experimenting.

1.1 What is a Bioreactor?

According to Merriam-Webster Dictionary, a bioreactor was defined in 1974 as “a device or apparatus in which living organisms and especially bacteria synthesize useful substances (as interferon) or break down harmful ones (as in sewage)”. Therefore, Mancl and Rector (1999), to avoid confusion, referred to a sand filter as a sand bioreactor for the onsite wastewater treatment. Similarly, here according to the media used a bioreactor is defined for e.g for gravels it is referred as gravel bioreactor so as for clay, sawdust, Moringaoleifera (drumsticks) and textiles.

The term, sand filter has been used for various purposes and represents a different treatment process for professionals with different backgrounds. To wastewater treatment plant operators, a sand filter is considered a polishing unit operation. A tertiary wastewater treatment plant may be equipped with sand filters. A sand filter is used in a filtration process to polish effluent from a secondary wastewater treatment process. The polishing process is mainly used to remove particulates in the effluent. This type of sand filter operates under hydraulic loading with head loss, and backwashing. The sand filter polishing process is called depth filtration [Metcalf and Eddy, 2003].

To drinking water treatment plant operators, a sand filter is considered a filtration device. In drinking water treatment processes, a sand filter is used as a gravity granular-media filtration device. The filtration mechanisms involve interception, straining, flocculation, and sedimentation [Viessman and Hammer, 1985].

1.2 Why Bioreactor?

Various media bioreactors were studied to as an economical method of treatment for the Wet Weather Management Plan (WWMP) [Sharon and Campanella 2006, Jing 2008]. Bioreactors in WWMP have application for single onsite Sanitary System Overflow (SSO) discharge point treatment and they treat influent quickly. They have the ability to produce effluent with low biological oxygen demand (BOD5) and total suspended solids (TSS) values and operate under varying hydraulic conditions.

Thus, fixed media bioreactors are also readily accessible for monitoring and maintenance. In addition, they have an important property that they can restart up and have stable effluent quality shortly after a long rest time without wastewater loading [Tao Jing,2008]. Therefore, in this thesis, the fixed media bioreactors were considered further study and analysis .

The goal of this research is to evaluate the performance of fixed media bioreactors in the treatment of normal household water. Specific objectives were to:

- Examine the effectiveness of natural media of bioreactors for the normal household water treatment
- Evaluate the impact on effluent quality by changing the media.
- Evaluate the impact of varying flow rates on bioreactor performance.
- Analyze and model the effect factors of treatment performance by different statistical methods.

This work may serve as suggesting this type of treatment system an alternative for waste water treatment and household water quality enhancement at low price at remote rural places.

1.3 Situation of sewage treatment in India

In order to further carry out the feasibility of the proposed work it is required to study the ground reality of water and waste water treatment scenario in India. According to a report submitted by Central Pollution Control Board in 2005 to the government of India, the sewage generation and treatment capacity in various cities of India is illustrated as follows in table 1 below:

City category & population	Number of cities	Sewage generation, MLD	Installed sewage treatment capacity, MLD	Capacity gap in cities having STPs, MLD (A)	Sewage generation in cities having no STPs, MLD (B)	Total capacity gap, MLD (A+B)	Planned treatment capacity, MLD
Class I cities having more than 10 lac population	39	13503	4472 (In 29 cities)	6135	2896	9031	1549
Class I cities having 5 to 10 lac population	32	3836	485 (In 13 cities)	1293	2058	3351	123
Class I cities having 2 to 5 lac population	119	4807	768 (In 34 cities)	804	3235	4039	4
Class I cities having 1 to 2 lac population	224	4018	322 (In 36 cities)	373	3323	3696	32.5
All the above Class I cities together	414	26164 (100%)	6047(23.1%) (In 112 cities)	8605 (32.9%)	11512 (44%)	20117 (76.9%)	1708.5 (6.5%)
Class II towns having 0.5 to 1 lac population	489	2965 (100%)	200 (>143*) (4.8%) (In 22 towns)	Nil	2822 (95.2%)	2822 (95.2%)	34.1 (1.15%)
All Class I cities and Class II towns	893	29129 (100%)	6190 (21.3%)	8605 (29.5%)	14334 (49.2%)	22939 (78.7%)	1742.6 (6.0%)

Table 1.1 Sewage generation and treatment capacity in Class I cities and Class II towns (Sewage generation estimated on the basis of 2001 population)

As stated previously of Rohilla 2013, the data shown above confirms that fact that water infrastructures studies in India do not consider our rural villages and methods installed are heavy, out-dated and costly. This makes it difficult for villages to have these systems. In this scenario a fixed media bioreactor will act as a good alternative for treatment purposes in villages. This is due to fact that materials for manufacturing bioreactors are locally available and derived from the waste of technical procedures such as carpentry. Therefore, social aspect, economic benefit as well waste management aspect is also taken into consideration while working on these bioreactors.

1.4 Work done on bioreactors till now?

Various researchers have worked on layered media bioreactor till now in one form or other. Chien-Lin Chen in 2003 has studied the low temperature impact on intermittent sand bio reactors. Jing Tao, 2008 has compared the treatment of SSO with fixed media bioreactors. Five types of fixed media biofilters were used having media as peat , textiles ,sand, felt/sand and peat/sand. Rashmi Singh Gaur, 2009 has researched on treatment of turkey fat containing waste water in coarse sand and gravel/coarse sand bioreactors. Further relevant discussion into specific work of several authors is dealt in the Chapter 2.

1.5 Types of studies done on bioreactors

Various bioreactors have been studied as mentioned above. Types of studies been done on this reactors involve measurement of BOD_5(Biological Oxygen Demand) , COD (Chemical Oxygen Demand), pH , microbial growth , degradation and size effect on treatment ability of a reactor [Gaur 2009, Jing 2008] .

1.6 Types of studies not undertaken

After studying the literature related to bioreactors it has been observed that till now no studies involves report work on physics of flow of waste water through various column bio reactors of different media. Other aspects of the studied should also include,

- Temperature change studies of different media with depth or temperature gradient.
- pH gradient has also not been studied with flow.
- Electrical Conductivity (EC) changes in water after treated through bioreactors.
- TDS (Total Dissolved Solids) properties and respective changes in treated water.
- Effect of flow rate change of influent on the pH, EC, COD change
- Study of physics through Organic and Inorganic media.

1.7 Summary

As discussed earlier, Chapter 2 will detail the work on bio reactors till date. It will also discuss on the contribution of various researchers around the globe. The problem formulation, methodology and experimental set up are explained in the third chapter. The results from the experiments conducted are analyzed and its physics discussed in the fourth chapter. The implications of this work as well as conclusions are finally enumerated in the fifth chapter. It will also discuss future research that needs to be conducted for further investigations into relationship of this transport phenomena and biological degradation that occurs when impure water is passed through these column based bio-reactors.

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Chapter 2

Literature Review On Microbial Bioreactor

According to Merriam-Webster Dictionary, a bioreactor is defined as “a device or apparatus in which living organisms and especially bacteria synthesize useful substances [as interferon] or break down harmful ones [as in sewage]”. Since the late 1880s sands beds have been used to treat wastewater in communities [Mancl and Peeples 1991]. Bioreactor technology got obsolete during twentieth century because of mechanical system came into place.

2.1 Bioreactor: Types and Manufacturing

Reactor can be classified as [Rittman and Mc Carty 2001]

1) Basic Reactors

a) **Batch Reactor:** This is a basic waste water container with an automatic or manual stirrer. Waste water thus collected is place for microbial growth and these microbes can feed on to the waste organic materials for its survival and growth. Stirring at a specified pace can improve microbial growth and treatment of waste due to increase in microbial feeding on the waste. This can be appended with similar container for a continuous batch process. These reactors are characterized by high BOD removal rates[Rittman and McCarty 2001].

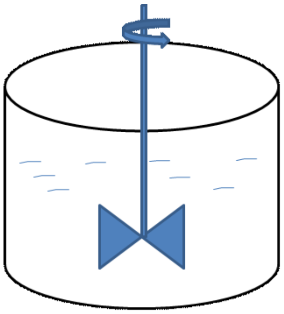

Figure2.1 Schematic Representation of Batch Reactor with a mixing stirrer

b) **Continuous-Flow-Stirred-Tank Reactor (CFSTR):** This reactor has application in activated sludge treatment of municipal and industrial waste water and anaerobic digestion of sludge and concentrated waste.

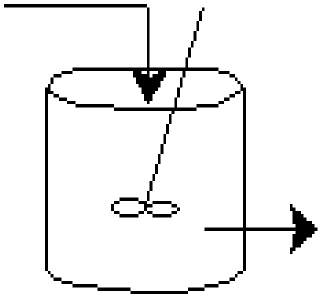

Figure 2.2 Schematics of a Continuous Flow Stirred Tank Reactor [Source: www.engin.umich.edu]

c) **Plug-Flow Reactor (PFR):** Plug flow reactor are used for activated sludge treatment of municipal and industrial waste. Plug flow implies a constant velocity flow at every part of the reactor. This means that a residence time which is the same for every waste water streamline and can be ascertained, since velocity is constant and the magnitude is the same for all streamlines.

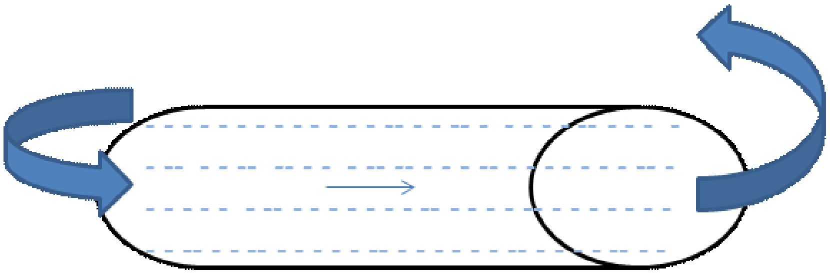

Figure 2.3 Schematic representation of a plug flow reactor

2) Biofilm Reactors

a) **Packed Bed:** This bio reactor is used for aerobic and anaerobic treatment of waste waters and organic removal, nitrification and de-nitrification.

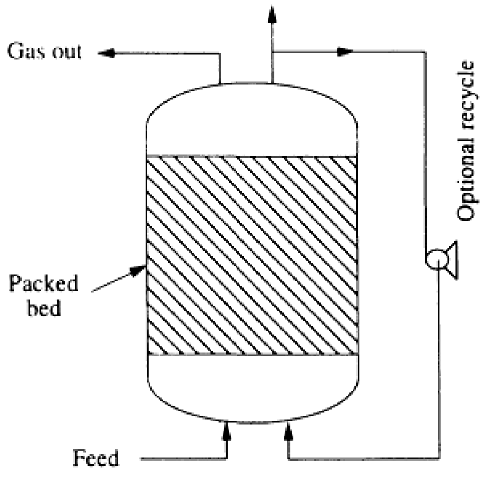

Figure 2.4 Pictorial representations of packed bed biofilm reactors

[Source; http://www.metal.ntua.gr/~pkousi/elearning/bioreactors/page_13.htm]

b) **Fluidized Bed:** Fluidized beds are used for treatment of low BOD concentrated wastewater, for anaerobic treatment and toxic organic biodegradation. The Kunii-Levenspiel bubbling bed model is used to describe the processes in this bio-reactor [Kunii and Levenspiel 1968]. The gas enters the bottom of the bed as shown in Fig. 5 and in the form of bubbles (uncolored circles in Fig. 5) rises through the fluid column. As the gas rises, mass transfer takes place as the bubbles come into contact with the waste (clouds shown in Fig. 5) particles [Kunii and Levenspiel 1968]. This interaction product rises up with the gas bubbles forms foam on the surface of the fluid column. This treated solids or foam exits through another pipe. The rate of the interaction of waste with the bubble and residence time of the bubbles in the fluid column affects the treatment of the waste [Kunii and Levenspiel 1968].

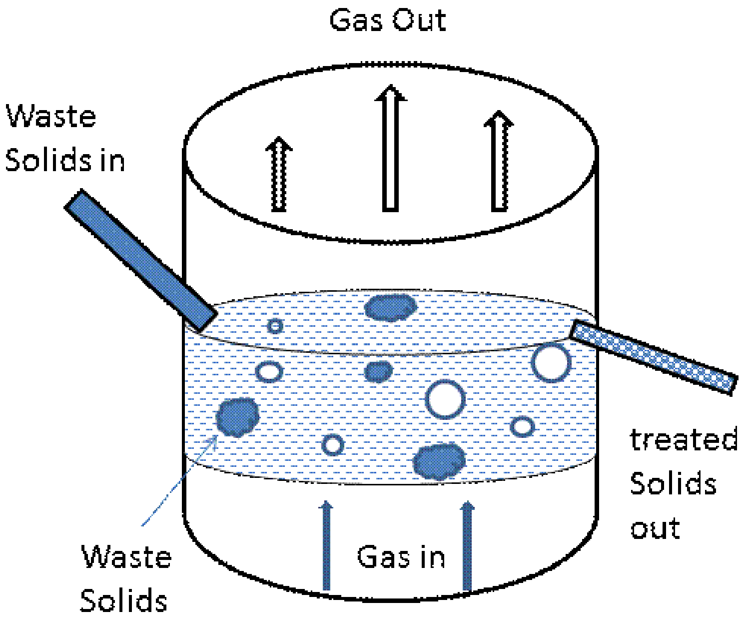

Figure 2.5 Kunii and Levenspiel Fluidized Bed Model

c) **Rotating Biological Contactor:** This bioreactor helps in organic removal, nitrification and aerobic treatment of waste water. One of such reactors is pictorially illustrated in Fig. 6

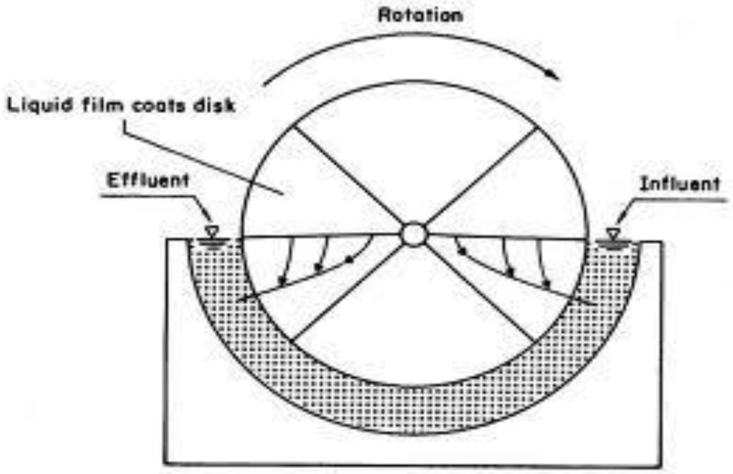

Figure 2.6 Rotating Biological Contractor [www.metal.ntua.org]

2.2 Bioreactor: Positive Aspects and Feasibility Chances

Research on the packed bed reactors is provided much importance in this thesis. Here, the following discussion will enumerate the work that had been done on these reactors till date. Gaur et al. worked on packed bed reactor filled with sand and pea gravels of varying heights. These reactors were used to treat turkey fat containing waste water. A set of varying depth of coarse sand was used in a bioreactor and another had an additional pea gravel layer as shown in Fig. 7 and Fig. 8 respectively [Gaur et al., 2009].

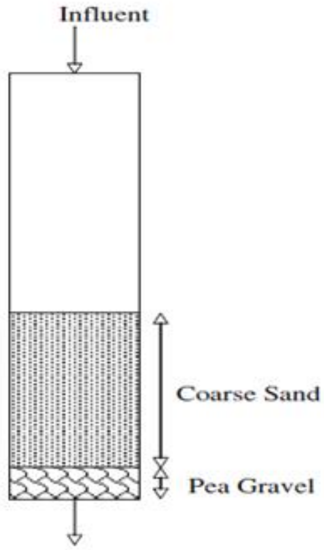

Figure 2.7 Sand bioreactor with varying depths of coarse sand and pea gravel

[Source: Gaur et al., 2009]

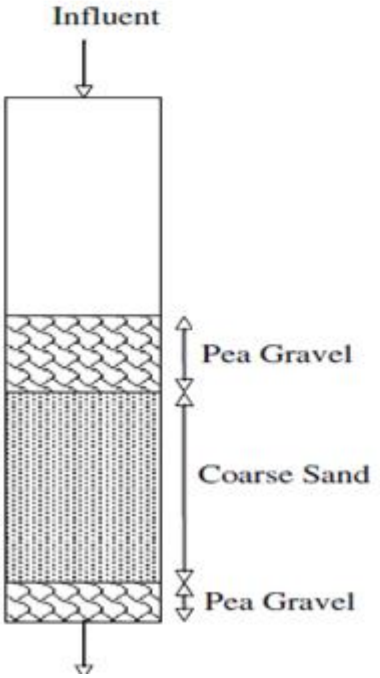

Figure 2.8 Sand bioreactor appended with pea gravel layer on top of layers of coarse sand and pea gravel [Gaur et al. 2009]

Relative removal of COD has enhanced in reactor having pea gravels. Gaur et al. did not derive any relationship between the COD removal, materials used, dosages as well as electro-kinetic parameters which can signify the effectiveness of these reactors in treating or filtering. In this thesis an effort to model COD change as a function of different parameters such as column height, dosage rate etc. will be performed.

Another waste water treatment experiment was conducted by Tao et al. 2008. They used packed bed reactor having textile, peat, sand, felt and sand, peat and sand as media also used for treatment of Sanitary Sewer Overflow water. Fig. 9 illustrated the experimental set up of these reactors by Tao et al. [Tao et al., 2009].

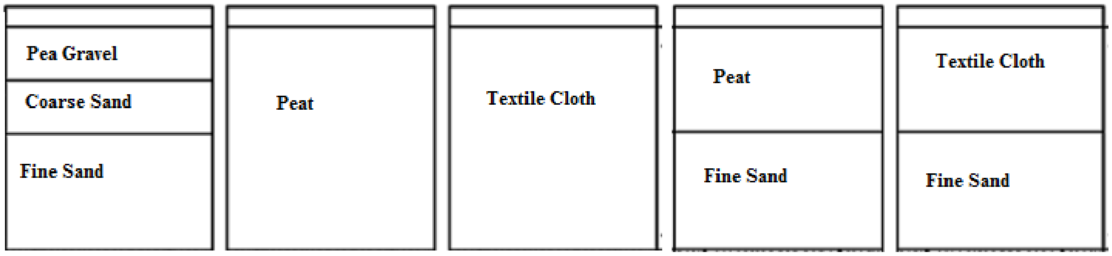

Figure 2.9 Five different experimental columns analysed by Tao et al, 2009.

Most of the waste water treatment systems are characterized by a microbial growth consuming the nutrients within the waste [Mancl and Tao 2011]. These microbes colonize the surface of the bioreactor media also where they have easy access to waste (their food) and get an optimal environment or climate for their growth. These microbes grow on different types of media, like sand, cloth, and plastic.

If the media is well structured, the microbes can grow optimally on its surface [Mancl and Tao 2011]. In unsaturated media, empty soil pores provides the necessary air required by the microbial growth. Fig.10 illustrates the percolation of waste water through random size media. The waste materials get trapped between the media and provide locations for optimal growth of microbes leading to bio-film formation. The effluent waste water traversing through sand bio-reactors were found to lower the biochemical oxygen demand [BOD_5] and ammonia levels [Mancl and Tao 2011]. Mancl and Jing also state that these reactors were feasible for withstanding varied dosages of waste water. This property would help communities during different weather conditions as well as places with variable waste water flows. For example, these systems can be viable for rainy seasons when abundant down pour can occur. Other fact being household waste water discharge of water is a very random event dependent on occupants and their human behavior [Plappally and Lienhard 2012]. Recently arsenic polluted potable water filtration was also accomplished using bio reactor columns named MIT Kanchan Filters [Plappally and Lienhard 2013]. This is a regular filter with layer of fine sand, coarse sand and gravel appended with another perforated basin on the top of the layers containing layers of brick pieces and iron nails which gets the influent arsenic polluted water. Iron nails in contact with arsenic form complexes and get removed by getting trapped within the sand. Microbes in water are also removed by adsorption, trapping, natural death and predation by microbes growing in the sand media. Research also shows that if sand bioreactors loaded with wastewater after a gap of 4–6 months can immediately treat the wastewater [Kang et al. 2007a; Tao et al. 2011].

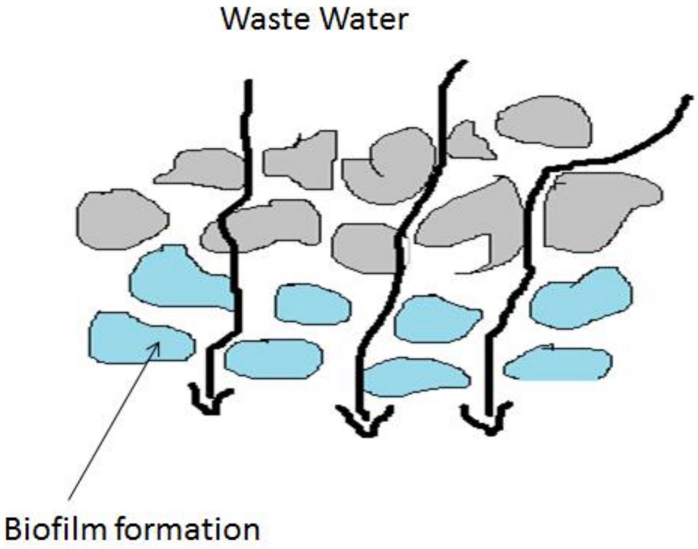

Figure 2.10 Biofilm formation due to percolation of waste water through any treatment media [Source: Mancl and Tao, 2011]

Research shows that Gaur et al's sand pea gravel bioreactors appended with pea gravel showed improvement in the relative removal of COD (chemical oxygen demand) for waste water containing turkey fat. Pea gravel served as a sieve that entrapped the fat containing organic matter [Gaur et al., 2009]. Thus, wastewater goes through physical, biological, and chemical processes in sand and fixed media bioreactor [Mancl and Slater, 2002; Hygnstrom et al., 2006].Soil act as a filtration media also for waste water.

Similarly bacteria and colloidal organic matter are strained by soil and the accumulation of the wastewater particles in the soil creates an even finer filter [Gerba et al., 1975]. Cation exchange complex, pH and aluminium oxides of soil facilitate the chemical process responsible for the treatment of wastewater [Gerba et al, 1975; Bohn et al., 1985;

Ujang and Henze, 2006]. Therefore in this thesis a Scanning Electron Microscopy elemental analysis of clay and gravel is performed to characterise their chemical features.

Bitton and Gerba, 1994 and Slater and Mancl, 2004 asserted the fact that unsaturated flow conditions in soil bioreactors was desirable for treatment of waste water. This result influenced the aim and objective of this particular thesis.

If the retention time of the water within the media is increased, this helps in increases interaction time of the microbes with the waste [Bitton and Gerba 1994]. This also appends the fact that there is an increase in adsorption with increase in residence time of waste water within the media [Ausland 2002]. This would certainly improve the treatment efficiency of the media [Ausland 2002].

In the unsaturated condition, initially water traverses through numerous random pathway through the media layers [Watson et al. 1994]. This initial effect allows the increase in probability of straining thus providing a better treatment in an unsaturated condition than a saturated condition [Gerba et al. 1975]. Unsaturated drier soils improve microbial adsorption capacity of the columns also [Lance et al, 1976]. These results also reiterate the aim and objectives of this thesis to study unsaturated flow electro-kinetics.

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Chapter 3

Materials And Experimental Methodology

3.1 Introduction

Experiments performed on sand and sand-gravel bioreactor columns with different media showed an effective treatment of waste water [Gaur 2009, Jing 2008]. They are also easy to make using locally available waste and natural materials and are cost effective. A schematic diagram of this type of reactor is shown below

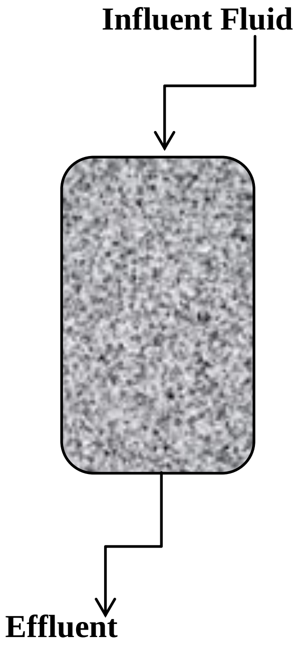

Figure 3.1 Fixed Media Packed Bed Reactor

R.S Gaur, 2009 has used bioreactors having media as sand and sand and pea gravels. Similarly, Tao Jing used felt, sand, peat and their combinations as media in the reactors. Fig 3.2 and Fig 3.3 shows the schematic diagram of reactors used by R S Gaur and Jing Tao in their experiments. Therefore, in this experiment similar packed bed reactors were used of different media.

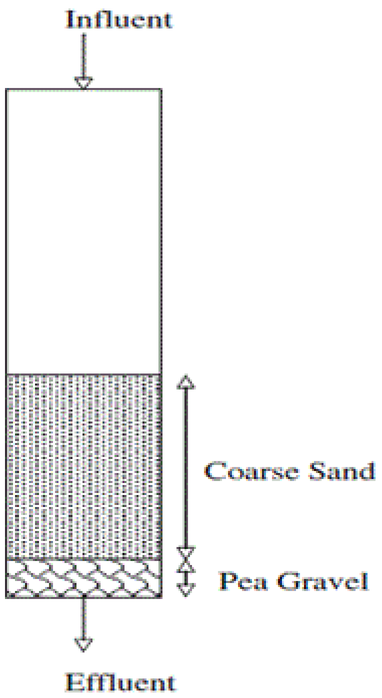

Figure 3.2 Sand Bioreactor with pea gravel cap [Source Rashmi et al., 2009]

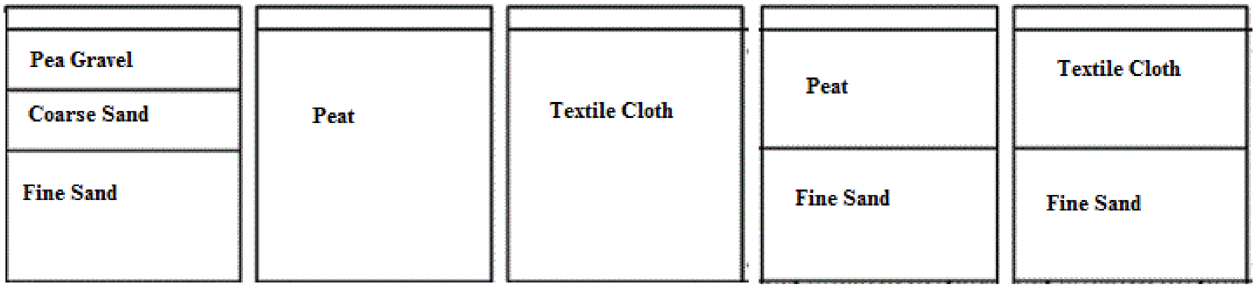

Figure 3.3 Different media bioreactors [Source Tao et al., 2008]

3.2 Materials and Equipments

1. The column bioreactors of size 30cm x 10cm x 10cm and 15cm x 10cm x 10cm are used for conducting the experiments. These reactors are made up of transparent acrylic sheets. Mayur Plastics Jodhpur had moulded these acrylic sheets into columns which are used as reactors. Thickness of the sheets is 2mm. Exact precision of size has been taken care while manufacturing these reactors. Fig. 3.4 shows a gravel column bioreactor used for the experiments conducted here.

Figure 3.4 Thirty centimetre acrylic column filled with gravels

2. Peristaltic pump of Ravel Hiteks Pvt. Ltd. of model RH-P100VS-100-PC has been used for dosage of influent water. Technical details of the pump are as below[Ravel Peristaltic Pump Manual]:

Make & Model : RAVEL , RH-P100VS-100-PC
No. of channels : One
Flow Rate : 0. 1 to 99.9ml/min (1000 steps of variable flow)
Tubing : 3 mm I.D. with 1.5 mm Wall thickness
Set(batch) Volume : 0 to 999.9 ml
Interval Time : 0 to 99.9 seconds
Motor : DC Stepper Motor (Continuous Duty)
Pressure : Up to 2 Kg / Sq.cm
Accuracy : +/- 1 %
Supply : 230v, 50Hz, single phase AC supply
Dimension : 120 x 240 x 280mm (H x W x D)
Weight : 10 Kg. (App.)

Picture shown below is of the peristaltic pump used.

Figure 3.5 Peristaltic Pump used as a part of the experimental set up showing readings monitor and the water carrying pipe.

3. pH meter(pH700) and conductivity meter(CON 700) of Eutech Instruments has been used for measurement of pH and electrical conductivity of the water.

Figures 3.6 pH and Conductivity Meter

[Source http://www.eutechinst.com/pdt_type_con_con700.html]

The devices were appended with electrodes as required to perform the analysis.

4. K- type thermocouples used for the measurement of temperature have been procured from Unitech Instrumentation, Mumbai. Real time data of temperature is taken using NI Lab View 2011. Wireless Sensor Nodes (WSN) 3212 and a Gateway (S.No. 1548d11 NI 9792) of NI for computer interface is used for the

whole process of data acquisition. Fig. 3.7 illustrated the laptop computer monitor showing the NI Graphical User Interface for the real time temperature plots. Fig 3.7 illustrates how the thermocouples were inserted to perform the temperature measurement exercise.

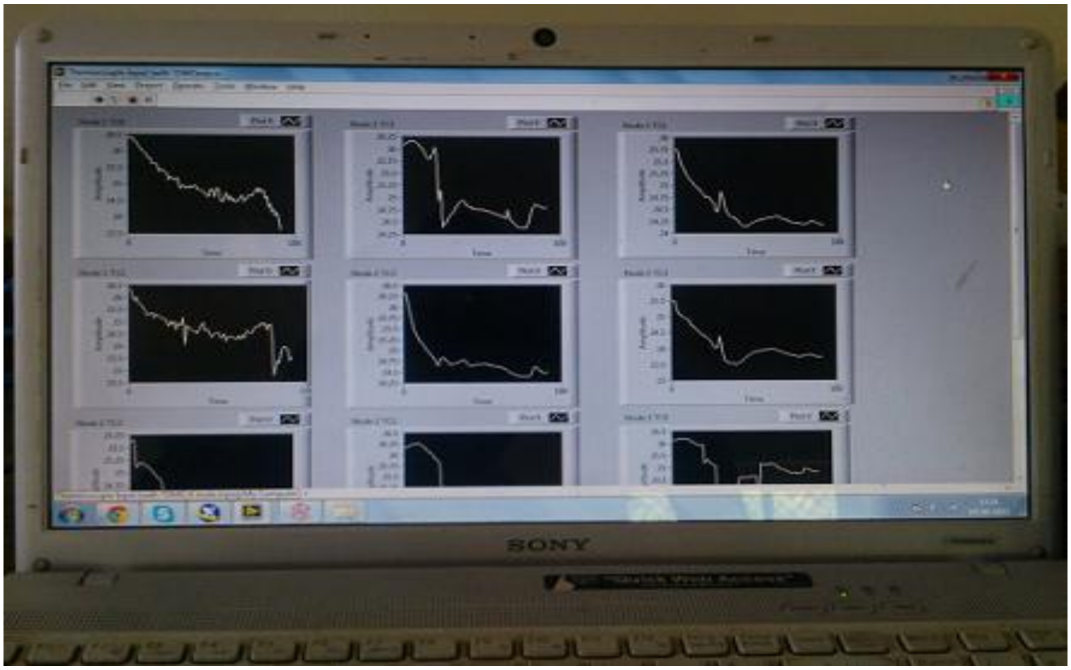

Figure 3.7 Laptop showing the NI Graphs used for real time data acquisition of temperature

Figure 3.8 Thermocouples inserted in the reactor

5. A table stand for supporting the acrylic column reactors was made. These carried a wooden base as shown and a white cloth mesh was at the lowest part of the media layer to prevent media from flowing off the columns.

Figure 3.9 The table stand support for conducting the experiments

6. For the analysis of COD thermoreactor Spectroquant TR 320 of Merck, Germany has been used. It has the ability to heat the 12 samples in one go for digestion at a temperature of 148˚C for two hours. Fig. 3.10 illustrates its image .

Figure 3.10 Spectroquant TR 320 Thermoreactor

7. Other small things used are a cotton clothes for packing the base of the column to prevent flow of materials from the reactor, beakers of different sizes to collect effluent water, test tubes for storing the effluent samples for testing.

3.3 Schematic diagram of whole setup

Fig 3.11illustrates the whole setup for the experiments performed. The peristaltic pump extracts the water from the source using the inlet pipe. Water thus extracted is dosed on to the column reactor where the water is intended to flow downwards under the effect of gravity and traverses through the media in the column. Here the media column is 30 cm in height made of acrylic. Water is collected at the bottom of the column reactor using a gyrated beaker named the effluent collector.

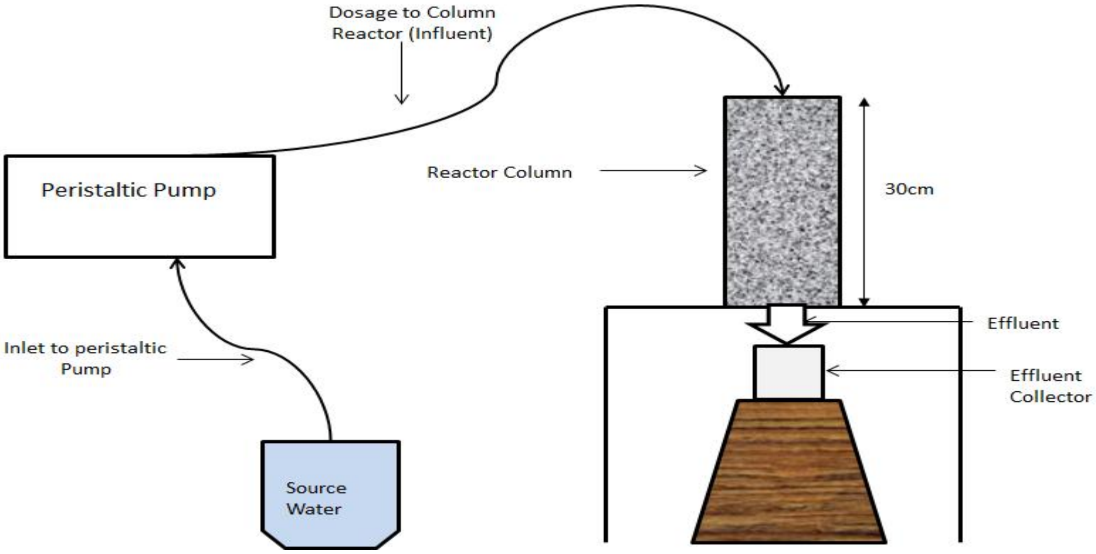

Figure 3.11 Schematics of the experimental setup used in this study to simulate gravity based column bioreactors.

3.4 Materials used in reactor

From the literature survey done it has been found that bioreactors can be made of different natural materials such as sand, pea gravels, peat, textiles etc. Here the bioreactors are made up of organic and inorganic materials respectively.

Organic materials

1. **Sawdust:** It is procured from the waste of local carpenter shop in Jodhpur. This is sieved from 1mm hole before using making approximate size of each particle equal or less than a mm. Sawdust used is illustrated below.

Figure 3.12 Sawdust

Acacia or Babool sawdust is used. About 21.19 % wood used in Jodhpur is Acacia [Pasha 2008]. It is cheaper than other varieties and can be easily available here in this part of Rajasthan, India [Pasha 2008].

2. **Moringa Oleifera (Drumsticks):** It is obtained from the local vegetable market, Ratanada Circle. Before using it in the reactor it was smashed into sheets and dried at 50˚C for 3 days such that no moisture is left. Then they are washed to remove organic carbon present due to burning off in the sun. These were again dried at room temperature and cut in 3-4 cm sheets. Below shown are the pictures of Moringa in the three different states before drying, after drying at 50˚C for 3 days and crushed 3-4 cm pieces used in the bio reactor columns.

Figure 3.13 Moringa before drying

Figure 3.14 Moringa after Drying

Figure 3.15 Crushed Moringa

Inorganic Materials

1. **Gravels:** These are obtained from a local stone crusher mill in Jodhpur. Size of the gravel is 6mm approximately. Gravels were washed and then dried before using them in the reactor so that dusts attached with them get removed. Picture shown in Fig. 3.16 is the type of gravels used.

Figure 3.16 Top view of the gravels in the columns used for the experiments

Characterization using SEM (Scanning Electron Microscopy) has also been conducted for it. The results and microscopic view obtained from it are as below

Element	Weight%	Atomic%
C K	18.97	27.30
O K	50.24	54.29
Na K	1.80	1.35
Al K	4.07	2.61
Si K	20.99	12.92
K K	2.36	1.04
Fe K	1.57	0.49
Totals	100.00	100.00

Table 3.1 Scanning Electron Microscopy Results for the elemental analysis of the gravels used.

Figure 3.17 Microscopic view of gravels

2. **Clay:** Ball clay is used in the reactor. It is procured from Ahmed & Co. a local vendor in Jodhpur. Its characterization using SEM shows the following results.

Element	Weight%	Atomic%
C K	18.61	27.60
O K	52.69	58.64
Mg K	1.48	1.08
Al K	1.00	0.66
Si K	2.32	1.47
K K	0.35	0.16
Ca K	22.99	10.21
Fe K	0.56	0.18
Totals	100.00	100.00

Table 3.2 Scanning Electron Microscopy results for the chemical analysis of ball clay

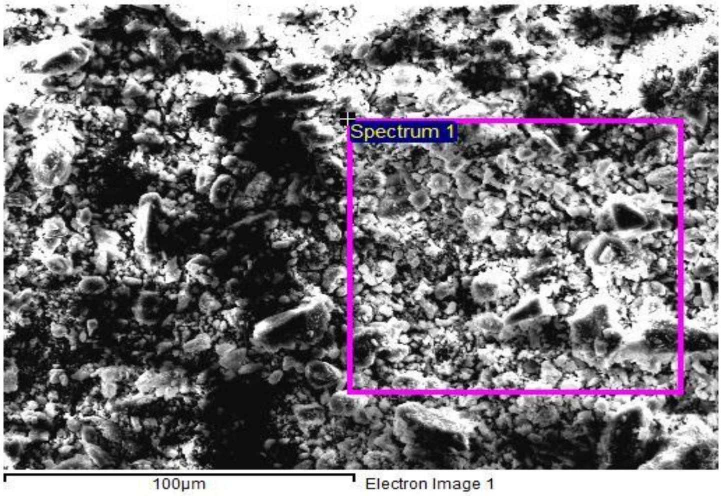

Figure 3.18 Microscopic view of ball clay

3. **Textile or cloth:** Another inorganic material used was cloth taken from the waste of a local tailor shop in Jodhpur. The waste contains cotton clothes, Terri cotton and fibre clothes.

Figure 3.19 Textile cloth pieces used in the experiments

3.5 Complete Setup

While conducting experiments the whole set up using all the materials and devices discussed above is shown below in Fig. 3.20.

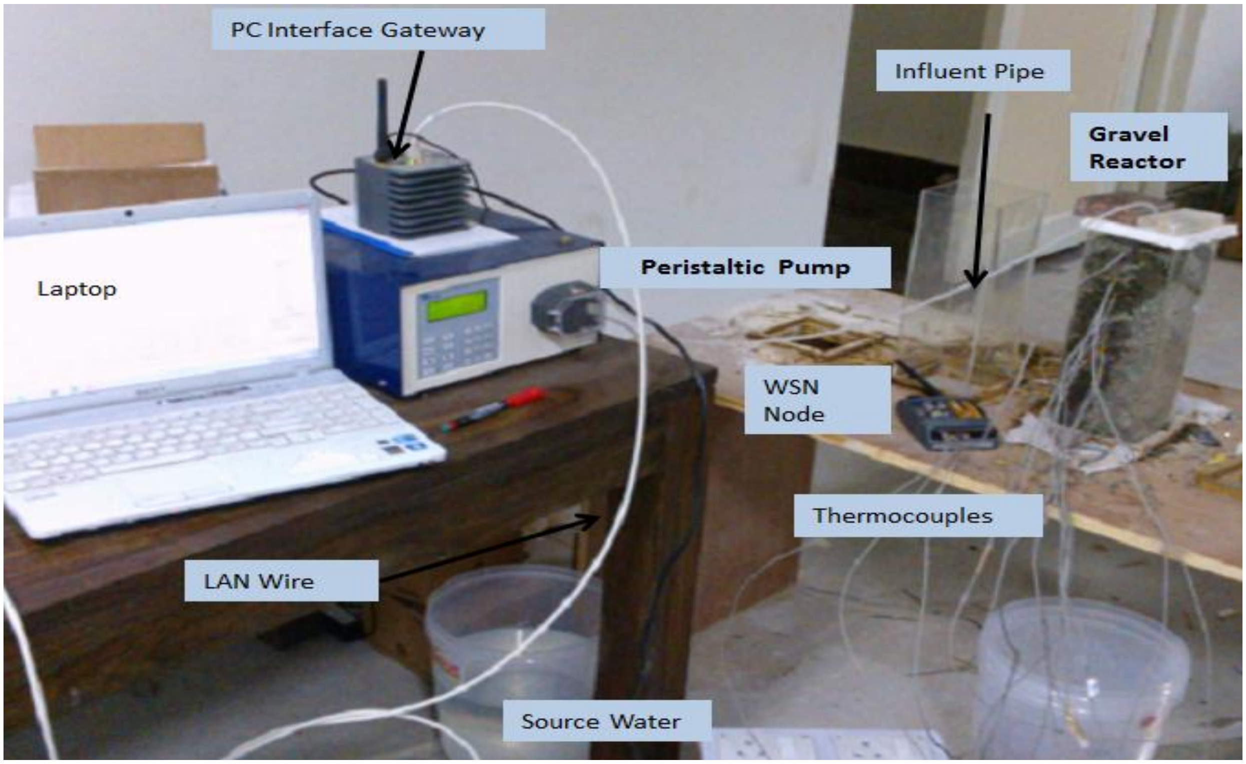

Figure 3.20 Experimental Setup

3.6 Experimental Methods

After setting the whole setup involving reactor and other components as shown in Fig. 3.20 various electro-kinetic parameters were measured for influent and effluent water. Parameters studied are pH of influent and effluent fluid, Electrical Conductivity, COD (Chemical Oxygen Demand) and temperature change with height and time.

Tests on these parameters and change in their behaviour were observed by changing Column height. It is the height up to which media is present in the acrylic columns. Here, experiments are conducted for two heights i.e.

a) 15cm
b) 30cm

These respective heights of gravel are shown in Fig. 3.21 and Fig. 3.22

Figure 3.21 Gravel reactor of height 15cm used in this study

Figure 3.22 Gravel reactor of column height 30cm used in the experiments

Flow Rate was controlled by peristaltic pump. Experiments were done for two distinct flow rates 10ml/min, 50ml/min, respectively.

Experimental Procedure:

1) Initially a media is selected for reactor from the materials discussed above.
2) Acrylic columns are then filled with the media selected so that they can act as a reactor.

3) A column height is selected to perform experiment on.
4) Then for the particular height and media two experiments are done. One with 10ml/min dosage and another one for 50ml/min water dosage into the reactor. It is taken care that all experiments were performed at a 32^{o}C room temperature.
5) After the dosage of influent in the reactor effluent coming out is collected in the measuring beaker kept beneath as shown in Fig. 3.23.

Figure 3.23 Discharged effluent was collected in a beaker and noted consecutively for calculation of cumulative time as well as for flow rate of effluent

6) Samples of effluent are taken after every 50ml or 100ml collection and time is also noted for each collection so that percolation rate can be measured. Total number of effluent samples collected for each case is 30 or more.
7) Then tests for pH, conductivity and COD are performed for the samples collected. As shown in Fig. 3.24.

Figure 3.24 Conductivity Measurement

8) For the calculation of temperature gradient thermocouples are inserted in the reactor and their real time value is obtained using NI devices as shown in fig. 3.8 and 3.7 respectively. The inlet water temperature was an average of 32°C.
9) After that by changing the height and keeping media same water is dosed for two different specific flow rate until the dry or unsaturated columns are wet or saturated by flowing water.
10) Similarly, same experiments are conducted for other media by changing height and flow rate.

3.7 Statistical Analysis Methods

The water when percolating through the dry or unsaturated bioreactor undergoes random processes. For characterizing the random processes and variables, stochastic methods are incorporated [Benjamin and Cornell 1970]. The bioreactor induces random changes in the properties of influent water percolating through the media within the acrylic columns of gravel, clay, sawdust, and *Moringa*.

The electro kinetic properties of the water are given more importance since solute fluxes through a porous media depend on the pressure gradient, electrical conductivity change, and ionic mobility [Churaev 2000]. It is very clear from the above discussions that all the materials used are porous in nature and hence can be simulated using Darcy's Law. Therefore it is known that flow rate is directly proportional to the pressure gradient. Therefore in this experimental study flow rate will substitute pressure gradient term and is assumed to express all the required properties related to pressure variations. It is assumed that ionic mobility expressed in terms of pH change Y can be expressed as [Ang and Tang 2012]

$Y = f(X_1, X_2 \ldots\ldots\ldots, X_k)$ ……………………………………………..Eq. 1

Where X_1, X_2 …. X_k represent all other random variables influencing the pH change. In this assumption, caution needs to be exercised since these influencing random variable can be correlated to each other. The covariance between the variable can be expressed as illustrated as shown in Eq. 2 [Soboyejo 2012]

$$\begin{array}{c|ccccc|} & X_1 & X_2 & . & . & X_k \\ X_1 & {\sigma_{X_1}}^2 & \sigma_{X_2}\sigma_{X_1}. & . & . & \sigma_{X_k}\sigma_{X_1} \\ X_2 & \sigma_{X_1}\sigma_{X_2} & {\sigma_{X_2}}^2 & . & . & \sigma_{X_k}\sigma_{X_2} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ X_k & \sigma_{X_1}\sigma_{X_k} & \sigma_{X_2}\sigma_{X_k} & . & . & {\sigma_{X_k}}^2 \end{array}$$ …………………………………Eq. 2

The Correlation Coefficent between the variables can be expressed as

$$\rho_{X_i X_j} = \frac{Cov(X_i X_j)}{\sigma_{X_i}\sigma_{X_j}}$$ …………………………………………………..Eq. 3

It can be better expressed as

$$\begin{array}{c|ccccc|} & X_1 & X_2 & . & . & X_k \\ X_1 & 1 & \rho_{X_1X_2} & . & . & \rho_{X_kX_1} \\ X_2 & \rho_{X_2X_1} & 1 & . & . & \rho_{X_kX_2} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ X_k & \rho_{X_1X_k} & \rho_{X_2X_k} & . & . & 1 \end{array} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. 4}$$

In order to do any regression, it is necessary to convert all the correlated or dependent predictor random variables X_1, X_2………, X_k to completely non-correlated or independent predictor variables. These new independent variables are referred to as V_1, V_2………, V_k. Here variables like column height, volume flow rate, change in conductivity etc. may serve as dependent or correlated random variables. Mathematical procedures are developed for the conversion of each independent Xi predictor variable to new independent Vi predictor variable for i = 1, 2……., k. In other words, if the required response variable is Y, here it may be change in pH in influent and effluent water. Therefore [Benjamin and Cornell 1970],

$Y = f_1 (X_1, X_2\ldots\ldots, X_k) = f_2 (V_1, V_2\ldots\ldots, V_k)$ ………………………………Eq. 5

Here the calculations are performed using Minitab 16. Theoretically conversion of dependent to independent variables is performed as follows.

The data in the (k x k) matrix formulation in Eq. 4, shows that the data for the statistical correlation coefficients, between any pair of predictor variables X_i and X_j, where $\rho_{X_jX_i} = \rho_{X_iX_j}\ where\ \ i \neq j$. When i = j, we have the value of the statistical correlation coefficient as 1.0; these are indicated as 1 along the diagonal of the (k x k) matrix in Eq 4.

A new vector ϕ which satisfies $X\phi = \lambda\phi$ for some number λ is called an eigenvector of the matrix X. λ is called the eigenvalue of X corresponding to ϕ[Halder and Mahadevan 2000].

Therefore

$(X - \lambda I)\phi = 0.$ ……………………………………………………………………Eq. 6

Here the value of (X - λI) takes ϕ towards a null vector, and hence (X - λI) should not have an inverse and its determinant must be 0.

$\det(M - \lambda I) = 0$ ……………………………………………………………………..Eq. 7

Here Eq. 7 is the characteristic equation of the X. Eq. 7 can be rewritten as [Soboyejo 2012]

$$\begin{vmatrix} (1-\lambda_i) & \rho_{12} & . & . & \rho_{1k_1} \\ \rho_{21} & (1-\lambda_i) & . & . & \rho_{2k} \\ . & . & . & . & . \\ . & . & . & . & . \\ \rho_{k1} & \rho_{k2} & . & . & (1-\lambda_i) \end{vmatrix} = 0$$

……………………………………………….Eq. 8

The solution of the Eq. 8 gives the λ_is or eigen values [Haldhar and Mahadevan 2000]. This is the variance of the new uncorrelated independent variable V_i for i = 1, 2, …….., k. Eq. 6 can be represented as

$$\begin{bmatrix} (1-\lambda_i) & \rho_{12} & . & . & \rho_{1k_1} \\ \rho_{21} & (1-\lambda_i) & . & . & \rho_{2k} \\ . & . & . & . & . \\ . & . & . & . & . \\ \rho_{k1} & \rho_{k2} & . & . & (1-\lambda_i) \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ . \\ . \\ \theta_k \end{bmatrix} = 0$$

……………………………………….Eq. 9

For each eigenvalue , λ_i, the corresponding eigenvectors are $[\theta_1^i \ \ \theta_2^i \ \ .... \ \ \theta_k^i]^T$.

The eigenvectors are $\begin{bmatrix} \theta_1^1 & \theta_1^2 & . & . & \theta_1^k \\ \theta_2^1 & \theta_2^2 & . & . & \theta_2^k \\ . & . & . & . & . \\ . & . & . & . & . \\ \theta_k^1 & \theta_k^2 & . & . & \theta_k^k \end{bmatrix}$

Normalization of eigen values can be performed as shown below [Soboyejo 2012]

$$\left\{\frac{\left(\theta_1^i\right)^2}{\left(\theta_1^i\right)^2+\left(\theta_2^i\right)^2+\ldots\ldots\ldots\left(\theta_k^i\right)^2}\right\}^{\frac{1}{2}}$$

$$\left\{\frac{\left(\theta_2^i\right)^2}{\left(\theta_1^i\right)^2+\left(\theta_2^i\right)^2+\ldots\ldots\ldots\left(\theta_k^i\right)^2}\right\}^{\frac{1}{2}}$$

$$\left\{\frac{\left(\theta_3^i\right)^2}{\left(\theta_1^i\right)^2+\left(\theta_2^i\right)^2+\ldots\ldots\ldots\left(\theta_k^i\right)^2}\right\}^{\frac{1}{2}}$$

$$for \quad i=1,\ 2,3 \quad (k=k) \qquad \text{……………………………………………Eq. 10}$$

Eq. 10 represents the normalized eigen vectors and can be represented by [T]. Now the random variables X_i can be converted to new independent variable V_i as shown in Eq. 11 below [Soboyejo 2012].

$$\underset{(k\times 1)}{\begin{bmatrix} \dfrac{V_1-0}{\sqrt{\lambda_1}} \\ \dfrac{V_2-0}{\sqrt{\lambda_2}} \\ \cdot \\ \cdot \\ \dfrac{V_k-0}{\sqrt{\lambda_k}} \end{bmatrix}} = \underset{(k\times k)}{[T]^{-1}} \underset{(k\times 1)}{\begin{bmatrix} \left(\dfrac{X_1-\mu_{X_1}}{\sigma_{X_1}}\right) \\ \left(\dfrac{X_2-\mu_{X_2}}{\sigma_{X_2}}\right) \\ \cdot \\ \cdot \\ \left(\dfrac{X_k-\mu_{X_k}}{\sigma_{X_k}}\right) \end{bmatrix}} \qquad \text{…………………………………………Eq. 11}$$

Eq. 11 gives the standardized form of the relationship to remove the correlation from the random variables collected from the experiments conducted as mentioned above.

Therefore the new regression equations with the independent variables will be written as [Haldhar and Mahadevan 2000, Soboyejo, 2012],

$$\frac{X_i - \mu_{X_i}}{\sigma_{X_i}} = f_i(V_1, V_2 ....V_k)$$

$$X_i = \mu_{X_i} + \sigma_{X_i} f_i(V_1, V_2 ....V_k) \;\; for \;\; i = 1,2,.......k \qquad \text{.........................Eq. 12}$$

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Chapter 4

Results and Data Analysis

In this chapter motivation is derived from the fact that drier soils have larger adsorption capacities in column bioreactors [Lance et al, 1976]. There is an increase in retention time of wastewater in unsaturated or dry media that brings constituents closer to the porous media surface that leads to improvement in mechanical straining, and they also are responsible for better aerobic conditions. Therefore in this thesis importance is provided to the property variations in the transition period from unsaturated or dry media condition to wet or saturated media condition.

Darcy's Law states that in a porous media Flow rate (Q) is directly proportional to change in hydraulic head or pressure head (ΔP), Cross-section area of flow and inversely proportional to the length of the column. This is valid as long as flow is laminar. Mathematically,

$$Q = -k \Delta PA/L \qquad 1$$

In this study gravitational flow reactor is considered. Water is added from the top of the column and effluent is collected beneath. During the treatment processes for which these bioreactors are meant for, there is mass transport with absorption, adsorption and chemical change occurring in water. Therefore the experiments conducted basically illustrate irreversible nature. Onsager in 1931 stated that chemical flux transport can be expressed as entropy generated.

The bioreactor system is to be utilized for water purification. The mobility of ions determines conductivity. The degree of purification plays a major role in transport of ions. This means a pH change in influent and effluent water can help in study the transport of ions. Churaev 2000, gave a linear relationship between molar fluxes as a function of pressure gradient and concentration. The porous material considered here are gravels, clay, moringa sheets, and textiles show electro-kinetic properties when they came in contact with water [Plappally, 2010].

Molar fluxes are linear function of change in pressure gradient and change in electrical conductivity [Churaev 2000]. Since the pressure gradient is directly proportional to flow rate according to Darcy's law. In this thesis flow rate is used as a major variable to predict electro-kinetic properties. Therefore the main objective in this thesis is to predict electro-kinetic properties as a function of flow rate, conductivity change, length (here height of column) and also the time taken by water to make the dry or unsaturated columns wet or saturated.

Prigogine also stated that the irreversibility are due to chemical transport within a porous media occurring for a specified change of time. This also meant that a change in structure of the column due to a specific flow occurring for a specific time will change the transport of chemicals through material.

Experiment 1:
Size =30cm Flow Rate: 10ml/min(Gravels)
Graphical Results:

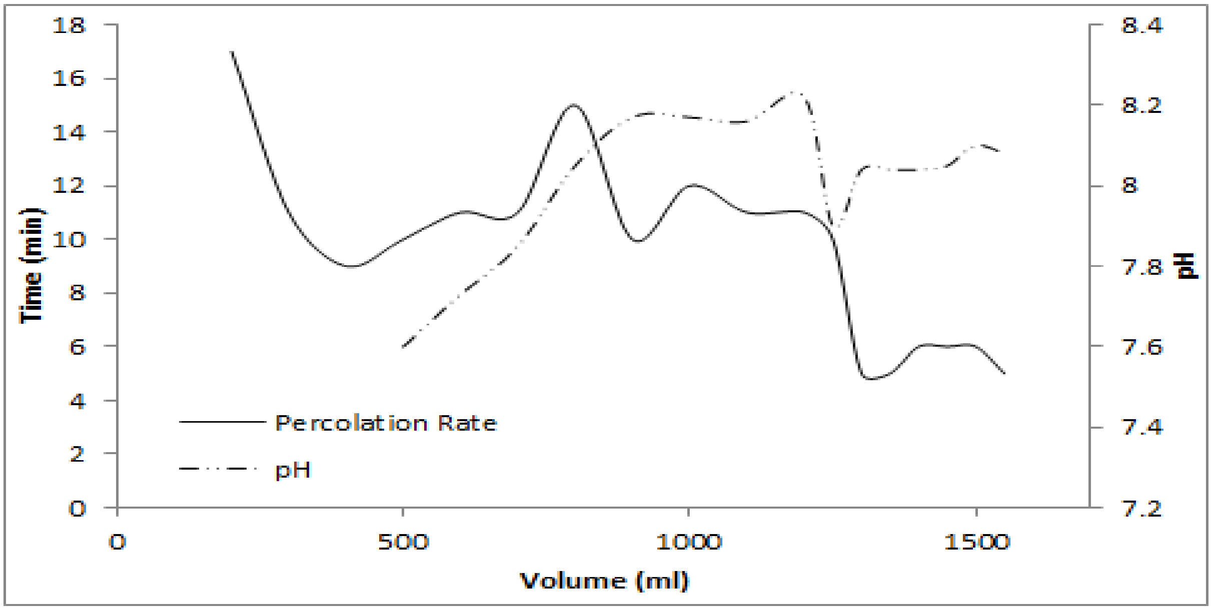

Figure 4.1: Variation of pH as a function of time and water that percolated through the gravel column reactor

From Fig. 1, with increase in the time of water flow through the gravel bioreactor an overall improvement is pH of the effluent is noted. Average influent pH is 7.7. An improvement in the flow with time decreases the pH of the effluent. This phenomenon may be due to adsorption or trapping of the ions thus increasing their residence time of ions within the bioreactor [Ausland 2002]. This is also the reason for a slight decrease in electrical conductivity which can be observed for these experiments in Fig. 4.2 with a slow influent flowrate of 10ml/min through gravels.

Similarly in the initial dry or unsaturated condition, water may traverse through numerous random pathway washing down alkaline salts off the gravel surface [Watson et al. 1994]. Thus increasing the pH in the effluent water collected in the beaker. With time, once water has found his path through the gravel a slight decrease in pH is observed. This means that water almost washed all the alkaline generating surface compounds off the gravels and as time passed gravel have started to contribute to treatment.

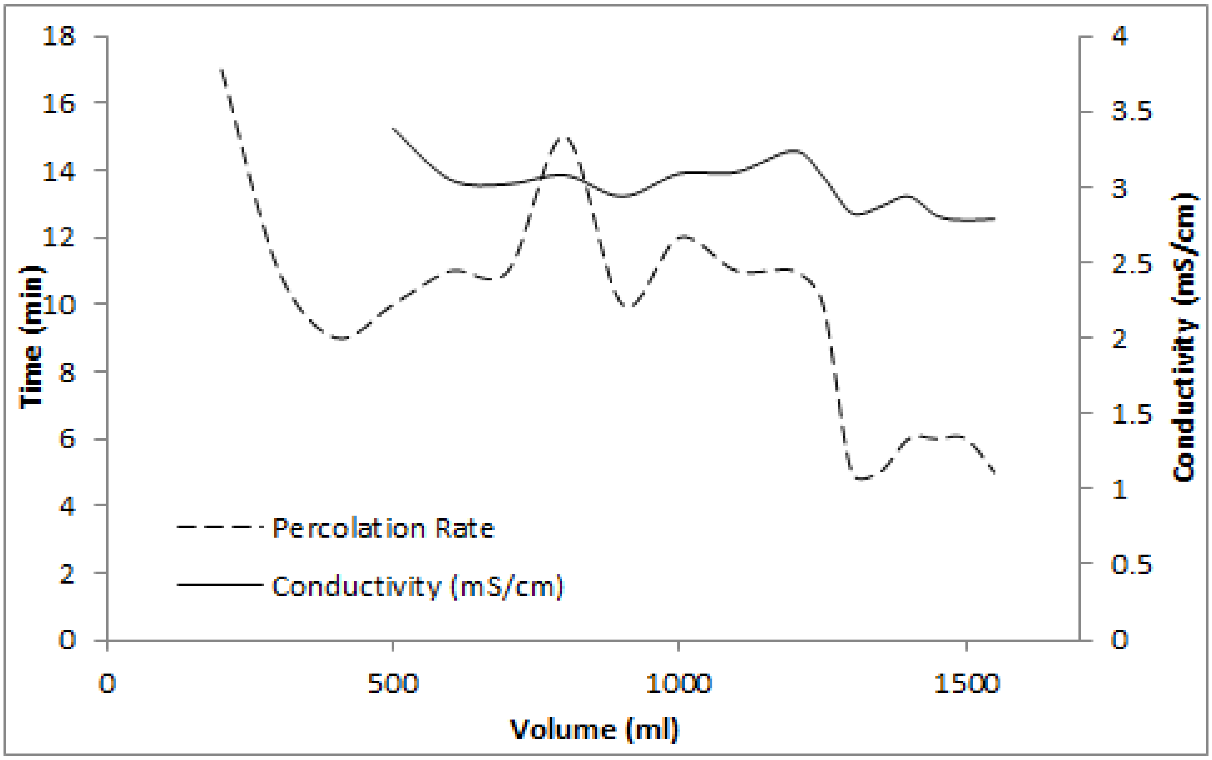

Figure 4.2: Slight decrease in conductivity with increase in cumulative amount of water flowing through gravel bio reactor at a flow rate of 10ml/min.

Experiment 2:

Size =30cm Flow Rate: 50ml/min

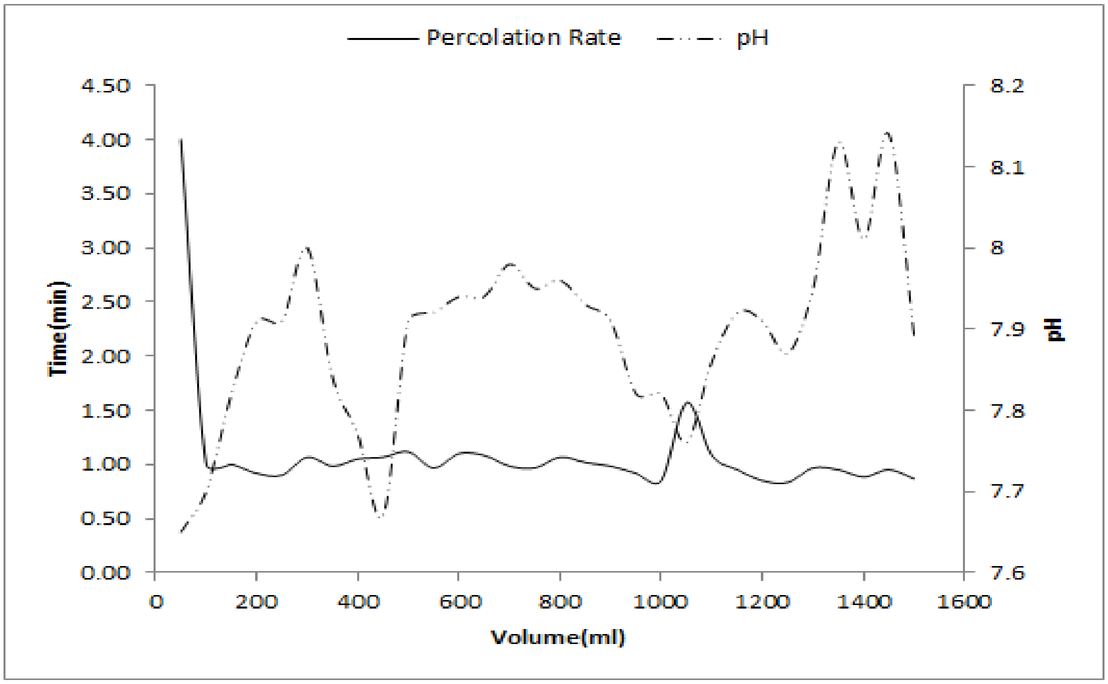

Figure 4.3: The Variation in pH at a flow rate of 50ml/min through a gravel column of 30cm.

Increase in flow rate can lead to decrease in interaction time with the gravel. Also an increase in velocity can decrease in mobility of ions with time. This may lead to a constant pH change. Thus the water flow through the gravel may lead to steeper decrease in electrical conductivity of the effluent. This is clearly illustrated in Fig. 4.4 and Fig 4.3 respectively.

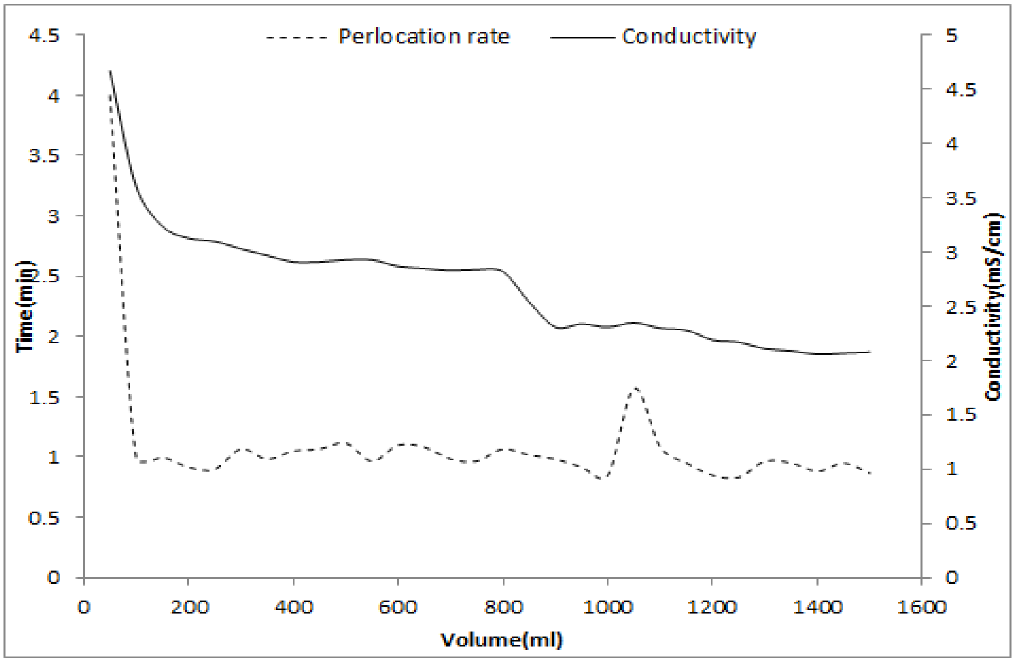

Figure 4.4: Steep decrease in electrical conductivity at a high dosage rate of 50ml/min through gravel bio reactor.

The amount of organic compounds in water decreased with time. This is represented by decreasing curve of COD with increase in percolation rate. Also COD decreased with decrease in time for every 50ml filtrate collection. This results shown in Fig 4.5, is specific to a flow rate of 50ml/min and a gravel reactor column of 30cm .

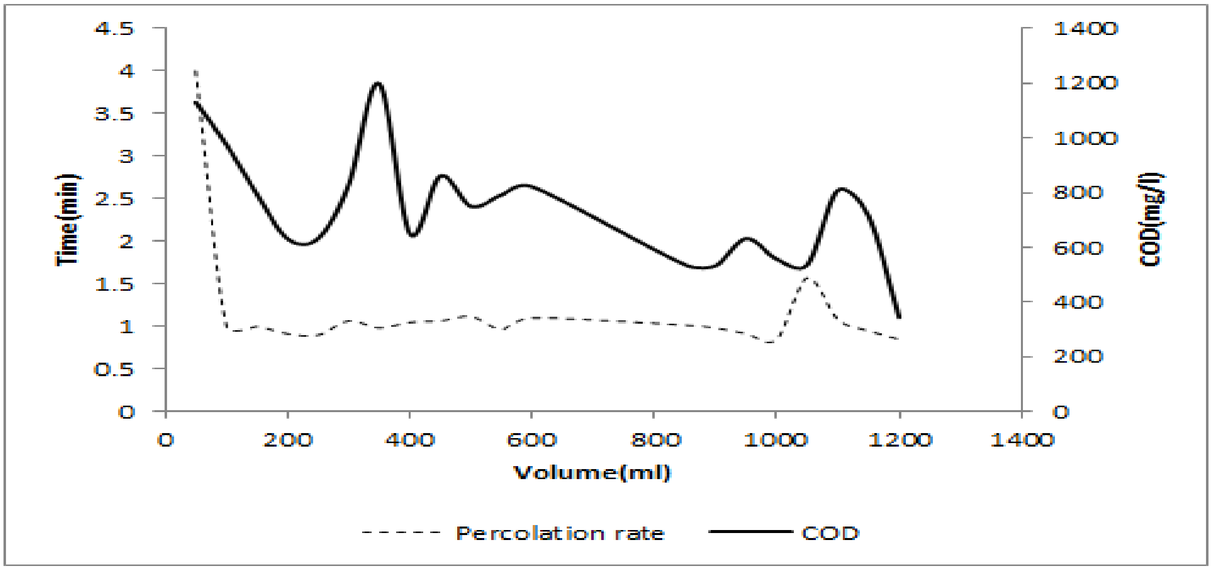

Figure 4.5: Variation of amount of organic compounds in the influent.

From Fig. 4.6, it can be observed that the ratio of influent to effluent COD or the COD ratio is increasing with time for every 50ml of filtrate collected. This is an indication of the positive treatment characteristics of a gravel reactor.

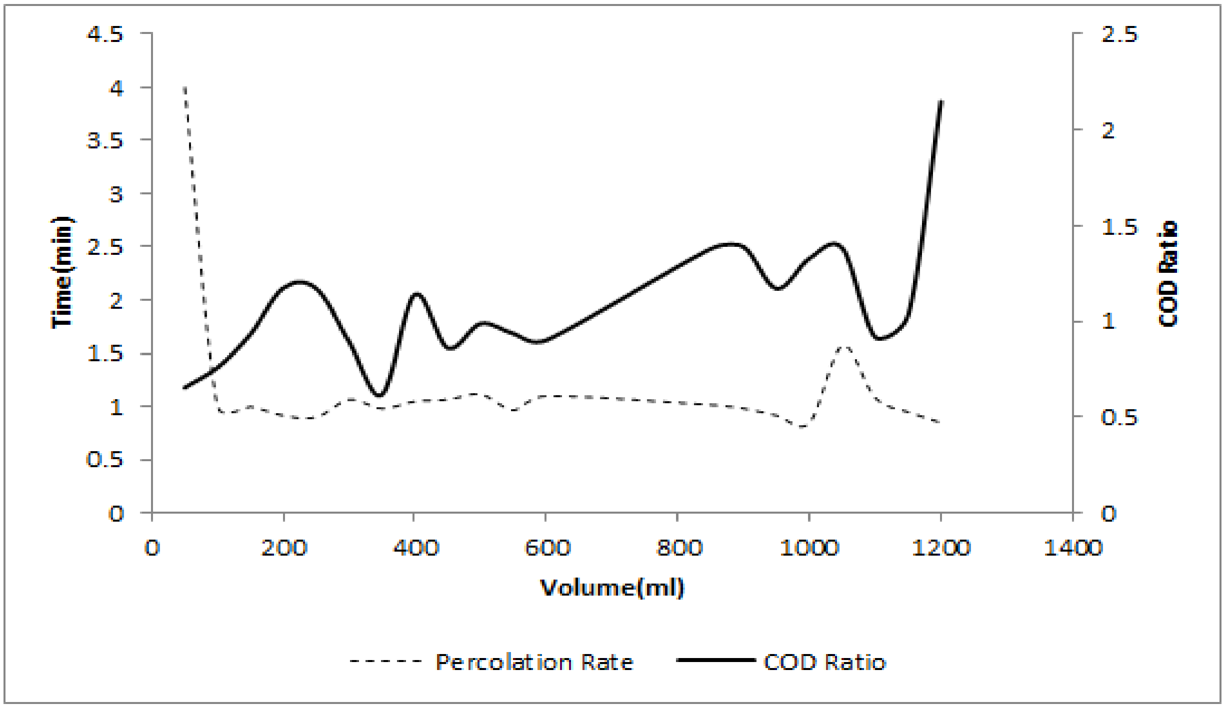

Figure 4.6: The improvement in COD ratio with increase in cumulative discharge.

Experiment 3:

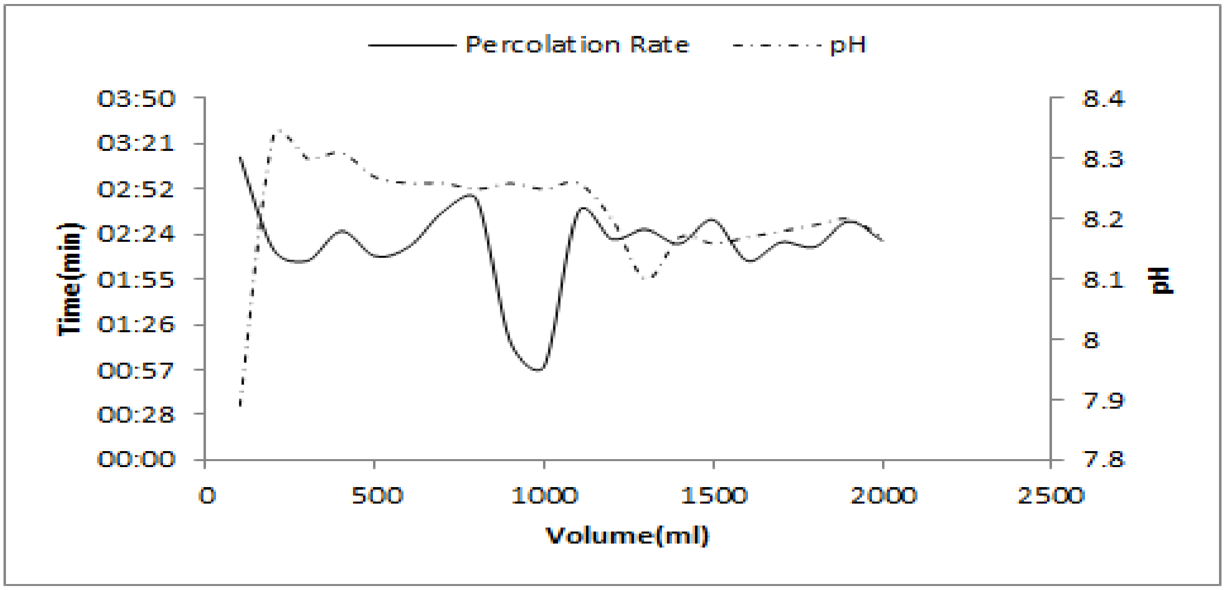

Fig. 4.7: The pH of the effluent is plotted as function of time and cumulative discharge volume for gravels at a dosage rate of 50ml/min and 15cm column height

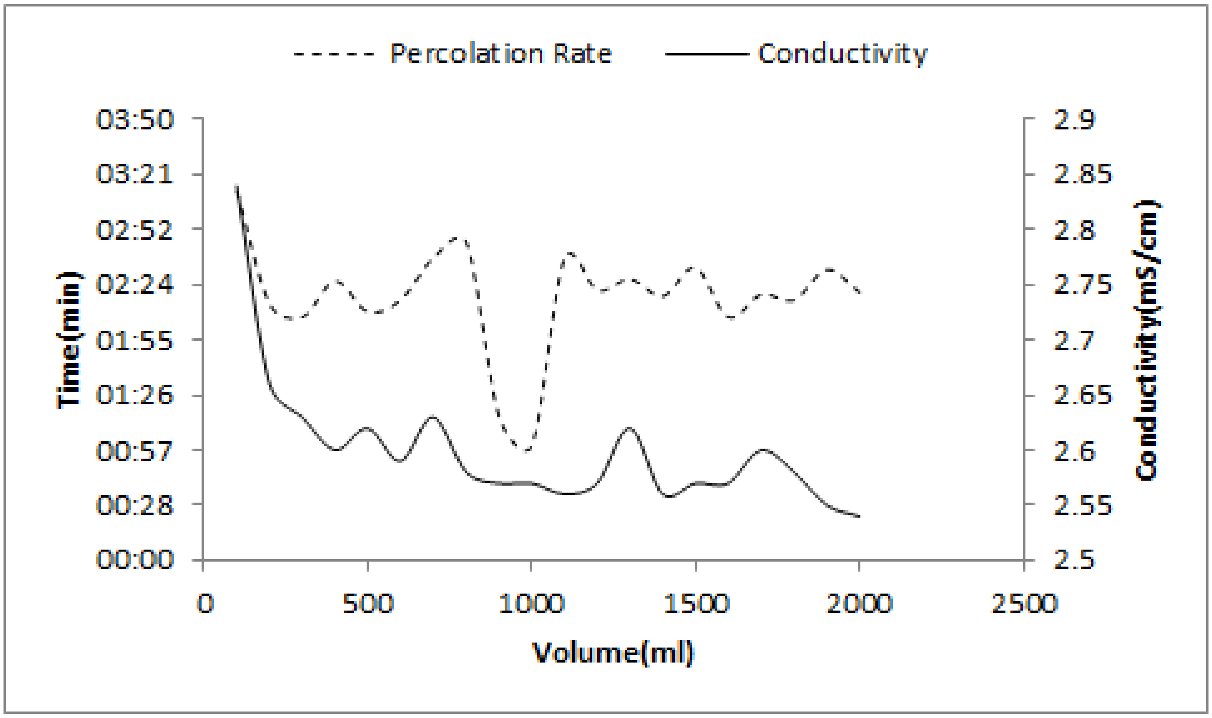

Fig 4.8 The electrical conductivity of the effluent is plotted as function of time and cumulative discharge volume for gravels at a dosage rate of 50ml/min

Experiment 4:

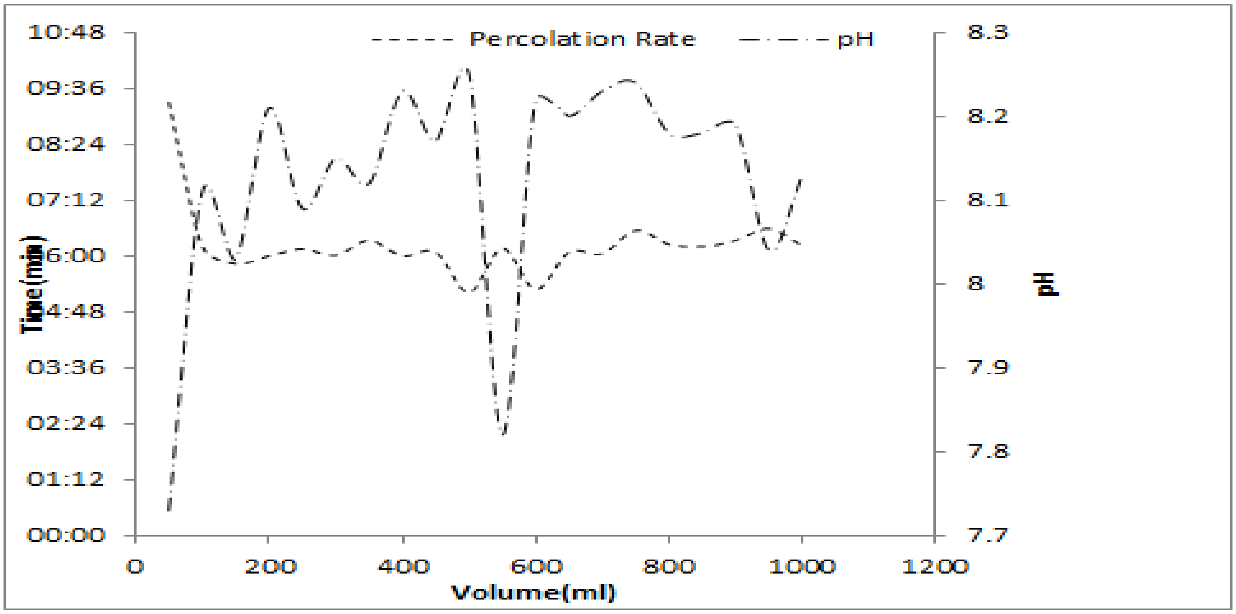

Fig 4.9: The pH of the effluent is plotted as function of time and cumulative discharge volume for gravels at a dosage rate of 10ml/min and 15cm column height.

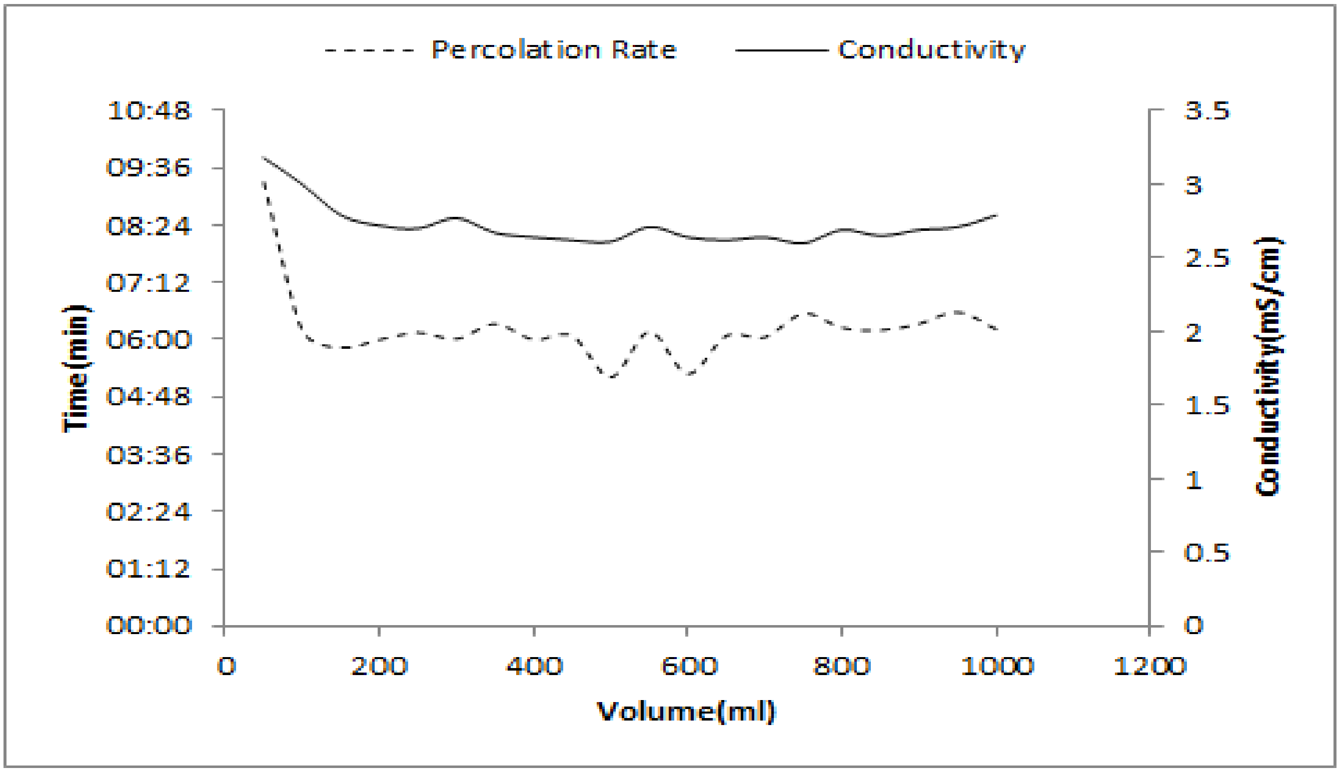

Fig 4.10: The electrical conductivity of the effluent is plotted as function of time and cumulative discharge volume for gravels at a dosage rate of 10ml/min

Experiment 5:

Media :Clay It took 2hr 35 min to saturate a clay column of 30cm x 10cm x10cm at a dosage rate of 10ml/min. The water after initial percolation of the dry clay started to form the initial effluent in 4.01min. Clay acted as confining layer as after saturation water got confined on upper portion and negligible seepage took place after that with time

Fig. 4.11: Due to saturation the air within the clay escaped and got saturated and was transported downwards.

Experiment 6:
Media: Saw Dust

It took 46min 14 secs to saturate a sawdust column of 30cm x 10cm x10cm at a dosage rate of 50ml/min. The water after initial percolation of the dry sawdust started to form the initial effluent in 46.14min. This also shows that clay is more permeable then sawdust. This means that sawdust provides more residence time for water treatment.

Observation:

a) Gradual saturation layer by layer or plug flow is observed when water percolated down with a constant velocity through sawdust. By observing the results in Fig 4.12, it can be said that a same residence time exists at a specific cross section of the column reactor where dry and wet regions meet.

b) Quality of water coming out is not good

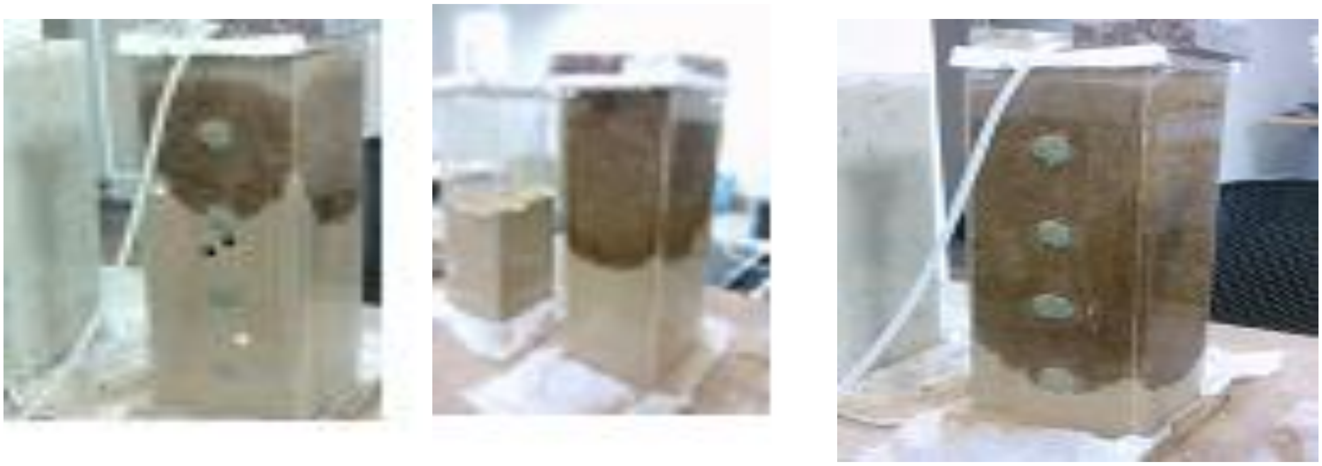

Figure 4.12 Gradual saturation layer by layer or plug flow is observed when water percolated down with a constant velocity through sawdust

Experiment 7:
Media: Clothes

The water after initial percolation of the dry cloth textile fabric started to form the initial effluent in 3.42min. The dosage rate in this case was 50ml/min for a 15cm column.

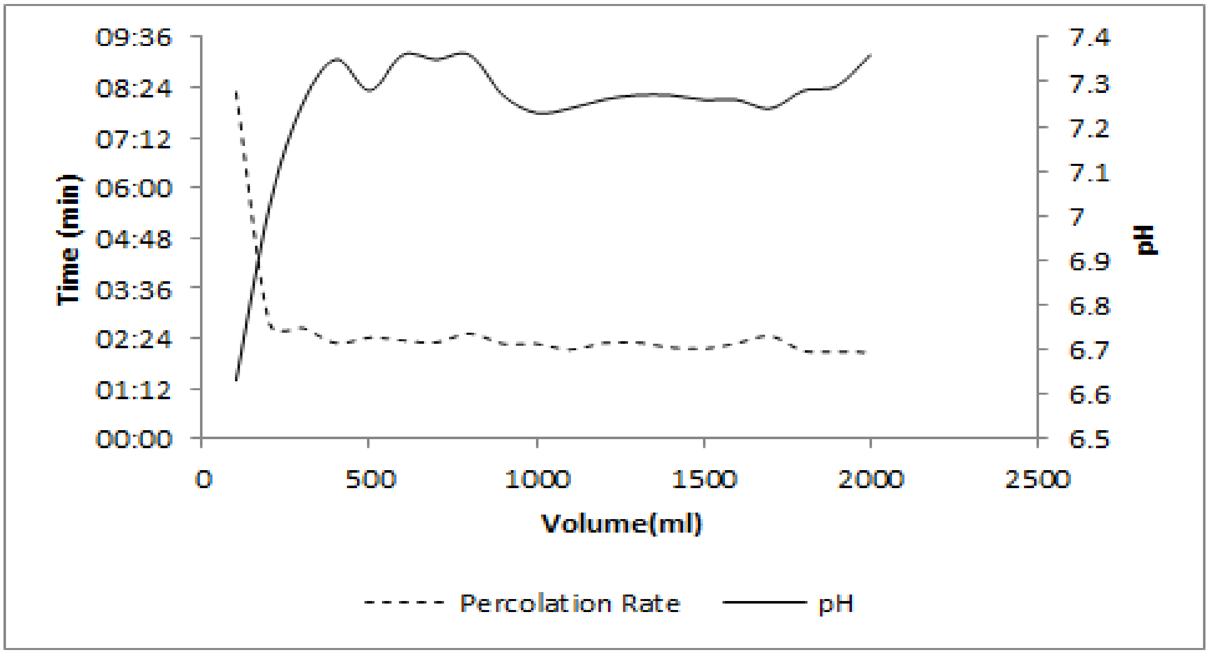

Fig 4.13: The pH of the effluent is plotted as function of time and cumulative discharge volume for clothes at a dosage rate of 50ml/min and 15cm column.

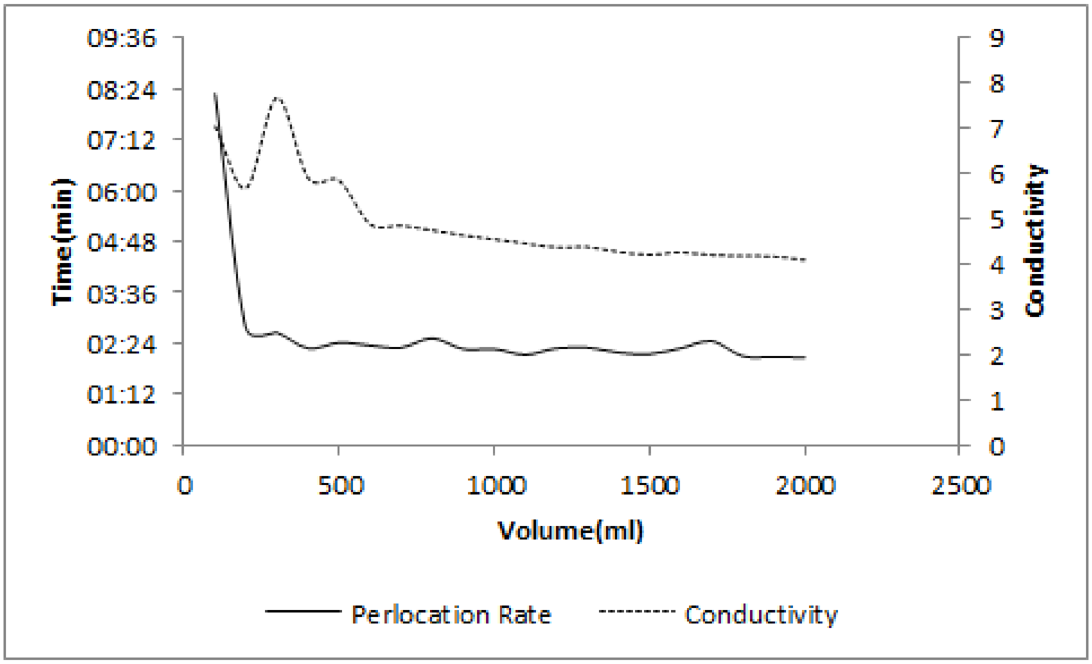

Fig 4.14: The electrical conductivity of the effluent is plotted as function of time and cumulative discharge volume for clothes at a dosage rate of 50ml/min and 15cm column.

Comparison of Gravel and Clothe results:

Fig 4.15: The pH of the effluent is plotted as function cumulative discharge volume in milliliters for gravels and clothes at a dosage rate of 50ml/min and 15cm column.

Conductivity:

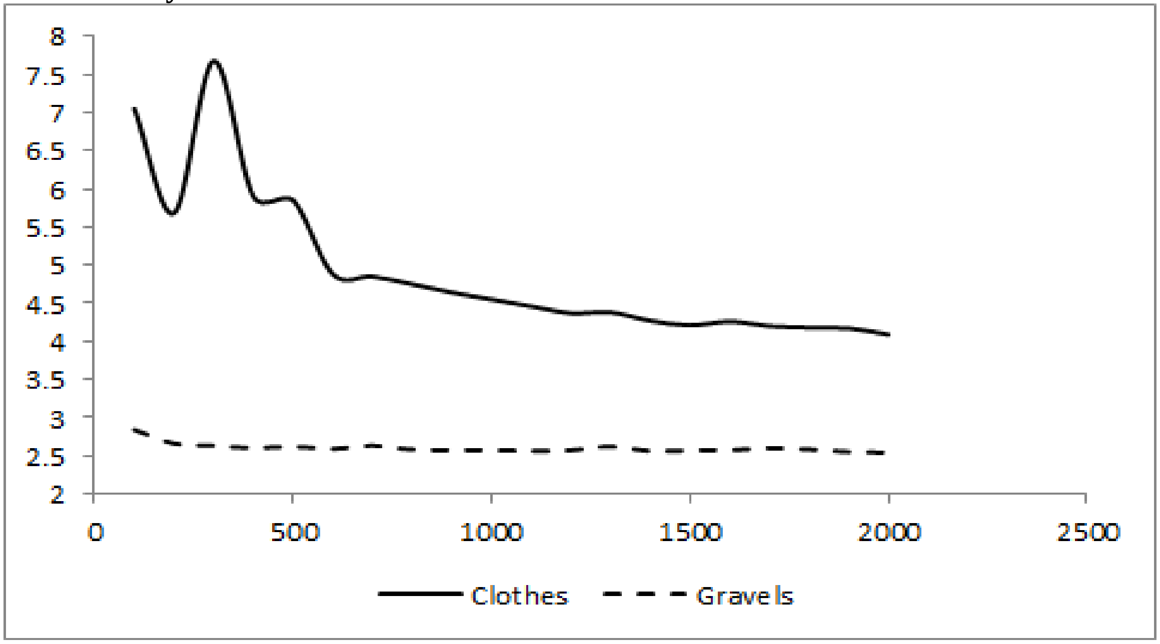

Fig 4.16: The Electrical Conductivity of the effluent is plotted as function cumulative discharge volume in millilitres for gravels and clothes at a dosage rate of 50ml/min and 15cm column.

Analysis for pH change

Y= ΔpH
Predictor Variables:
X_1= Column Height (cms)

X_2= Flow rate (ml/min)

X_3= Cumulative Time(min)

X_4= ΔEC (Conductivity Influent- Conductivity Effluent)

R^2= Coefficient of determination

S = Error in the model

The table 4.1 illustrates linear regression modelling of change in pH between influent and effluent from the bioreactor. In this table the results are for water percolation through the column of cloth textile fabric. The change in pH is modelled as a function of X_1 , column height, X_2 flow rate, X_3 cumulative time and X_4 change in electrical conductivity.

Predictor Variables	**a**	**b_1**	**b_2**	**b_3**	**b_4**	**R^2**	**S**
X_1	-0.079	0.0344				42.6	0.28
X_2	-0.485	0.0359	0.0192			73.1	0.1984
X_3	-0.309	0.0327	0.0180	-0.00236		75.1	0.1924
X_4	-1.12	0.504	0.0168	0.00326	-0.188	82.9	0.1611

Table 4.1 The summary of constants a , b_1,b_2,b_3 and b_4, coefficient determination R^2 and error S of the model for clothes

Table 4.1 shows the step-by-step improvement in prediction with increasing predictor variables and decreasing error S of the model. Correlations exist between the predictor variables X_1, X_2, X_3 and X_4 as shown in Table 4.2. It should be noted that regression is performed with only statistically independent variables.

Predictor Variables	**X_1**	**X_2**	**X_3**	**X_4**
X_1	1	-0.051	-0.0369	0.399
X_2	-0.051	1	-0.195	-0.255
X_3	-0.0369	-0.195	1	0.524
X_4	0.399	-0.255	0.524	1

Table 4.2 Correlation coefficient between the predictor random variables

X_1, X_2, X_3 and X_4 for clothes

Using the mathematical steps as discussed in chapter 3 the correlations described in Table 4.2 can be removed. Then according to equation 12 in chapter 3 we can get the pH change as a function of uncorrelated predictor variables.

$Y= \Delta pH = 0.609 - 0.116\ V_h + 0.205\ V_q + 0.160\ V_t - 0.350\ V_{\Delta EC}$ ……………………………Eq. 1

$S = 0.161196 \quad R^2 = 82.9$

Moringa Analysis:

The Table 4.3 illustrates linear regression modelling of change in pH between influent and effluent from the bioreactor. In this table the results are for water percolation through the column of moringa. The change in pH is modelled as a function of X_1 , column height, X_2 flow rate, X_3 cumulative time and X_4 change in electrical conductivity.

Predictor Variables	**a**	**b_1**	**b_2**	**b_3**	**b_4**	**R^2**	**S**
X_1	1.80	0.0427				90.4	0.1068
X_2	1.75	0.0416	0.00116			92.3	0.0971
X_3	1.84	0.0405	0.00349	-0.00223		92.6	0.0966
X_4	1.83	0.0682	0.00457	-0.00512	0.0137	94.3	0.0863

Table 4.3 The summary of constants a , b_1,b_2,b_3 and b_4, coefficient determination R^2 and error S of the model for moringa

Table 4.3 shows the step-by-step improvement in prediction with increasing predictor variables and decreasing error S of the model. Correlations exist between the predictor variables X_1, X_2, X_3 and X_4 as shown in Table 4.4. It should be noted that regression is performed with only statistically independent variables.

Predictor Variables	**X_1**	**X_2**	**X_3**	**X_4**
X_1	1	0.177	0.095	-0.911
X_2	0.177	1	0.978	0.180
X_3	0.095	0.978	1	0.273
X_4	-0.911	0.180	0.273	1

Table 4.4 Correlation coefficient between the predictor random variables X_1, X_2, X_3 and X_4 for moringa

Using the mathematical steps as discussed in chapter 3 the correlations described in Table 4.4 can be removed. Then according to equation 12 in chapter 3 we can get the pH change as a function of uncorrelated predictor variables.

$Y = \Delta pH = 2.79 – 0.0363 V_h -0.232 V_q + 0.243 V_t + 0.536 V_{\Delta EC}$ ………………….Eq. 2
S = 0.0863858 R2 = 94.3%

Gravel Analysis:

The Table 4.5 illustrates linear regression modelling of change in pH between influent and effluent from the bioreactor. In this table the results are for water percolation through the column of gravel. The change in pH is modelled as a function of X_1 , column height, X_2 flow rate, X_3 cumulative time and X_4 change in electrical conductivity.

Predictor Variables	**a**	**b_1**	**b_2**	**b_3**	**b_4**	**R^2**	**S**
X_1, X_2, X_3, X_4	0.570	-0.0168	-0.00494	-0.00363	-0.0114	57.6	0.13856

Table 4.5 The summary of constants a , b_1,b_2,b_3 and b_4, coefficient determination R^2 and error S of the model for gravel

Table 4.5 shows the improvement in prediction with increasing predictor variables and decreasing error S of the model. Correlations exist between the predictor variables X_1, X_2, X_3 and X_4 as shown in Table 4.6. It should be noted that regression is performed with only statistically independent variables.

Predictor Variables	**X_1**	**X_2**	**X_3**	**X_4**
X_1	1	0.543	-0.476	0.437
X_2	0.543	1	-0.623	0.519
X_3	-0.476	-0.623	1	-0.046
X_4	0.437	0.519	-0.046	1

Table 4.6 Correlation coefficient between the predictor random variables X_1, X_2, X_3 and X_4 for gravel

Using the mathematical steps as discussed in chapter 3 the correlations described in Table 4.6 can be removed. Then according to equation 12 in chapter 3 we can get the pH change as a function of uncorrelated predictor variables.

$Y = \Delta pH = -0.0878 - 0.0262\ V_h - 0.122\ V_q - 0.0830\ V_t - 0.179\ V_{\Delta EC}$ ………………Eq. 3

S = 0.1386 R2 = 57.6%

Clothes + Moringa + Gravels: General model formulation for any reactor irrespective of any material

The Table 4.7 illustrates linear regression modelling of change in pH between influent and effluent from the bioreactor. In this analysis the word bioreactor is generally stated. The variables from the gravel, cloth, moringa, bioreactors are arranged in such a way that they result in formation of this new data analysis. In this analysis derivation of a new term signifies as well as characterizes different material aspects studied in the different bioreactor columns experimented here. From Eq. 1,2,3 in this chapter the intercept constant coefficient 'a' imbibe all the properties of the material under test, cloth, moringa, gravel respectively. In all the bioreactor experiments with cloth, moringa and gravel the flow rate was the only constant which change within the experiment. Here, following Soboyejo et. al 2001, a new formulation for X_2' has been derived. The newly derived formula can be written as Eq. 4.

X_2'= 'a' x X_2 ……………………………………………………………………..Eq. 4

Where a is derived from Eq. 1, Eq. 2, and Eq. 3. The X_2 values are the dosage rates for the bioreactors experimented and discussed here.

In this table the results are for water percolation through the column of any treatment media. The change in pH is modelled as a function of X_1 , column height, X_2 flow rate, X_3 cumulative time and X_4 change in electrical conductivity.

Predictor Variables	**a**	**b_1**	**b_2**	**b_3**	**b_4**	**R^2**	**S**
X_1	-0.102	0.0415				7.7	1.0517
X_2'	-0.131	0.0407	0.000345			8.1	1.0522
X_3	-1.04	0.0542	0.000636	0.0140		27.1	0.9400
X_4	0.134	-0.00400	0.00235	0.00115	-0.0609	85.6	0.4195

Table 4.7 The summary of constants a , b_1,b_2,b_3 and b_4, coefficient determination R^2 and error S of the general model for any treatment media

Table 4.8 shows the step-by-step improvement in prediction with increasing predictor variables and decreasing error S of the model. Correlations exist between the predictor variables X_1, X_2, X_3 and X_4 as shown in Table 4.8. It should be noted that regression is performed with only statistically independent variables.

Predictor Variables	**X_1**	**X_2'**	**X_3**	**X_4**
X_1	1	0.149	-0.205	-0.342
X_2'	0.149	1	0.196	-0.231
X_3	-0.205	0.196	1	-0.304
X_4	-0.342	-0.231	-0.304	1

Table 4.8 Correlation coefficient between the predictor random variables X_1, X_2', X_3 and X_4 for any treatment material

$Y = \Delta pH = 0.758 + 0.755\ V_h - 0.0366\ V_q + 0.111\ V_t + 0.533\ V_{\Delta EC}$………………….Eq. 5

$S = 0.419538 \quad R^2 = 85.6\%$

Equation 5 is a new multiparameter stochastic equation which can be used for characterizing the electro kinetic behaviour of any bioreactor irrespective of the material. The coefficient of determination is found to be good enough to provide accurate results with a very small error of the model S.

Temperature Analysis:

For any porous media when in contact with water shows variation in electro kinetic properties [Churaev, 2000]. Porous media with water in contact is characterized by thermo osmosis. This is movement of ions due to change in thermal energy or temperature of the environment [Plappally et al. 2010].

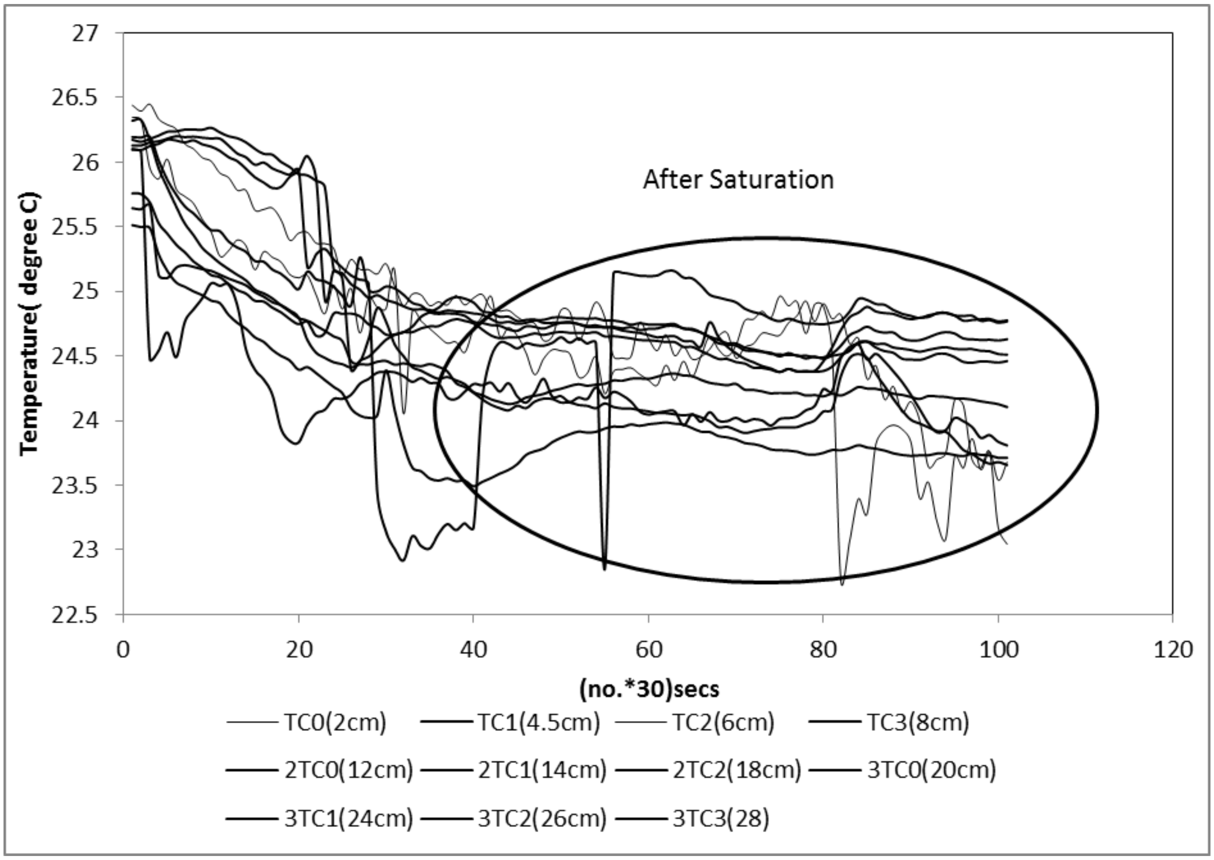

Figure 4.17 A decreasing trend in temperatures within the bioreactor with time in the clay reactors

The trend followed by clay bioreactors for temperature change is also similar to the trend other bioreactors may follow for internal bioreactor temperatures. The relationship for phenomena as shown in Fig. 4.19 between temperature and time can be expressed as [Plappally et al. 2009, Soboyejo 1965, Soboyejo 1973].

$Y_i = X_i / (a_i + b_iX_i)$……………………………………………………………………Eq. 6

Here Y_i represents the temperature within in the bioreactor recorded at distinct heights. The X_i represents the variable of time in this case.

Using Soboyejo 1965, In our case we can express Eq. 6 in this form

$T_i = t_i / (a_i + b_it_i)$…………………………………………………………………..Eq. 7

Where T_i = Temperature in ˚C, t_i = Time in secs. The Eq. 7 can also be written as

$Z = t_i/T_i = a_i + b_it_i$……………………………………………………………………..Eq. 8

According to Eq. 8 the following data analysis for all the bioreactor variants experimented here is performed.

Study for gravels 10ml/min:

Predictor Variables	**a**	**b_1**	**R^2**	**S**
t_i	-0.245	0.0420	99.9	0.5149

Table 4.9 The summary of constants a , b_1, coefficient of determination R^2 and error S of the general model for gravels at an experimental dosage rate of 10ml/min.

Sawdust 50ml/min:

Predictor Variables	**a**	**b_1**	**R^2**	**S**
t_i	0.489	0.390	98.2	1.85

Table 4.10 The summary of constants a , b_1, coefficient of determination R^2 and error S of the general model for sawdust at an experimental dosage rate of 50ml/min.

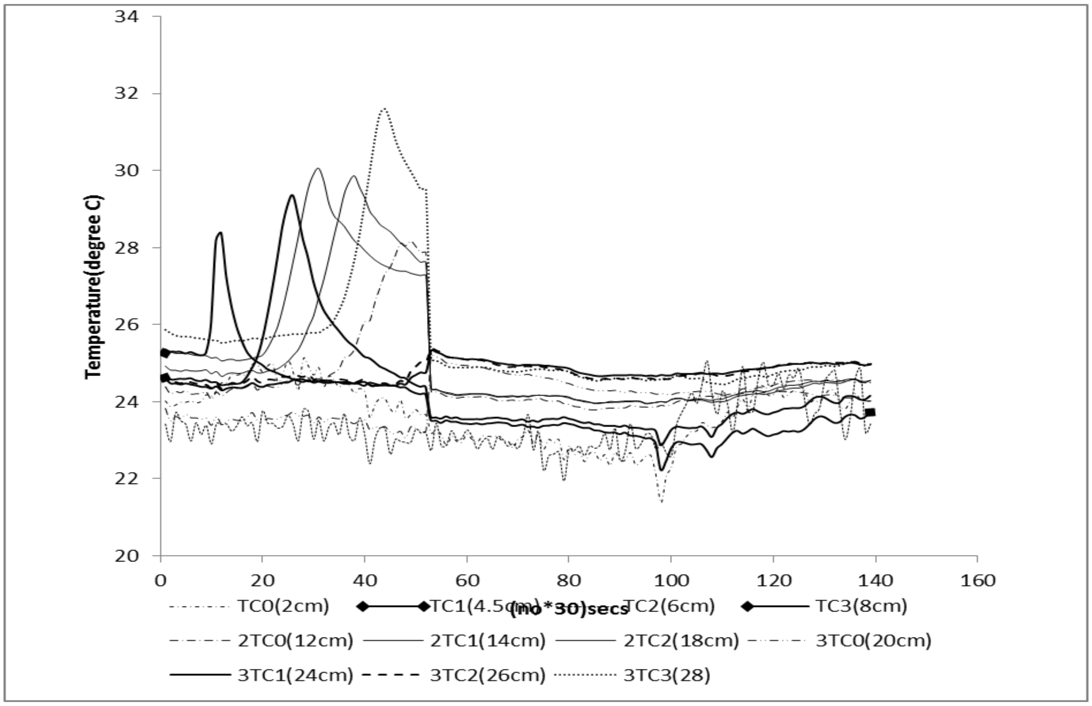

Fig. 4.18: Reactor Temperature as a function of time in Sawdust Column when dosed with water at a rate of 50ml/min

Sawdust 10ml/min:

Predictor Variables	**a**	**b_1**	**R^2**	**S**
t_i	-0.577	0.0413	99.8	0.673

Table 4.11 The summary of constants a , b_1, coefficient of determination R^2 and error S of the general model for sawdust at an experimental dosage rate of 10ml/min.

Layer Analysis: Generalization Irrespective of any Bioreactor Media

Predictor Variables	**a**	**b_1**	**R^2**	**S**
t_i	-0.0855	0.0375	99.7	0.6503

Table 4.12 The summary of constants a , b_1, coefficient of determination R^2 and error S of the general model for any treatment media at any specific dosage rate.

The birth process model assumed in Eq. 8 is able to predict the temperature change within a bioreactor irrespective of any height. This new model can be used to characterize any type of bioreactor column media with a gravitational influent flow and of rectangular crossection.

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Chapter 5
Summary and Conclusions

1. The electro-kinetic characteristics of different material bioreactor columns for treating water and waste water are experimentally studied. Separate columns of unsaturated gravels (~6mm) and ball clay were assessed for electro-kinetic characteristics by dosing water at a hydraulic loading rate of 50ml/min and 10ml/min.
2. Similarly locally available organic materials such as sawdust, Moringa oleifera sheets and textile clothe pieces were also empirically analyzed. Size effects of the bio-reactor columns were also studied.
3. A multi-parameter stochastic linear model for change in pH as a function of column height, dosage rate, time for specific volume discharge and change in electrical conductivity between influent and effluent was derived. A general stochastic model was also developed to characterize pH change in any bioreactor irrespective of the material media.
4. The chemical oxygen demand ratio within the gravel improved to unity showing increased containment of organic compounds with time. Organic textile clothes reactor also illustrated increased conductivity with increasing flow but conductivity dipped with increase in column height.
5. A birth process model is proposed to simulated temperature within a bioreactor as a function of time irrespective of any specific material used as bioreactor media.