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# Mathematical Modelling of Cassava Wastewater Treatment Using Anaerobic Baffled Reactor

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***Abstract:*** The performance of an anaerobic baffled reactor (ABR) was evaluated in the treatment of cassava wastewater as a pollutant residue. An ABR divided in four equal volume compartments (total volume 4L) and operated at 35°C was used in cassava wastewater treatment. Feed tank chemical oxygen demand (COD) was varied from 2000 to 7000mg $L^{-1}$. The objective of the study was to formulate an improved mathematical model to describe cassava wastewater treatment without taking into account its inhibition characteristic. In the study, Kincannon-Stover model constants $⍰_{max}$ and $K_s$, were found to be $0.8803 \mathrm{mg/L.d}$ and $0.2113 \mathrm{COD/m^3.day}$ respectively and Monod Model constants $⍰_{max}$ and $K_s$, were found to be $100 \mathrm{mg/L.d}$ and $98 \mathrm{mgCOD}$ respectively. The coefficient of determinations ($R^2$) of Kincannon-Stover and Monod Models were evaluated as 0.634 and 0.986. This showed that the Monod model is a more applicable model for describing the kinetics of the organic removal in anaerobic baffled reactor for treating cassava wastewater.

***Keyword:*** *Mathematical Modeling; Anaerobic Baffled Reactor (ABR); Cassava Wastewater; COD Removal; Treatment*

## I. INTRODUCTION

Wastewater treatment in developing countries is a problem to manage. The major components of the effluents from garri processing industries is cyanide and starch, and in most cases, these effluents are channeled into pits where they continue to accumulate and gradually percolate into the surrounding soils thereby posing serious health and environmental hazard. The wastewater from cassava processing or its derivative (garri) ends up with domestic sewage if processed in small quantities while others end up being carried with industrial wastes if processed in large industrial quantities. Lastly, others percolate into the soil depending on the processors. Wastewater from cassava processing, if released directly into the environment before proper treatment, is a source of pollution. In many areas where traditional processing is practiced, wastewater is normally discharged beyond the "factory" wall into roadside ditches or fields and allowed to flow freely, settling in shallow depressions. Eventually this will percolate into the subsoil or flow into streams. Cassava roots contain cyanogenic glucosides (the precursors of HCN) in various concentrations depending on the variety and growing conditions (Bolhuis, 1954). This cyanide is released during peeling, slicing and crushing. The bound cyanide is converted to free cyanide during the milling operation. About 40% to 70% of the total cyanide appears in the water used to wash the starch from the disintegrated tissue (Maduagwu and Umoh, 1988). The press water, although produced in relatively low volumes (250 – 300 litres per tonne of roots), is the main problem because of its high biological oxygen demand (BOD) of 25,000 – 50,000 mg/l with a typical cyanide concentration in excess of 400 mg/l (Gomez et al., 1984). Cyanide, being an acidic component will naturally have an inhibiting action on the biological degradation of cassava wastewater. Cassava wastewaters are often discharged into sewers or allowed to percolate into the soil causing environmental degradation. This effect on the environment is significant as the air we breathe becomes contaminated with the odor emanating from it, an effect yet to be addressed properly in developing countries due to inadequate equipment and lack of research materials. The cassava wastewater may introduce some toxic elements e.g. cyanide in sewage which may inhibit the usual degradation processes. It is therefore very important to establish the pathway of degradation, the level of inhibition and the extent of treatability of cassava wastewater. The objective of this study is to formulate an improved mathematical model to describe cassava wastewater treatment without taking into account its inhibition characteristic.

## Materials and Method

The laboratory scale ABR was constructed from 6mm thick stainless steel, with external dimensions of lengths, widths, depths and working volumes as shown in Table 1. Figure 1 shows a schematic diagram of the reactor. The reactor was divided into 4 equal compartments by vertical baffles with each compartment of each the reactors having down-comer and riser regions created by a further vertical baffle.

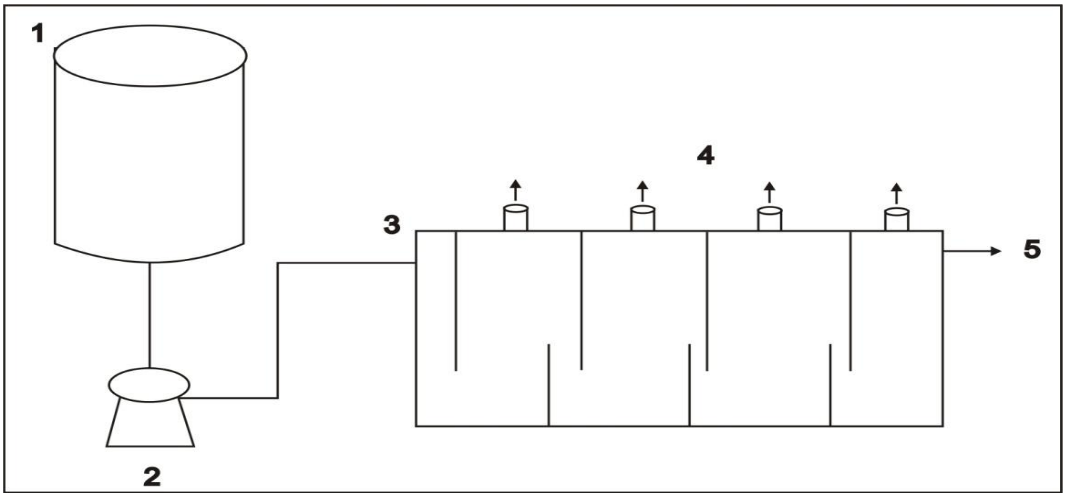

**Figure 1: The Reactor - Scheme of the ABR. 1. Feed Tank; 2. Peristaltic Pump; 3. Influent; 4. Sampling Ports; 5. Effluent.**

For each of the reactors, the widths of up-comers were multiples of the widths of down-comer (Fernanda et al., 2001). The lower parts of the down-comer baffles were angled at $45^0$ in order to direct the flow evenly through the up-comer. This produced effective mixing and contact between the wastewater and anaerobic sludge at the base of each riser. Each compartment was equipped with sampling ports that allowed biological solids and liquid samples to be withdrawn. The operating temperature was maintained constant at 35+0.5°C by putting the reactor in a water bath equipped with a temperature regulator (Movahadyan et al., 2007). The influent feed was pumped using variable speed peristaltic pump.

**Table 1: Dimensions of the Reactor**

| Dimensions | Reactor 1 |
|---|---|
| Length (cm) | 53 |
| Width (cm) | 16 |
| Depth (cm) | 30 |
| Working Volume (L) | 13.57 |
| Up-comer Width/ Down-comer Width | 2.6 |
| No of Compartments | 5 |
| Volume of Each Compartment (L) | 2.7 |

## Start-up of ABR

Start-up without seed sludge was rather difficult and time consuming for suspended growth anaerobic reactors. The following 3 steps were taken: (i) the reactor was filled with cassava wastewater and allowed to rest for 15 d (ii) the sludge bed was allowed through a process of sludge accumulation by settling and sludge improvement and (iii) after 15 d, feeding of the wastewater was resumed (Movahadyan et al., 2007). The resumed wastewater feeding helped the development of sludge bed at the bottom of individual chambers of the ABR. This process of feeding the system followed by two weeks rest is based on the experiment made in Kanpur (India) for the start-up of a UASB plant without inoculum (Draaijer et al., 1992).

## Characterization of Wastewater

The cassava wastewater from a cassava processing factory at Imo Polytechnic Umuagwo in Eastern Nigeria was used as feed. The supernatant of the wastewater after the simple gravity settling, used in the investigation, had low TSS, as approximately 90% of the solids were removed. The supernatant wastewater was diluted to achieve the COD concentration required for each loading rate with water. In order to achieve pH and alkalinity adjustment, the supernatant was neutralized by NaOH and $NaHCO_3$. A COD:N:P ratio of 300:5: 1 was kept during operation using $NH_4C1$ and $K_2HPO_4$. The micro-nutrient deficiency was added occasionally to correct growth conditions.

**Procedure for Experiment**

The wastewater was collected twice a day from the cassava processing plant, and it was intermittently mixed to feed the reactor with a consistent quality. The wastewater was fed to the reactor with the help of a variable speed peristaltic pump. The ABR was operated at various hydraulic retention times (HRTs) by varying the flow rate of influent wastewater ($Q_{inf}$), thereby varying the organic loading rate (OLR). The wastewater flew from the down-comer to the up-comer within an individual chamber through the sludge bed formed at the bottom of the individual chambers. After receiving treatment in the particular chamber, wastewater entered the next chamber from the top. Due to the specific design and .positioning of the baffle, the wastewater is evenly distributed in the up-comer and the vertical up-flow velocity ($V_{up}$) could be significantly reduced. The treated effluent was collected from the outlet of the 3rd compartment. The reactor was kept in a temperature controlled chamber maintained at 35 $^{O}$C.

**Mathematical Modeling of Cassava Wastewater Treatment**
**Nomenclature:**

$S_i$ = Substrate concentration in the influent ($mgl^{-1}$)
$S_e$= Substrate concentration in the effluent ($mgl^{-1}$)
$k_s$= Half saturation constant ($mgl^{-1}$)
μ = Specific growth rate of organism (per day)
$\mu_{max}$ = Maximum specific growth rate of organism (per day)
V = Volume of reactor (L)
$r_A$ = Rate of utilization of substrate (mg/l.day)

**Kincannon-Stover Model for ABR**

Equation (1) is Kincannon-Stover model. This equation was first used for RBC (Rotating Biological Contactor) systems. In that model the disc surface area (A) is used to represent some relationship to the total attached-growth active biomass concentration in a RBC. Where ds/dt is the substrate removal rate (mg/1. day). In the equation it was assumed that the suspended solid in the RBC system is negligible in comparison to the attached biomass (Broch-De et al., 1994).

$$r_A = \frac{ds^1}{dt} = \frac{\mu^1{}_{max}\left(\frac{QS_i}{A}\right)}{K_s^1 + \left(\frac{QS_i}{A}\right)} \qquad (1)$$

Previous studies (Broch-De et al., 1994).have shown that suspended biomass in the reactor is a significant factor in producing high and stable removal efficiency in moving bed biofilm reactors. It was demonstrated that the suspended biomass in the reactor contributed approximately one half of the total waste removal. This is extendable to ABR system because majority biomass of ABR is suspended and ABR reactors perform almost similar to plug flow reactor and it was predicted that Kincannon-Stover model was better for performance description of ABR reactor. Therefore in equation (1) volume (V) of the reactor instead of the surface area of the carrier elements can be used. By this modification results in:

$$r_{v\,COD} = \frac{ds}{dt} = \frac{\mu_{max}\frac{QS_i}{V}}{K_s + \left(\frac{QS_i}{V}\right)} \qquad (2)$$

A mass balance of substrate into and out of the volume can be made as follows:

$$\frac{dS}{dt} = \frac{Q}{V}\,(S_i - S_e) \qquad (3)$$

By equation (2), (3) we have the following relationship:

$$\frac{dS}{dt} = \frac{Q}{V}\,(S_i - S_e) = \frac{\mu_{max}\frac{QS_i}{V}}{K_s + \left(\frac{QS_1}{V}\right)} \qquad (4)$$

By linearization of equation (4), equation (5) is obtained as follows

$$\left(\frac{ds}{dt}\right) = \frac{V}{Q(S_i - S_e)} = \frac{K_s}{\mu_{max}}\left(\frac{V}{QS_i}\right) + \frac{1}{\mu_{max}} \qquad (5)$$

By plotting V/Q ($S_i$-$S_e$), the inverse of the loading removal rate, against V/Q$S_i$, the inverse of total organic loading rate, a straight line was obtained. By measuring the intercept and slope of this line the $\mu_{max}$ and $K_s$ was determined.

By substituting equation (5) in equation (3) the following equation is obtained:

$$QS_i = QS_e + \left(\frac{\mu_{Max}\left(\frac{QS_i}{V}\right)}{K_s + \left(\frac{QS_i}{V}\right)}\right) V \tag{6}$$

This equation can then be solved for either the volume of reactor or the effluent substrate concentration. Thus:

$$V = \frac{QS_i}{\left(\frac{\mu_{max} S_i}{S_i - S_e}\right) - K_s} \tag{7}$$

$$S_e = S_i - \frac{\mu_{max} S_i}{K_s + \frac{QS_i}{V}} \tag{8}$$

**Monod Model for ABR**

The Monod model is described as

$$r_A = \frac{ds}{dt} = \frac{Q}{V}(S_i - S_e) = \mu . X \tag{9}$$

$$\frac{Q}{V}(S_i - S_e) = \frac{\mu_{max} S_e}{K_s + S_e} X \tag{10}$$

By linearization of equation (10), equation (11) is obtained as follows

$$\frac{XV}{Q(S_i - S_e)} = \frac{K_s}{\mu_{max}} \frac{1}{S_e} + \frac{1}{\mu_{max}} \tag{11}$$

Experimental results were applied to Equations (11) in order to plot a graph. In this, graph XV/Q($S_i$-$S_e$) was plotted against 1/$S_e$

**Kincannon-Stover Model for ABR Treatment Cassava Wastewater**

From the regression equation: $y = mx + c \;\; \equiv y = \; 0.240x + \; 1.136$

$$\frac{1}{\mu_{max}} = c = intercept; \quad \mu_{max} = \frac{1}{c} = \frac{1}{1.136} = 0.8803 mg/L.d$$

$$\frac{K_s}{\mu_{max}} = m = slope; \; K_s = \; \mu_{max} * \; m$$

$$K_s = \; 0.8803 \; * \; 0.240 = 0.2113 COD/m^3.day$$

Substituting $\mu_{max}$ and $K_s$ into equation 8 gives: $S_e = S_i - \frac{0.8803 S_i}{\left(17 + \frac{QS_i}{V}\right)}$

**Monod Model for ABR Treatment Cassava Wastewater**

From the regression equation: $y = mx + c \; \equiv y = \; 0.98\, x + \; 0.01$

$$\frac{1}{\mu_{max}} = c = intercept; \; \mu_{max} = \frac{1}{c} = \frac{1}{0.01} = 100 mg/L.d$$

$$\frac{K_s}{\mu_{max}} = m; \; K_s = \; K * \; m$$

$$K_s = \; 100 * \; 0.98 = \; 98 mgCOD/L.day$$

Substituting $\mu_{max}$ and $K_s$ into equation 8 gives: $r_A \; = \; \frac{ds}{dt} = \frac{Q}{V}(S_i - S_e) = \frac{\mu_{max} X \, S_e}{K_s + S_e} = \frac{100 \; X \; S_e}{98 + S_e}$

## II. CONCLUSION

The state-of-the-art in the field of ABR for treatment of wastewater is reviewed in this paper, based on a substantial number of relevant references published recently; it can be concluded that the ABR could be applied to treat various wastewaters with satisfactory results if integrated with proper technology. As a high-rate anaerobic reactor, ABR has considerable potential for wastewater treatment. By Kincannon-Stover model the reactor volume and effluent substrate concentration can be determined if the model constants are available. In the study, Kincannon-Stover model constants $\mu_{max}$ and $K_s$, were found to be $0.8803 mg/L.d \; and \; 0.2113 COD/m^3.day$ respectively and Monod Model constants $\mu_{max}$ and $K_s$, were found to be $100 mg/L.d \; and \; 98 mgCOD$

respectively**.** The coefficient of determinations ($R^2$) of Kincannon-Stover and Monod Models were evaluated as 0.634 and 0.986. This showed that the Monod model is a more applicable model for describing the kinetics of the organic removal in anaerobic baffled reactor for treating cassava wastewater.

**Table 2: Non-Inhibited Cassava Wastewater Treatment (Kincannon– Stover Model)**

| S/N | $\frac{Q\ (S_i - S_e)}{V}$ (mg/L.d) | $\frac{Q\ S_i}{V}\ X\ 10^9$ (mg/L.d) | $y = \frac{V}{Q\ (S_i - S_e)}\ X\ 10^{-4}$ (/L.d/mg) | $x = \frac{V}{Q\ S_i}\ X\ 10^{-10}$ (L.d/mg) |
|---|---|---|---|---|
| 1 | 250.00 | 1.40 | 40.00 | 7.10 |
| 2 | 500.00 | 1.40 | 20.00 | 7.10 |
| 3 | 400.00 | 1.40 | 25.00 | 7.10 |
| 4 | 500.00 | 1.40 | 20.00 | 7.10 |
| 5 | 500.00 | 1.40 | 20.00 | 7.10 |
| 6 | 300.00 | 1.40 | 33.00 | 7.10 |
| 7 | 600.00 | 1.40 | 17.00 | 7.10 |
| 8 | 600.00 | 1.40 | 17.00 | 7.10 |
| 9 | 700.00 | 1.40 | 14.00 | 7.10 |
| 10 | 600.00 | 1.40 | 17.00 | 7.10 |
| 11 | 900.00 | 1.80 | 11.00 | 5.50 |
| 12 | 1000.00 | 2.40 | 10.00 | 4.20 |
| 13 | 1500.00 | 2.40 | 6.70 | 4.20 |
| 14 | 1600.00 | 2.40 | 6.30 | 4.20 |
| 15 | 1700.00 | 2.40 | 5.90 | 4.20 |
| 16 | 1700.00 | 2.40 | 5.90 | 4.20 |
| 17 | 1900.00 | 5.00 | 5.30 | 0.20 |
| 18 | 2700.00 | 5.00 | 3.70 | 0.20 |
| 19 | 2800.00 | 5.00 | 3.60 | 0.20 |
| 20 | 2500.00 | 5.00 | 4.00 | 0.20 |
| 21 | 2200.00 | 10.00 | 4.50 | 0.10 |
| 22 | 4200.00 | 10.00 | 2.40 | 0.10 |
| 23 | 4000.00 | 10.00 | 2.50 | 0.10 |
| 24 | 4100.00 | 10.00 | 2.40 | 0.10 |

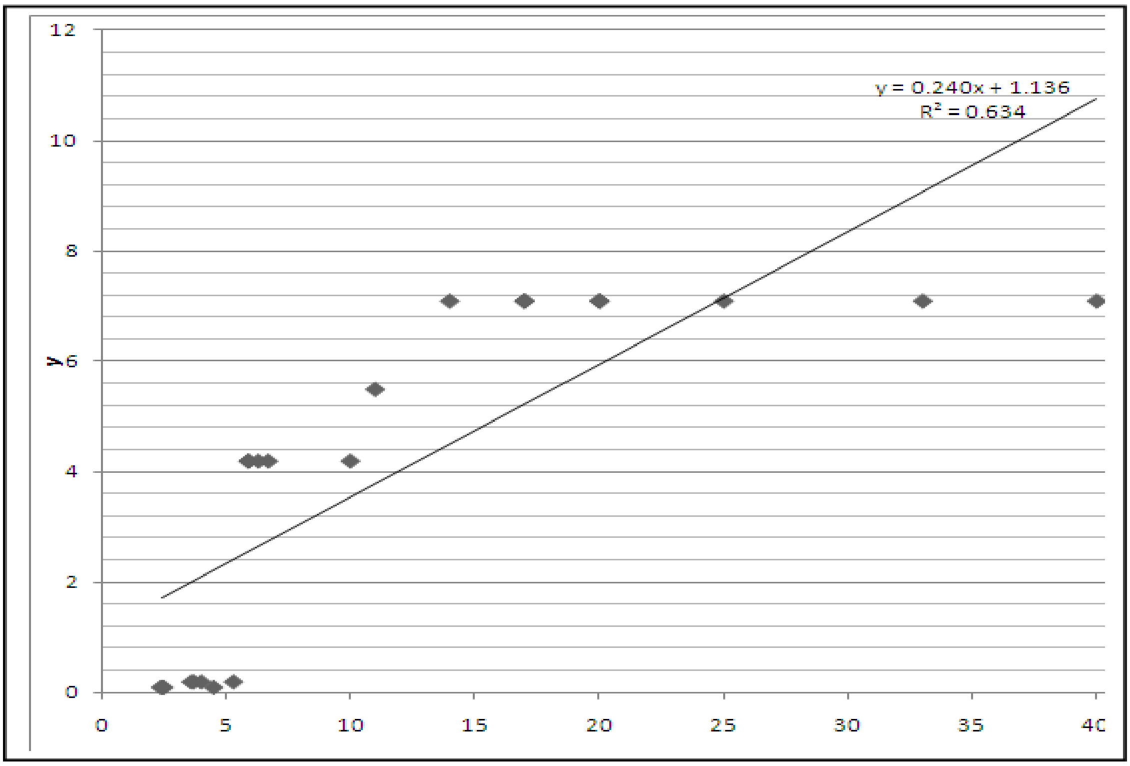

**Figure 2: A Scatter Plot of Inverse of Substrate Removal Rate ($y = \frac{V}{Q\ (S_i - S_e)}$ (/L.d/mg)) Versus Inverse of Total Loading Rate ( $x = \frac{V}{Q\ S_i}$ (L.d/mg)) ( Kincannon– Stover Mode)l**

Table 3: Non-Inhibited Cassava Wastewater Treatment (Monod Model)

| S/N | $x_t = SV_i - SV_e$ (mg/ L.d) | $\frac{Q\,(S_i - S_e)}{V}$ (mg/ L.d) | $\frac{V}{Q\,(S_i - S_e)}$ (mg/ L.d) | $y = \frac{x.V}{Q\,(S_i - S_e)}$ (mg/ L.d) | $S_e$ (mg/L | $x = \frac{1}{S_e}$ (L/ mg) |
|---|---|---|---|---|---|---|
| 1 | 2.60 | 250.00 | 0.004 | 0.0104 | 96.15 | 0.01 |
| 2 | 2.20 | 500.00 | 0.002 | 0.0044 | 227.27 | 0.004 |
| 3 | 1.40 | 400.00 | 0.0025 | 0.0035 | 285.71 | 0.004 |
| 4 | 0.60 | 500.00 | 0.002 | 0.0012 | 833.33 | 0.001 |
| 5 | 0.00 | 500.00 | 0.002 | 0 | 0 | 0 |
| 6 | 0.20 | 300.00 | 0.003333333 | 0.000666667 | 1500.00 | 7E-04 |
| 7 | 0.60 | 600.00 | 0.001666667 | 0.001 | 1000.00 | 0.001 |
| 8 | 1.00 | 600.00 | 0.001666667 | 0.001666667 | 600.00 | 0.002 |
| 9 | 1.40 | 700.00 | 0.001428571 | 0.002 | 500.00 | 0.002 |
| 10 | 1.70 | 600.00 | 0.001666667 | 0.002833333 | 352.94 | 0.003 |
| 11 | 2.00 | 900.00 | 0.001111111 | 0.002222222 | 450.00 | 0.002 |
| 12 | 2.20 | 1000.00 | 0.001 | 0.0022 | 454.55 | 0.002 |
| 13 | 2.40 | 1500.00 | 0.000666667 | 0.0016 | 625.00 | 0.002 |
| 14 | 2.60 | 1600.00 | 0.000625 | 0.001625 | 615.38 | 0.002 |
| 15 | 3.10 | 1700.00 | 0.000588235 | 0.001823529 | 548.39 | 0.002 |
| 16 | 3.30 | 1700.00 | 0.000588235 | 0.001941176 | 515.15 | 0.002 |
| 17 | 3.30 | 1900.00 | 0.000526316 | 0.001736842 | 575.76 | 0.002 |
| 18 | 3.40 | 2700.00 | 0.00037037 | 0.001259259 | 794.12 | 0.001 |
| 19 | 3.40 | 2800.00 | 0.000357143 | 0.001214286 | 823.53 | 0.001 |
| 20 | 3.40 | 2800.00 | 0.000357143 | 0.001214286 | 823.53 | 0.001 |
| 21 | 3.40 | 2200.00 | 0.000454545 | 0.001545455 | 647.06 | 0.002 |
| 22 | 3.50 | 2200.00 | 0.000454545 | 0.001590909 | 628.57 | 0.002 |
| 23 | 3.50 | 400.00 | 0.0025 | 0.00875 | 114.29 | 0.009 |
| 24 | 3.50 | 4100.00 | 0.000243902 | 0.000853659 | 1171.43 | 9E-04 |

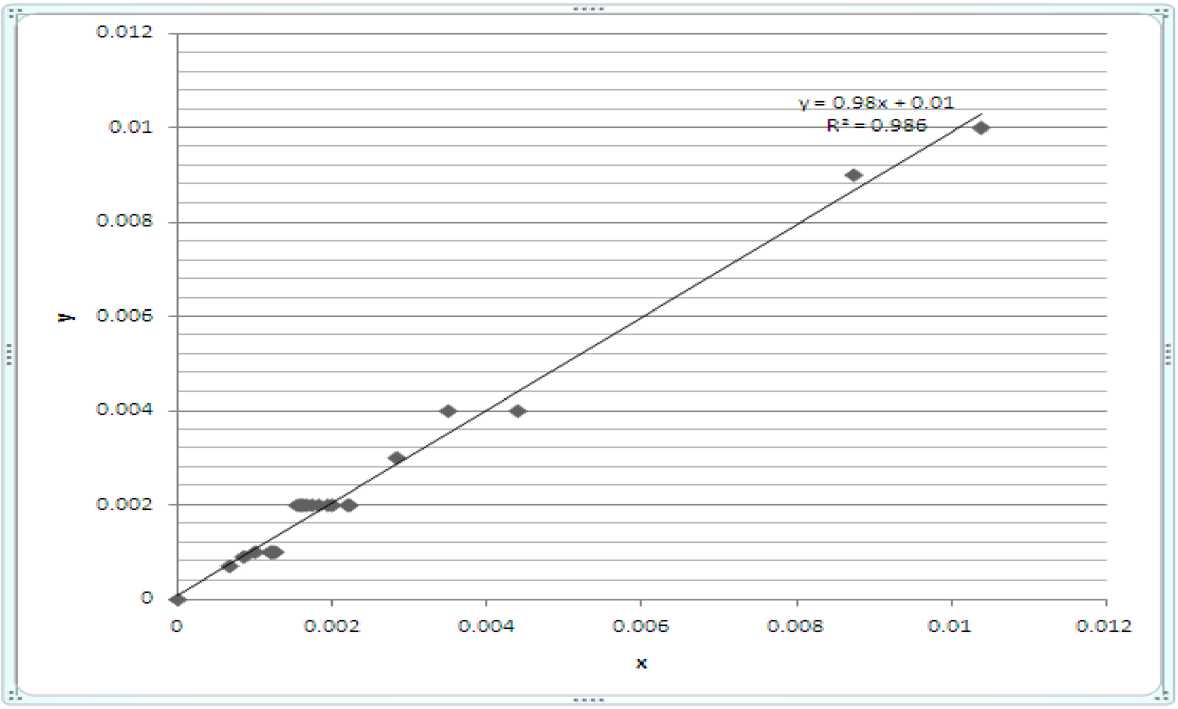

Figure 3: A Scatter Plot of $y = \frac{XV}{Q\,(S_i - S_e)}$ (L.d/mg) Versus $x = \frac{1}{S_e}$(L/ mg) (Monod Model)

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