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Modeling of Microbial Growth in a Wastewater Treatment Plant: A Case Study of Textile Industry in Kaduna, Nigeria

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Abstract

Modern-day industrialization and urbanization does not go without its own problems. Some of these problems include the extensive generation of waste from industries and densely populated urban centers. Some of these wastes generated are highly toxic to both aquatic life and environment in general. Therefore, to ensure our safety in this planet, there should be some form of treatment given to these wastes before they are discharged to the environment. This work is aimed at developing mathematical model, which would be used to predict the specific growth rate and biomass concentration of the microbes in wastewater plant. The results of simulation showed a remarkable agreement with the experimental results and the specific growth. The biomass concentration depends on the effluent substrate concentration, influent substrate concentration, and dilution rate.

***Keywords**: Biomass, substrate, effluent, reactor, specific growth rate, wastewater.*

Introduction

Effluents are discharged from the industry. They consist of water and varieties of potential hazardous substances (Odigure 1999). If untreated waste water is allowed to accumulate in the environment and the decomposition of the organic material allowed to proceed, it can lead to the production of large quantity of malodor gases. In addition untreated wastewater usually contains numerous pathogenic or disease causing micro-organisms. It also stimulates the growth of some aquatic plants (Alba, *et al*. 1973). Therefore, the ultimate goal of wastewater management is the protection of the environment in a manner commensurate with public health, economic, social and political concerns. Environmental management system involves a self-regulatory and self-correcting approach to environmental improvement based on the established principle of total quality and continuous improvement (Imre 1986; Best and Khan 1986). Over the last few years, private companies and government have paid considerable attention to the potential benefits of enhancing good environmental management system.

In other to ensure our safety in this planet, wastewater from the process industries should be treated either chemically or biologically using microorganisms. The objectives of biological treatment are to coagulate and remove the colloidal solid and to stabilize organic matter to a reasonable extent (Fogler 1997; Wesley 1989). The advantages of using microbes in liquid waste treatment are efficiency, effectiveness, and minimal cost of maintenance and do not require the use of toxic or hazardous chemical. However it must be noted that after treatment the cell tissue of the microbes has to be removed or else it would constitute a source of BOD, which implies treatment has not achieved (Micheal 1987; Wesley 1989). The removal of the cell tissue can be achieved by introducing predators like protozoan and rotifers to clean up the water before it is discharged. The microorganisms, which treat this wastewater, like any other

living things, grow; and their growth is an indication of the degree of treatment (Horan 1990). The objective of this write up is to develop a mathematical model and computer simulation of the kinetics of microbial growth. This can be achieved via realization of the following aims:

1. Determine the specific growth rate of the microbes and the values of biomass concentration using the model equation.
2. Collation of experimental analysis on the plant to confirm the validity of the model.
3. Simulate the developed computer programs to serve as predictive tool, which constitute an edge in the industries.

Experimental Methodology

To enhance the understanding of the proposed model and to verify its validity, experimental analysis were carried out on the plant to determine the following parameters: Suspended solid, Amount of volatile suspended solid (VSS), pH, temperature and chemical oxygen demanded. The results obtained were recorded and presented in Table 1.

The model equation was programmed using Q basic program. The obtained simulated results are presented in Table 2. The simulated results obtained will be used to test the validity of the model equation in respect to the experimental results.

Conceptualization of Modeling Techniques

The objectives of this model are to predict the values of the specific growth rate of the microorganism in the plant and the biomass concentration, given the substrate utilized and the dilution rate. The wastewater plant of textile industry in Kaduna, Nigeria is used as case study. The plant is continuous flow activated sludge system with sludge recycle; the sludge is drawn from the line. Before the substrate (wastewater) gets to the reactor, it is passed through tanks, which help in stabilizing wastewater from the plant. Usually wastewater from the plant is alkaline with a pH above 7, this is due to the predominant use of sodium hydroxide in the factory. After treatment in the reactor, the product is passed into the separator/ sedimentation tank, where the top product of the sedimentation tank if fed into the bio-combination tank where activated carbon is used to absorb color and dye materials from the effluent. To ensure that the effluent does not still contain infectious bacterial and micro-organism, chlorine is added in calculated quantity, from this point the water is run to the Kaduna river. The stage of interest is the reactor/aeration tank as shown in Fig. 1 below.

Assumptions

The following assumptions were made in developing mathematical models for activated sludge systems.

(i) Concentration of the substrate is constant per day.

(ii) All microorganisms are taken as homogeneous material and the function of their cell is invariant as a result of vigorous mixing in the tank.

(iii) No microbial activity occurs in the settling/separation tank and all biodegradable is in soluble form.

(iv) No sludge accumulated in the settling tank and a reasonable efficiency of solid/liquid separation accomplished.

(v) The process is assumed to be a steady state conditions and the total mass of the reaction mixture within the reactor volume remain constant but its concentration does change.

(vi) Only one nutrient is considered as the limiting nutrient in the substrate.

(vii) Complete mixing is achieved in the aeration tank.

Specific Growth Rate

From the first principle, the rate of bacterial growth can be defined as first order reaction:

$r_g = \mu x$ ..... (1)

But Monod (1942; cited after Bailey and Ollis 1987) suggested that:

$$\mu = \frac{\mu_m S}{K_s + S} \quad \text{..... (2)}$$

r_g = rate of bacterial growth (mass/unit volume time)
μ = Specific growth rate (time^{-1})
μ_m = Maximum specific growth rate (time^{-1})
S = concentration of growth limiting substrate in the effluent (mass/unit volume)
K_s = half velocity constant (mass/ unit volume)

Substituting equation 2 into 1 to obtain

$$r_g = \frac{\mu_m x S}{K_s + S} \quad \text{..... (3)}$$

This is considered as a mathematical model of the rate of microbial growth with respect to substrate concentration (S). However, equation (3) cannot be used to describe the growth rate. To account for other factors involved in the growth rate completely because it does not give an indication of the net growth rate. To account for other factors involved in the growth rate, there is need to introduce other parameters that affect the overall growth rate of the microbe. These include: temperature, pH and endogenous decay. The first two factors were relatively constant from the experimental results and these factors can be considered not to have an appreciably significant effect on the rate of microbial growth. However, the endogenous decay, which is the energy, required for cell maintenance and other factor such as death rate and predation must also be considered. These factors are lumped together and represented by r_d (Micheal 1987).

$$r_d = -K_d x - \mu \quad \text{..... (4)}$$

r_d = endogenous decay coefficient (time $^{-1}$)

X = concentration of cell (mass/unit volume)

Therefore, the net rate of microbial growth r^1_g will be the sum of the two growths.

$$r^1_g = r_g + r_d \quad \text{..... (5)}$$

Substituting equation (4) into (5):

$$r^1_g = r_s + (-K_d x)$$

$$r^1_g = r_s - K_d x \quad \text{..... (6)}$$

Substituting equation (3) into (6)

$$r^1_g = \frac{\mu_m x S}{K_s + S} - K_d x \quad \text{..... (7)}$$

Divide through by X

$$\frac{r^1_g}{x} = \frac{\mu_m S}{K_s + S} - K_d \quad \text{..... (8)}$$

r^i_g = net bacterial growth (mass/unit volume time)

But specific growth rate is

$$\mu = \frac{r^1_g}{x}$$

Therefore

$$\mu = \frac{\mu_m S}{K_s + S} - K_d \quad \text{..... (9)}$$

Equation (9) is the mathematical model for predicting growth of the bacterial. The constant m, K_s and K_d will be determined from the experimental results.

Biomass Concentration

A model for biomass concentration can be obtained by considering a material balance around the reactor in Fig. 1 (Robert and Green 1997).

$$\begin{pmatrix} \textit{Material} \\ \textit{in} \text{ with} \\ \text{fresh feeed} \end{pmatrix} + \begin{pmatrix} \textit{Material} \\ \textit{in} \text{ from} \\ \text{recycle stream} \end{pmatrix}$$

$$+ \begin{pmatrix} \textit{Formation} \\ \textit{by} \text{ biochemical} \\ \text{reaction} \end{pmatrix} - \begin{pmatrix} \textit{Out} \text{ put} \\ \text{to} \\ \text{seperator} \end{pmatrix}$$

$$= (\textit{Accumulation}) \quad \text{..... (10)}$$

Component balance of the substrate concentration:

$$F_0S_0 + F_RS + r_sv - (F_0 - F_R)S = v_r\frac{ds}{dt} \text{.....(11)}$$

Where:

F_o = Inlet flow rate into the reactor of the fresh feed (L/day)

F_R = flow rate of recycle feed (L/day)

S_o = influent substrate concentration (mg/L COD)

S = effluent substrate utilization rate (mg/L COD)

Since the system is operated under steady condition:

Accumulation = 0

$$ie\ \frac{ds}{dt} = 0$$

$$F_0S_0 + F_RS + r_sv_R - \left(F_0 - F_R\right)S = 0 \text{ ....(12)}$$

r_s = substrate utilization (mg/L day)

But Monod (1942; cited after Bailey and Ollis 1987) proposed that the rate of microbial growth is proportional to the substrate utilization:

$$r_g\alpha = r_s$$

$$r_g = -Yr_s \text{ ..... (13)}$$

Y = maximum yield coefficient (mg/mg) (Defined as the ratio of the mass of cells formed to the mass of substrate consumed during the finite period of cell logarithmic growth).

Substituting equation (3) into (13):

$$Yr_s = \frac{-\mu_m xS}{K_s + S}$$

$$r_g = \frac{\mu_m xS}{Y\left(K_s + S\right)} \text{ ..... (14)}$$

Substituting equation (14) into equation (12) to obtain:

$$\frac{\mu_{mxS}}{Y(K_s + S)} = \frac{F_0}{v_R}\left(S_0 - S\right)$$

$$x = \frac{F_0Y\left(K_s + S\right)\left(S_0 - S\right)}{v_R\mu_{mS}} \text{ ..... (15)}$$

But $\frac{F_0}{v_R} = D$

Therefore,

$$x = \frac{DY\left(K_s + S\right)\left(S_0 - S\right)}{\mu_m S} \text{ ..... (16)}$$

Where D = dilution rate (day^{-1}). (Dilution rate is the rate at which microorganisms are being washed out fro the reactor).

However, for an activated sludge system with recycle, the dilution rate can be derived from equation (17) noting that at steady state accumulation (ds/dt) =0, also Xo = 0 for a sterile system.

Component balance for the biomass:

$$F_0X_0 + F_RX_R + r_gv_R - \left(F_0 + F_R\right)X = 0 \text{ .... (17)}$$

Taking X_0 = and divide equation (17) by F_0

$$\frac{X_R}{F_0}\left(X_R - X\right) - \frac{F_0X}{F_0} + \frac{v_Rr_g}{F_0}$$

But $R = \frac{F_R}{F_0}$ and $D = \frac{F_0}{v_R}$

$$R\left(X_R - X\right) - X + \frac{r_g}{D} \text{ ..... (18)}$$

Knowing that:

$$r_g = \mu x \text{ and } \frac{X_R}{X} = E_a$$

Equation 18then becomes:

$$R\left(E_a - 1\right) - 1 + \frac{\mu}{D} = 0$$

Therefore,

$$D = \frac{\mu}{1 - R\left(E_a - 1\right)} \text{ ..... (19)}$$

Substitute equation 19 into 16

$$x = \frac{\mu\, Y(S_0 - S)(K_s + S)}{\mu_m S(1 - R(E_a - 1))} \quad \text{..... (20)}$$

Imre (1986) and Micheal (1987) have shown that the variation of growth rate with temperature in wastewater treatment as:

$$\mu_T = \mu_{20}\alpha^{(T-20)} \quad \text{..... (21)}$$

$\mu_T$is the specific growth rate at any temperature and μ_{20} is the specific growth at 20^{o}C which is equal to 3.60/ day (Bailey and Ollis 1987) is a constant ranging between 1.00 and 1.08 (Richardson and Coulson 1992).

Substituting equation 21 into 20 we have:

$$x = \frac{\mu_{20}\,\alpha^{(T-20)} Y(S_0 - S)(K_s + S)}{\mu_m S(1 - R(E_a - 1))} \quad \text{..... (22)}$$

Bailey and Ollis (1987) show that:

$$pH = \frac{\mu_m}{1 + \frac{H}{Ka_1} + \frac{Ka_2}{H}}$$

$$\mu_m = pH\left(1 + \frac{H}{Ka_1} + \frac{Ka_2}{H}\right) \quad \text{..... (23)}$$

Where H = hydrogen ion activities or concentration

Ka_1 and Ka_2 are inhibitors constants.

Putting equation 23 into 22 to obtain:

$$x = \frac{\mu_{20} Y(S_0 - S)(K_s + S)\alpha^{(T-20)}}{\mathrm{pH}\left(1 + \frac{\mathrm{H}}{\mathrm{Ka}_1} + \frac{Ka_2}{H}\right) S(1 - R(E_a - 1))} \quad \text{..... (24)}$$

Equation 24 is the model equation of the biomass concentration leaving the reactor with activated sludge system with recycles. The kinetics parameters and constants are determined from the experimental values.

Results and Discussion

The quality of the environment is adversely affected by the activities of process industries. Process industries discharge gaseous, liquid and solid waste into the environment treating the health of the population and damaging the quality of the environment by rendering the farmland and water bodies unusable (Best and Khan 1986; Wesley 1989).

It could be observed from Table 1 that the performance of the treatment plant is un-patterned. The influent substrate concentration obtained from the experimental analysis was not steady and it varied with respect to the magnitude of work done in the factory. The more the volume of work the more chemicals that are used and therefore, the higher the COD values of the influent substrate.

Results also shows that the flow rate of the plant varied with respect to the quantity of wastewater produced in the plant. The variation of substrate and flow rate caused an unsteady state condition in the plant since the plant has to respond to any variation in order to change the effect. Death rate and predation by higher organisms are lumped together and accounted for growth of the microorganisms, which is accompanied by secretion of substance into the reactor and results into enzyme inhibition. These substances will have an inhibitory effect on the growth of microorganisms though this inhibition could be either competitive or non-competitive, but in a continuous flow tank system, the effect of product enzyme inhibition is minimal (Pirt 1975).

The value of the specific growth of the microbes was calculated using a modified Monod equation that accounted for endogenous respiration and death rate the simulated results is as shown in Table 2. In evaluating the model some kinetic parameters such as K_d, Y K_s, m, Ka_1 and Ka_2 were determined by statistical analysis of the experimental results and the value obtained for these parameters are 0.0203, 1.5145, 75.62, 0.903, 0 and 0.90, respectively.

Considering the scope of this write up, it could be deduced that the model developed is un-segregated (all the cell have cellular properties) and unstructured (single component representation i.e. not considering the multi-component nature of the organism in the plant) model. The results obtained from the simulation of the model equation show a remarkable agreement with the experimental results as shown in Fig. 2 with correlation coefficient of 0.93 and standard deviation of 7.629 these values indicated that the simulated results varied slightly from the experimental results. The variation between the simulated and experimental results could be attributed to the following:

(i) Non-consideration of the wall growth organism during the material balance and its contribution to the total mass of microbes are neglected.

(ii) Variation in the substrate concentration and the flow rate, which alter the steady state conditions assumed during the conceptual stage of the modeling.

Conclusion

From the research work, it could be deduced that the model equation generated reasonably reflect the considered variable. Hence the simulation results conform to experimental results. It can be deduced that the biomass concentration and microbial growth depends on substrate concentration, maximum specific growth rate, maximum yield coefficient, and half velocity constant.

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The obtained experimental and simulated results are presented in Tables 1 and 2 below:

Table 1. Experimental results on plant operating conditions

Days	Temperature (^oC)	pH	Biomass Concentration (mg/L)	Flow rate (Q) m^3/day Concentration	Influent Substrate Concentration (mg/L)	Effluent Substrate Concentration (mg/L)
1	18	7.89	988	1142	326	65
2	19	7.58	791	1629	364	155
3	18	7.00	833	1471	333	113
4	18	7.65	685	1601	327	146
5	19	7.32	1355	961	406	48
6	18	7.60	1268	1142	323	65
7	18	7.25	992	1124	325	63
8	17	7.65	1106	1551	424	132
9	18	7.82	791	1064	266	57
10	16	7.45	1208	1408	420	101
11	17	7.00	924	1571	382	138
12	18	7.69	1200	1300	401	84
13	18	7.52	799	1611	360	149
14	19	7.00	750	1462	310	112
15	18	7.41	841	1954	422	377
16	17	7.40	269	1837	328	257
17	18	7.85	594	1716	345	188
18	18	7.63	829	1290	302	83
19	18	7.54	435	1434	221	106
20	17	7.25	356	1734	200	106
21	18	7.89	894	1052	292	56
22	18	7.58	769	1759	296	93
23	19	7.00	1276	1001	389	52
24	17	7.65	753	1097	259	60
25	18	7.32	852	1144	290	65
26	19	7.60	602	1534	265	106
27	16	7.25	454	1473	234	114
28	16	7.65	545	1352	236	92
29	15	7.82	492	1428	235	105
30	17	7.45	757	1698	232	32
31	18	7.00	750	1160	265	67

Table 2. Simulation results

Days	Flow rate (Q) m^3/day	Influent substrate conc. (S_0)	Effluent substrate conc. (S)	Dilution rate (day^{-1})	Biomass conc. x (mg/L)	Specific growth rate μ	Y Max. yield coefficient

		(mg/L)	(mg/L)			(day^{-1})	(mg/mg)
1	1142	326	65	0.993	964.400	0.397	0.49
2	1629	364	155	1.467	863.811	0.587	0.52
3	1471	333	113	1.302	840.708	0.521	0.51
4	1601	327	146	1.436	750.494	0.575	0.52
5	961	406	48	0.826	1286.430	0.330	0.48
6	1142	323	65	0.993	945.910	0.397	0.49
7	1124	325	63	0.975	948.974	0.390	0.49
8	1551	424	132	1.385	1129.110	0.554	0.52
9	1064	266	57	0.920	768.115	0.368	0.49
10	1408	420	101	1.240	1184.34	0.496	0.51
11	1571	382	138	1.408	945.470	0.563	0.52
12	1300	401	84	1.137	1178.640	0.455	0.50
13	1611	360	149	1.447	857.610	0.579	0.52
14	1462	310	112	1.297	766.682	0.519	0.51
15	1954	422	377	1.830	482.918	0.732	0.53
16	1837	328	257	1.694	452.249	0.677	0.53
17	1716	345	188	1.559	710.944	0.624	0.52
18	1290	302	83	1.131	824.454	0.452	0.50
19	1434	221	106	1.267	471.501	0.507	0.51
20	1734	200	106	1.267	382.543	0.507	0.52
21	1052	292	56	0.910	865.869	0.364	0.49
22	1759	296	93	1.194	775.533	0.478	0.52
23	1001	389	52	0.869	1206.490	0.348	0.48
24	1097	259	60	0.948	724.765	0.379	0.49
25	1144	290	65	0.993	820.053	0.397	0.50
26	1534	265	106	1.267	636.851	0.507	0.52
27	1473	234	114	1.306	477.792	0.523	0.51
28	1352	236	92	1.188	552.960	0.475	0.51
29	1428	235	105	1.262	514.133	0.505	0.51
30	1698	232	32	0.621	695.538	0.248	0.52
31	1160	265	67	1.010	716.620	0.404	0.50

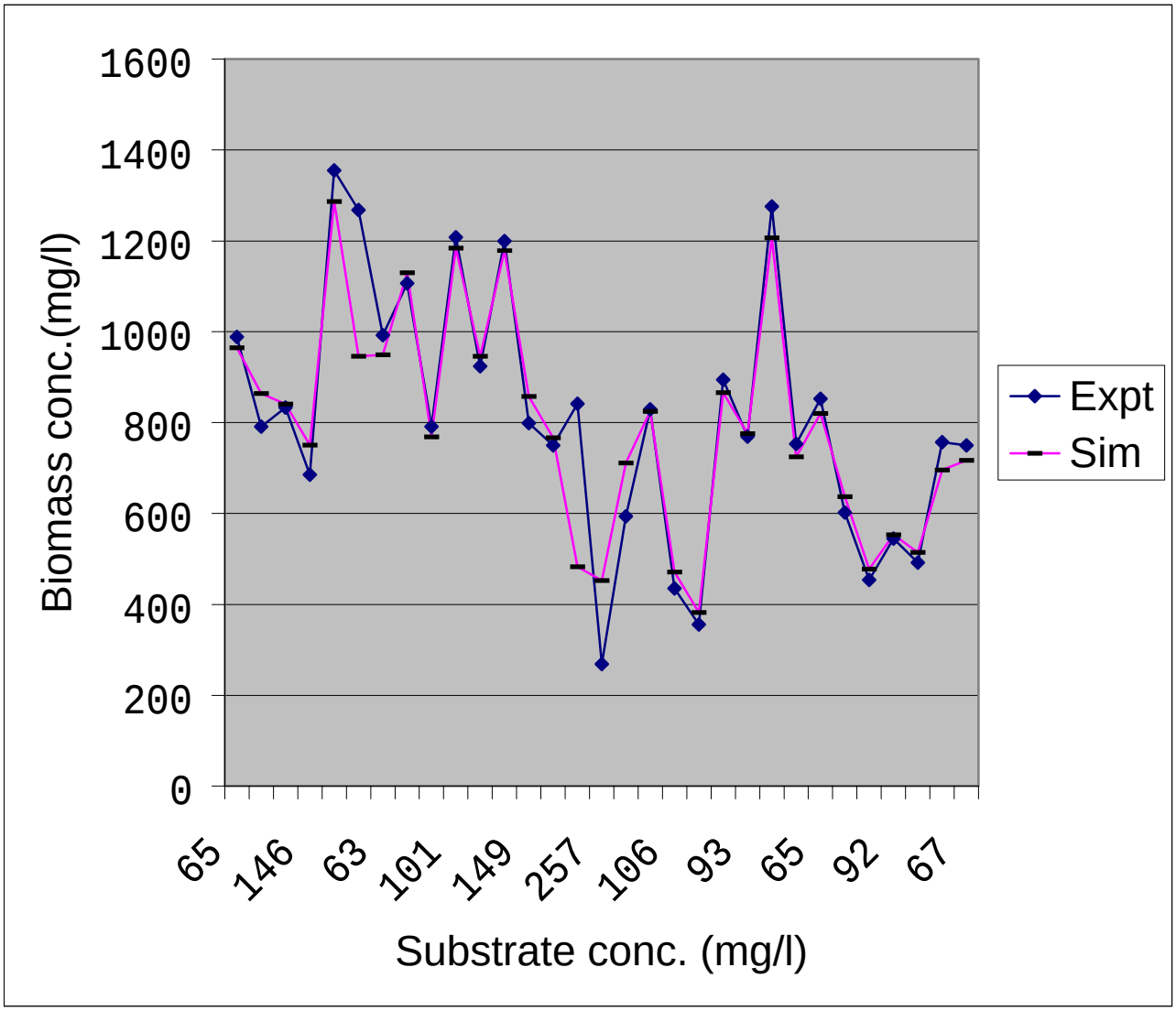

Fig. 2. Graph of biomass concentration *vs.* substrate concentration for experimental and Simulated results

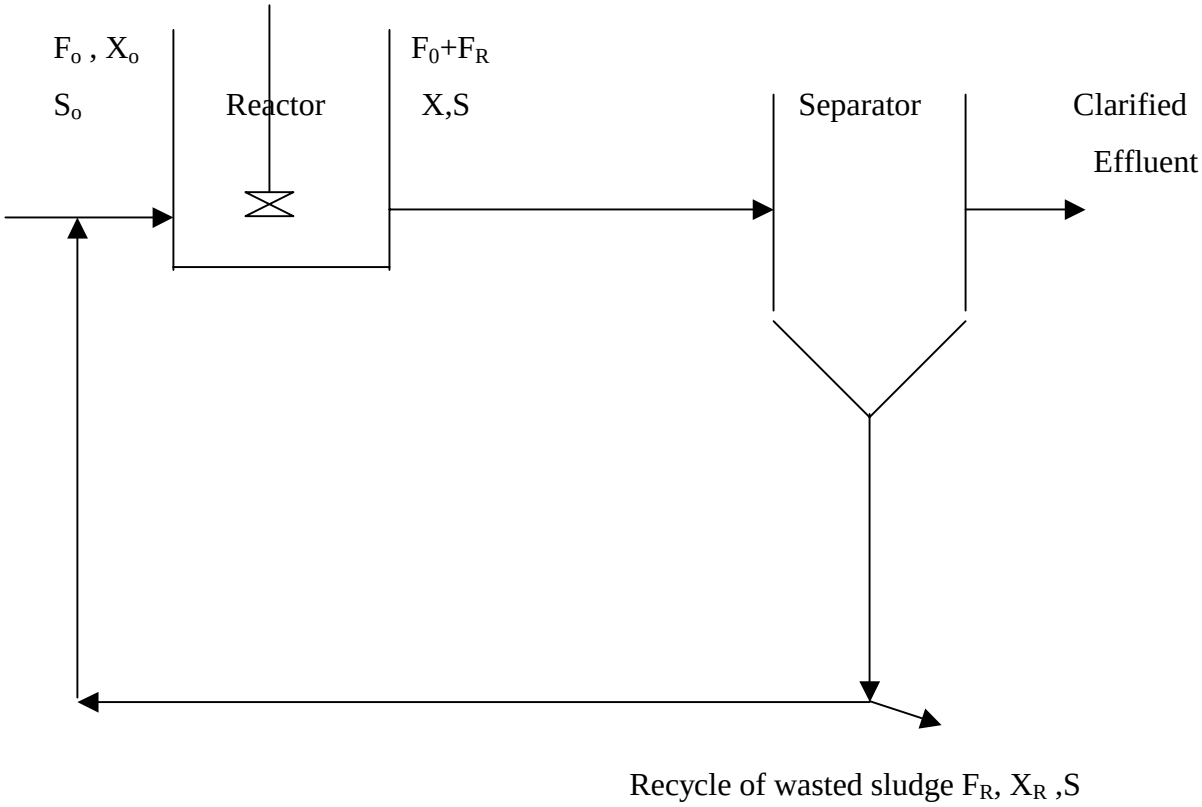

Fig. 1. Schematic diagram of reactor/aeration tank