

# Modeling and Simulation of an Activated Sludge System for Industrial Wastewater Treatment

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**Abstract**— Industrial wastewater generated during refining operations needs to be treated before being discharged so as to avoid environmental pollution and its detrimental effects. This work develops a model for an activated sludge bioreactor, which describes the dynamic behaviour of Biological Oxygen Demand (BOD) utilization and biomass growth. The activated sludge system was modeled from mass conservation principle, incorporating biodegradation kinetics. The model was solved numerically by employing the fourth order Runge-Kutta algorithm and simulated using Visual Basic 6.0 compiler. The model prediction of BOD degradation (30.67mg/l) as compared to plant data (30.0mg/l) showed a deviation of 2.23%. Functional parameters such as retention time; recycle ratio; and yield coefficient were simulated to study its variation on the system. These results, which are in concurrence with the plant design parameters implies that wastewater treatment plants could be described using system of CSTR configuration.

**Index Terms**— Wastewater, Activated sludge system, Simulation, Microorganisms, Treatment plant, Substrate.

## 1 INTRODUCTION

EFFICIENT and effective wastewater treatment techniques have assumed enormous attention over the last century.

Continued population growth and industrialization have resulted in the degradation of various ecosystems on which human life relies on. In the case of ocean and river quality, such pollution is primarily caused by the discharge of inadequately treated industrial and municipal wastewater. On initial discharge, these wastewaters can contain high levels of inorganic pollutants which can be easily biodegradable, but whose impact load on the ecosystems, either in Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), or Chemical Oxygen Demand (COD), may be in the tens of thousands mg/L (Ng, 2006). Wastewaters are used liquid of different density and composition that flow out of factories and industries, homes or establishment, which may be harmful. Wastewaters are usually classified as industrial wastewater or municipal wastewater. The characteristics of industrial waste vary greatly from industry to industry. For instance the food industrial waste is very much different from the waste from iron and steel industry.

Generally, there are four basic steps in the treatment of both domestic and industrial wastewater. These include: (a) Pre-treatment (b) Primary treatment (c) Secondary treatment and (d) Advanced treatment.

Pre-treatment step can either be physical or chemical or a combination of both. This refers to processes that prepare wastewater to a condition that it can be further treated in conventional secondary treatment biological process. It involves use of screens, grits channels, floatation (gravity, vacuum, electro, dissolved air or air flotation), and equalization technique. Primary treatment is often called clarification, sedimentation or settling. It involves mainly physical operations. It is the unit process where the wastewater is allowed to settle for a period in a settling tank, thus producing a somewhat clarified liquid effluent in one stream, and liquid-solid sludge (called primary sludge) in a second stream. The secondary treatment step is mainly biological. Secondary treatment is a process that is capable of

biodegrading the organic matter into non-polluting end products such as water, carbon dioxide CO<sub>2</sub> and biomass (sludge) Secondary treatment systems are broadly categorized as: *Suspended growth systems* example of which is the activated sludge system and *Attached growth systems or fixed film reactors* examples of which include; trickling or percolating filters, bio towers, and Rotating Biological Contactors (RBC).

With appropriate analysis and environmental control, almost all wastewaters containing biodegradable constituents with a BOD/COD ratio of 0.5 or greater can be treated easily by biological means [1]. In comparison to other methods of wastewater treatment, it also has the advantages of lower treatment costs with no secondary pollution [2]. Both aerobic and anaerobic processes can be used. Aerobic biological processes are commonly used in the treatment of organic wastewaters for achieving high degree of treatment efficiency, while in anaerobic treatment, considerable progress has been achieved in anaerobic biotechnology for waste treatment based on the concept of resource recovery and utilization while still achieving the objective of pollution control [3]

In general, aerobic systems are suitable for the treatment of low strength wastewaters (biodegradable COD concentrations less than 1000 mg/L) while anaerobic systems are suitable for the treatment of high strength wastewaters (biodegradable COD concentrations over 4000 mg/L) [4].

Industrial wastewater if discharged into the environment without proper treatment has detrimental effects on the environment. It results in water pollution; thus affecting living organisms both plants and animals alike. It becomes justifiable that adequate techniques should be designed for efficient and effective wastewater treatment to curb these detrimental effects. Simulation modeling is an effective tool in the design of such processes. It provides the needed environment to study the different parameters of the system before design and fabrication, thus all the mistakes are made on a pilot scale rather than on an industrial scale.

The aim of this research is to develop adequate mathematical models to predict Biological Oxygen Demand (BOD)

degradation in an industrial activated sludge system by applying mass conservation principle to predict substrate and biomass behavior, applying biodegradation kinetics to the system, obtaining industrial plant data, using fourth-order Runge-Kutta algorithm to solve the model equations with the aid of a Visual Basic 6.0 compiler program, validating the result and simulating functional parameters.

## 2 RESEARCH METHODOLOGY

### 2.1 Bio-reactor Model

The continuity equation for the mass balance of the bio reactor has depicted in figure 1, where used to develop the mathematical model to monitor the biomass and substrate concentration in the activation sludge bio reactor.

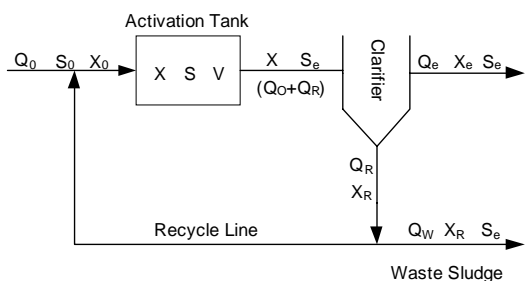


Fig 1: Hypothetical representation of an activated sludge reactor.

Assumptions made during model development include:

1. Readily biodegradable substrate, which serves as source of carbon and energy, are present and accessible to the heterotrophic bacteria.
2. The major reactions are oxidation of the carbonaceous substrates by endogenous decay of the heterotrophics.
3. Sufficient aeration is maintained in the bioreactor, that is oxygen is sufficiently present, so as to achieve good mixing of the liquid phase.
4. The limiting substrates are consumed by all of the different heterotrophic bacteria.
5. The feed stream is sterile; the biomass is acclimated and introduced at exponential growth phase.
6. The clarifier is ideal: with assumed constant volume. No reaction at the clarifier.
7. There is no longitudinal mixing, only well-mixed contents perpendicular to flow.
8. All particles reside for the same amount of time in the bioreactor.

### 2.2 Mass Balance for Microorganisms

$$\left[ \begin{array}{l} \text{Rate of accumulation of} \\ \text{microorganism within the system} \end{array} \right] = V \frac{dX}{dt} \quad (2)$$

$$\left[ \begin{array}{l} \text{Rate of flow of microorganism} \\ \text{into the system boundary} \end{array} \right] = XQ \quad (3)$$

$$\left[ \begin{array}{l} \text{Rate of flow of microorganism} \\ \text{out of the system boundary} \end{array} \right] = X_R Q_R + Q_W X_R + Q_e X_e \quad (4)$$

$$\left[ \begin{array}{l} \text{Net growth of microorganism} \\ \text{within the system boundary} \end{array} \right] = R_X V \quad (5)$$

Substituting (2) – (5) into equation (1) yields

$$V \frac{dX}{dt} = XQ - (Q_R X_R + Q_W X_R + Q_e X_e) + R_X V$$

Expanding and collecting like terms yields

$$V \frac{dX}{dt} = XQ - Q_R X_R - (Q_W X_R + Q_e X_e) + R_X V$$

$$V \frac{dX}{dt} = XQ \left( 1 - \frac{Q_R X_R}{QX} \right) - (Q_W X_R + Q_e X_e) + R_X V \quad (6)$$

Substituting the value of the kinetic  $R_X$  in (10) into (6) yields

$$V \frac{dX}{dt} = XQ \left( 1 - \frac{Q_R X_R}{QX} \right) - (Q_W X_R + Q_e X_e) + \left( \mu_m \frac{S}{K+S} - \varpi \right) XV$$

Dividing through by  $VX$  yields

$$\frac{V}{VX} \frac{dX}{dt} = \frac{XQ}{VX} \left( 1 - \frac{Q_R X_R}{QX} \right) - \frac{(Q_W X_R + Q_e X_e)}{VX} + \left( \mu_m \frac{S}{K+S} - \varpi \right) \frac{XV}{VX}$$

$$\frac{1}{X} \frac{dX}{dt} = \frac{Q}{V} \left( 1 - \frac{Q_R X_R}{QX} \right) - \frac{(Q_W X_R + Q_e X_e)}{VX} + \left( \mu_m \frac{S}{K+S} - \varpi \right) \quad (7)$$

$$\frac{1}{X} \frac{dX}{dt} = \frac{1}{\tau} (1 - R) - \frac{1}{\theta} + \left( \mu_m \frac{S}{K+S} - \varpi \right) \quad (8)$$

Multiplying (8) through by  $X$  yields

$$\frac{dX}{dt} = \frac{X}{\tau} (1 - R) - \frac{X}{\theta} + \left( \mu_m \frac{S}{K+S} - \varpi \right) X \quad (9)$$

where,  $\tau = V/Q$  is the period of aeration or hydraulic retention time,  $\theta = VX / (Q_W X_R + Q_e X_e)$  mean residence time or solid retention time of microorganisms in the reactor,  $R = Q_R X_R / QX$  is the reflux ratio.

### 2.3 Kinetics for Microorganisms

For mixed microbial consortia, as in activated sludge, the net growth rate accounting for both microbial explosion and endogenous death is expressed as

$$R_X = (\mu - \varpi)X \quad (10)$$

Where  $\mu$  = Specific microbial growth rate ( $h^{-1}$ ),  $\varpi$  = Microbial decay rate ( $h^{-1}$ ).

The specific growth rate for substrates presented by [5], [6] is expressed as

$$\mu = \mu_m \frac{S}{K_S + S} \quad (11)$$

Where  $S$  = Substrate concentration (mg/l),  $\mu_m$  = Maximum specific growth rate ( $h^{-1}$ ),  $K_S$  = Half saturation constant (mg/l). Substituting (11) into (10) gives:

$$R_X = (\mu - \varpi)X \quad (12)$$

## 2.4 Mass Balance for Substrates

$$\left[ \begin{array}{l} \text{Rate of} \\ \text{accumulation} \\ \text{of Substrate} \\ \text{within the system} \end{array} \right] = \left[ \begin{array}{l} \text{Rate of flow} \\ \text{of Substrate} \\ \text{into the system} \\ \text{boundary} \end{array} \right] - \left[ \begin{array}{l} \text{Rate of flow} \\ \text{of Substrate} \\ \text{out of the} \\ \text{system boundary} \end{array} \right] + \left[ \begin{array}{l} \text{Net depletion of} \\ \text{substrate within} \\ \text{the system} \\ \text{boundary} \end{array} \right] \quad (13)$$

$$\left[ \begin{array}{l} \text{Rate of accumulation of} \\ \text{substrate within the system} \end{array} \right] = V \frac{dS}{dt} \quad (14)$$

$$\left[ \begin{array}{l} \text{Rate of flow of substrate} \\ \text{into the system boundary} \end{array} \right] = QS_0 \quad (15)$$

$$\left[ \begin{array}{l} \text{Rate of flow of substrate} \\ \text{out of the system boundary} \end{array} \right] = Q_e S_e + Q_w S_e \quad (16)$$

$$\left[ \begin{array}{l} \text{Net growth of substrate} \\ \text{within the system boundary} \end{array} \right] = R_S V \quad (17)$$

Substituting (14) – (17) into (13) yields

$$V \frac{dS_n}{dt} = QS_0 - (Q_e S_e + Q_w S_e) + R_S V \quad (18)$$

The substrate utilization rate,  $R_S$  is expressed as

$$R_S = \frac{\mu X}{Y} \quad (19)$$

Assuming that the substrate in the waste stream is negligible and that the inflow flow rate is the same as the exit flow rate, and substituting the value of  $R_S$  in (19) into (18) yields

Substituting (11) into (19) yields:

$$R_S = \frac{\mu_m X}{Y} \left( \frac{S}{K_S + S} \right) \quad (20)$$

$$V \frac{dS}{dt} = Q(S_0 - S_e) + \frac{\mu_m X}{Y} \left( \frac{S}{K_S + S} \right) V \quad (21)$$

Dividing through (21) by  $V$  yields

$$\frac{dS}{dt} = \frac{Q}{V} (S_0 - S_e) + \frac{\mu_m X}{Y} \left( \frac{S}{K_S + S} \right) \quad (22)$$

$$\frac{dS}{dt} = \frac{1}{\tau} (S_0 - S_e) + \frac{\mu_m X}{Y} \left( \frac{S}{K_S + S} \right) \quad (23)$$

where,  $\tau = V/Q$  is the hydraulic retention time of substrates in the reactor.

(9) and (23) are the model equations predicting the growth of microorganism and the depletion of substrate in the activated sludge reactor.

## 2.3 Materials

The biomass and substrate concentrations obtained from an Industrial Activated Sludge Process of the wastewater

treatment unit at Eleme Petrochemicals Company, Nigeria are given in Table 1. The operating parameters are given in Table 2. The kinetics parameters as shown in Table were obtained from literatures. These values were used for this study because the experimental conditions for which the kinetics was obtained are in agreement with operating conditions of the wastewater treatment plant studied in this work.

For simplification, a constant maximum specific growth rate that does not change when the identity of limiting resource changes is assumed for this work, though previous study showed that the physiological state of an organism changes as the identity of limiting resource changes ( $\mu_{max}$ ,  $Y$  and  $K_s$  change when the identity of limiting resource changes [7]. This assumption was based on previous work describing microbial growth on essential substrates using Liebig's law if minimum and assuming a constant maximum specific growth rate [8], [9].

TABLE 1

BIOMASS AND SUBSTRATE CONCENTRATION FROM THE BIOLOGICAL TREATMENT UNIT

Component	Concentration (mg/l)	
	Inlet	Outlet
Biomass (MLVSS)	2400	8145.33
Substrate (BOD)	250	≤30.0

\* MLVSS – Mixed Liquor Volatile Suspended Solids (mg/l)

TABLE 2

PROCESS PARAMETERS FROM THE BIOLOGICAL TREATMENT UNIT

Parameters	Values
Design Flow Rate (l/h)	75,000
Reactor Volume (l)	1200000
Hydraulic Retention Time, $\theta$ (h)	16.0
Recycle Ratio	1.0

TABLE 3

KINETIC PARAMETERS [10]; [5], [11].

Parameters	Values
Half Saturation Coefficient, $K_S$ (mgBOD <sub>5</sub> /l)	60.0 mg/l
Maximum Specific Growth rate, $\mu_m$ (mgBOD <sub>5</sub> /mgVSS/h)	0.251h <sup>-1</sup>
Yield coefficient, $Y_G$ (mgVSS/mgBOD <sub>5</sub> )	0.6mg/mg BOD <sub>5</sub>

Endogenous decay coefficient, $\omega$	2.4day <sup>-1</sup> (0.1h <sup>-1</sup> )
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### 2.4 Solution Technique and Boundary Conditions

Initially (i.e at t=0), the concentration of substrate (BOD) in the waste water inoculated with the biomass is uniform at 250mg/l, while the concentration of biomass introduced is 2400mg/l.

The initial and boundary conditions of (15) and (23) may then be defined as

$$At \quad t = 0; X(0) = 2400mg / l, S(0) = 250mg / l \quad (24)$$

$$At \quad t = t, X = X(t), S = S(t) \quad (25)$$

(15) and (23) were solved simultaneously using the above initial and boundary conditions, and the parameters in Tables 1, 2, and using fourth order Runge-Kutta algorithm implemented in a Visual Basic 6.0 program Compiler.

### 3 RESULTS AND DISCUSSION

Table 4 shows the comparison between plant data and prediction of the model. (9) and (23), indicating that the predicted data agree reasonably well with the plant data. The results obtained were validated by comparing it with industrial plant data from a functional industrial wastewater treatment plant with a deviation of 2.23%, suggesting that the model can be used to study and optimize the behavior of an industrial wastewater bioreactor.

TABLE 4  
COMPARISON BETWEEN MODEL PREDICTION AND PLANT DATA

Parameter	Model Prediction	Plant Data	% Deviation
Exit BOD Concentration (Mg/l)	30.67	30.00	2.23

In industrial activated sludge systems, biodegradation occurs when the wastewater containing the substrate to be removed is brought into contact with flocculated microorganisms in the oxidation dish. The microorganisms feed on the substrate, thus reducing its concentration in the wastewater. From Figure 2, it could be seen that the BOD concentration reduces from an initial concentration of 250 Mg/l to 30.67 Mg/l. At this concentration; the wastewater can be discharged into the environment. Significant of note is the correlation between biomass concentration and BOD concentration within the reactor; the higher the biomass concentration, the lower the BOD concentration.

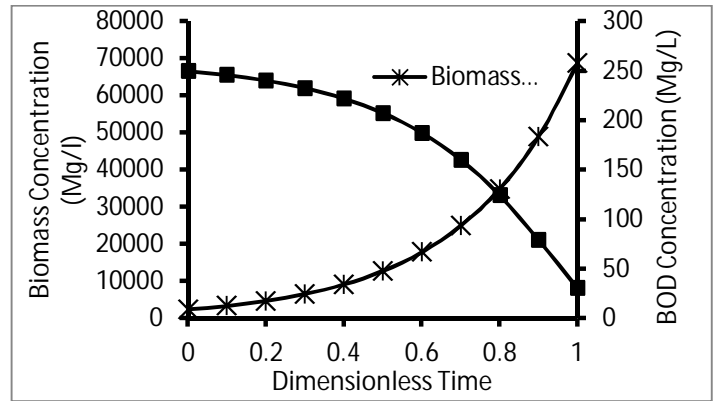


Fig 2: Profile of Biomass and BOD Concentration at each Bioreactor Stage

### 3.1 Result Simulation

To study the behavior of the system under different loading and operating conditions, a simulation study or sensitivity analysis was conducted on important parameters of the system. The parameters investigated in this study includes; retention time, recycle ratio, yield coefficient, and the reaction constant.

### 3.2 Variation of Retention

Retention time is an important design parameter for activated sludge systems. It is very essential for maximum biomass growth and substrate biodegradation. If the retention time is low, biomass growth is limited, thus there will not be enough microorganisms in the system. This will have an adverse effect on substrate biodegradation.

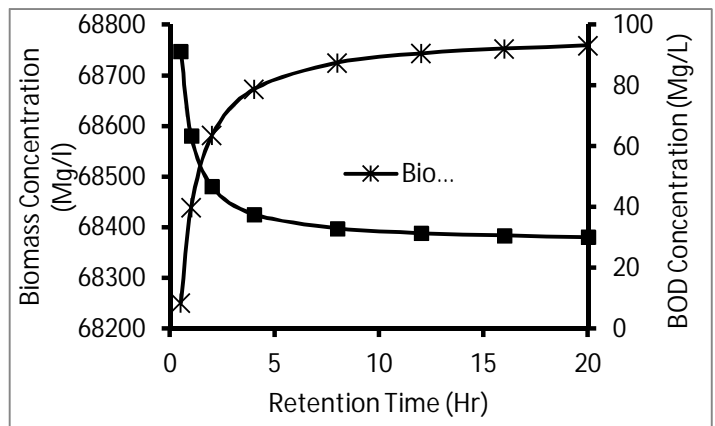


Fig 3: Variation of Biomass and BOD Concentration with Retention Time

Figure 3 shows the profile of the effect of the variation of retention time on the biomass concentration and BOD concentration. The graph follows the discussed trend. The biomass concentration increases with increase in retention time; suggesting that the longer retention time enables the microorganisms to grow within the system. The biomass concentration curve follows a typical microbial growth curve. Sharp growth is observed within the first eight (8) hours, followed by a period of stationary growth. The substrate (BOD) concentration curve follows a reverse pattern. The

concentration of the substrate reduces with increase in the retention time. This implies that the longer the wastewater stays in the system, the higher the rate of degradation. Correlating both curves, it can be observed that the period of higher biodegradation (91.36 Mg/l to 33.03 Mg/l) corresponds to the growth period of the microorganisms. At the stationary growth period, the rate of biodegradation is reduced to a nearly constant value.

### 3.3 Variation in Recycle Ratio

To increase the substrate utilization rate without increasing the specific substrate utilization rate, the acclimatized biomass is recycled to the reactor. This stabilizes the system and ensures that the microorganism is not overly depleted. All things being equal, increase in recycle ratio will lead to increase in the biomass concentration and a decrease in the concentration of the substrate. This is because the large microorganisms returned to the system leads to increase in the concentration of the biomass, these increases the biodegradation rate, thus leading to reduction in the concentration of the substrate.

Figure 4 shows the effect of the variation of the recycle ratio on the concentration of the biomass and the substrate (BOD). As expected, the biomass concentration increases with increase in the recycle ratio, also substrate (BOD) concentration reduces with increase in the recycle ratio. Thus, for maximum biodegradation, the system should be operated at 100% recycle ratio.

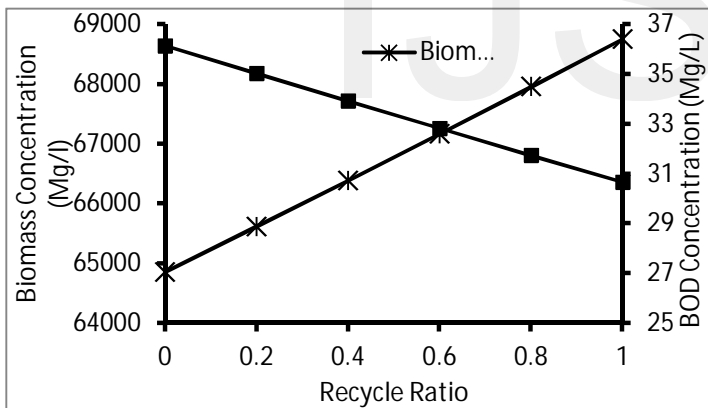


Fig 4: Variation of Biomass and BOD Concentration with Recycle Ratio

### 3.4 Variation of Yield Coefficient

During biodegradation all the substrate are not converted to biomass. Some of the substrates are used for cell maintenance. The cell yield or yield coefficient is used to describe the fraction of the substrate converted to biomass. It is the ratio of the mass of new cells formed to the mass of substrate consumed. The yield coefficient is an important design parameter for activated sludge systems. It is used to size the sludge disposal facility. An increase in the yield coefficient implies that more of the substrate is converted to biomass. Thus increase in yield coefficient results in increase in biomass concentration and a reduction in the concentration

of the substrate.

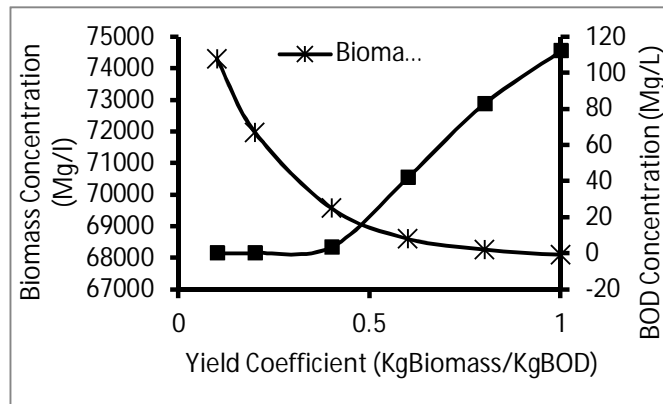


Fig 5: Variation of Biomass and BOD Concentration with Yield Coefficient

Figure 5 show the effect of the variation of yield coefficient on the concentration of biomass and the substrate. The graph follows the desired trend. The biomass concentration increases with increase in the yield coefficient. Also, the biomass curve follows a typical microbial growth curve with a lag phase between 0 to 0.4 yield coefficients; followed by a growth phase. The concentration of substrate (BOD) decreases with increase in the yield coefficient as more of the substrate is converted to biomass.

## 4 CONCLUSION

The importance of energy to the development of the economy cannot be over emphasized. In addition to electricity generation, fossil fuels especially petroleum is used in powering industrial plants and automobiles. It is a well-known fact that industrial wastewater is generated during refining operation. Industrial wastewater if discharged into the environment without proper treatment impacts negatively on the environment. It results in water pollution; thus affecting living organisms and the ecosystem. In order to maximize profit, wastewaters have to be efficiently treated at the best cost possible. Suspended growth systems which are aerobic processes that achieve a high microorganism concentration through the recycle of biological solids, is a time tested and proven method of treating industrial wastewater. The bacterial organisms convert biodegradable organic wastewaters and certain inorganic fractions into new biomass and other non-polluting end product. In comparison to other methods of wastewater treatment, it has the advantages of lower treatment costs with no secondary pollution. Also, aerobic biological processes are commonly used in the treatment of organic wastewaters for achieving high degree of treatment efficiency. As with other engineering processes, it is proper to

make all the mistakes on a pilot scale than to make them on an industrial scale. To ensure this, modeling and simulation plays an important role. It provides the environment needed to study the different parameters of the system before design and fabrication.

In recognition of the above fact, this work presents an activated sludge model for the treatment of Biological Oxygen demand (BOD) in industrial water. The case study was drawn from a functional petrochemical company in the Niger Delta region of Nigeria. The model result gives an effluent BOD concentration of 30.67 mg/l, which compares favourably with the plant data of 30.00mg/l with 2.23% deviation. Functional parameters such as retention time; recycle ratio; and yield coefficient were simulated to study their effect on the reactor.

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