Y. T. Puyate, Z. R. Yelebe / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 6, November- December 2012, pp.903-911

Estimation Of Monod Kinetic Parameters During Aerobic Digestion Of Biodegradable Organic Waste, Part 2: Analysis Based On Microbial Growth With Effect Of Bioaugmentation

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ABSTRACT

Monod kinetic parameters based on microbial growth during aerobic digestion of biodegradable organic waste are estimated. The analysis involves non-bioaugmentation and bioaugmentation of aerobic biodegradation of organic waste in bioreactors labeled "non-bioaugmented (i.e. control) bioreactors," and "bioaugmented bioreactors" respectively, using a mixed culture of indigenous microorganisms isolated from the waste for bioaugmentation. The maximum specific growth rates (μ_m) of microorganisms during biodegradation of the waste are 0.127 and 0.215 day^{-1} for the control and bioaugmented bioreactors respectively. Dimensional yield coefficients (γ') for the control and bioaugmented bioreactors are 2.93×10^{10} cfu/mg and 3.22×10^{11} cfu/mg respectively. It is shown that the substrate saturation constant, K_s, in Monod equation varies with time and microbial density during microbial growth. Models for predicting K_s as a function of time, and microbial density as a function of K_s, are also presented. Predictions of the models are compared with experimental data and good agreement is obtained.

Key words: Aerobic digestion, Bioaugmentation, Biodegradation, Monod kinetics, Organic waste.

1. INTRODUCTION

In most developing countries like Nigeria, handling and treatment of municipal solid waste (MSW) is a major concern to the government and the people. Nigeria for example, produces approximately 22 million tonnes of municipal solid waste annually based on an average of 0.5 kg solid waste generated by every Nigerian per day [1], majority of which is dumped in municipal landfills and/or heaped openly on the earth's surface at various locations in the cities. These methods of disposing solid waste which are commonly practiced in this part of the world have left an inheritance of abandoned dumpsites, contaminated soil and groundwater, poisoned lakes and streams, and disposal sites with toxic waste and methane explosion potential in many locations [2]. The development and implementation of better engineering systems for proper handling of solid waste generated by man, rather than just dumping them into the environment, is extremely important in protecting surface water, groundwater, soil, and maintaining air quality standards. According to Ogunbiyi [1], not less than 65% of our domestic waste is vegita, while the remaining 35% is made up of plastics, rubbers, cotton, leathers, metals, glasses, etc. With the ever-increasing cost of land, increase in human population, and difficulties in permitting new landfill sites, existing landfill space is becoming a valuable commodity.

Biodegradation (or microbial degradation) of organic pollutants is a biological treatment process accomplished primarily by microorganisms which utilize organic matter for metabolism [3,4]. Biological treatment of solid waste is a cost effective alternative to other waste treatment techniques and many experts regard biotreatment as the technology of the future [5]. Waste containing substantial amount of biodegradable organic compounds can be treated biologically under aerobic conditions. The biological oxidation of organic waste by micro-organisms under aerobic conditions to produce stable waste, water, and a mixture of carbon dioxide and other gases, is known as aerobic digestion and is one of the most common waste treatment techniques [6]. Although aerobic digestion is used worldwide for the treatment of industrial, agricultural, and municipal wastewater as well as sludge because of the proven feasibility of the process and the multitude of environmental benefits, the technology is also applied to the treatment of municipal solid waste in recent years [6,7].

Bioremediation involves the use of microorganisms to remove pollutants, and the process is becoming an increasingly important remedial option [8,9]. Adding nutrients to a contaminated site to stimulate the growth of the indigenous microbial community is known as biostimulation and it is used extensively for restoration of the environment at petroleum-polluted sites. Injecting microorganisms with extensive degrading activity into a contaminated site to breakdown a pollutant is known as

bioaugmentation. Biostimulation and bioaugmentation either in-situ or ex-situ are various modifications of bioremediation [9].

Monod growth kinetics [10] is widely used in modeling biodegradation of organic compounds and microbial growth in pure culture, waste treatment systems, and the natural environment. When Monod equation is coupled with biomass yield and decay, a number of kinetic parameters are required to describe the operation of a system. Studies have shown that the kinetics of microbial degradation is best represented by a batch culture [11], and a lot of work has been done on estimation of the kinetic parameters in Monod equation for various systems. For example, Lin and Weber [12] proposed a non-linear regression procedure for obtaining unbiased estimates of all Monod kinetic parameters using batch test data. Igoni et al. [13] estimated constant values of the kinetic parameters in Monod equation during anaerobic digestion of MSW. Simkins and Alexander [14] estimated the parameters of Monod kinetics that best describe mineralization of several substrate concentrations by dissimilar bacterial densities. Robinson and Tiedje [15] estimated the Monod growth kinetic parameters from a single substrate depletion curve, while Dang et al. [16] studied biodegradation kinetics with respirometric data. Literature on the biokinetics of aerobic digestion of MSW is scarce.

Yelebe and Puyate [17] presented an approximate model for predicting microbial density during aerobic biodegradation of MSW, where the substrate saturation constant (K_s) in Monod equation was neglected. Predictions of the model show significant deviations from experimental data, which was attributed to the neglected K_s in the analysis. Puyate and Yelebe [18] estimated Monod kinetic parameters based on substrate utilization during aerobic digestion of biodegradable organic waste with and without the effect of bioaugmentation. In this current paper, all kinetic parameters in Monod equation are estimated from experimental data [19] based on microbial growth during aerobic digestion of biodegradable organic waste in bioaugmented and non-bioaugmenetd batch reactors. The difference between the present analysis and the one presented in Puyate and Yelebe [18] lies in the kinetics of substrate utilization and microbial growth during biodegradation of organic waste in a batch reactor. Also, the substrate saturation constant (K_s) in Monod equation, substrate concentration, and microbial density are predicted by different equations in the present analysis and in Puyate and Yelebe [18] thereby providing general alternative procedures for estimating Monod kinetic parameters during aerobic biodegration process. A mixed microbial culture isolated from the waste is used for the bioaugmentation since mixed microbial populations composed of many different bacterial species often achieve a greater degree of biodegradation [20-22] than pure cultures which generally degrade only a limited number of the compounds found in a pollutant [23].

2. MATERIALS AND METHOD

Biodegradable organic waste composed of food waste, wood/leaves, and paper, was collected, chopped manually, and mashed to homogenize the mixture. Ten-fold serial dilution method [24] of analysis was used to enumerate and isolate three types of bacteria (*Bacillus species*, *Staphylococcus species*, and *Pseudomonas species*) from the waste. The isolated bacteria were then used to prepare a broth culture (consortium of bacteria) required for bioaugmentation of the biodegradation process. Details of the preparation of the liquid waste and broth culture used in the study are presented in Yelebe [19].

Fifty batch reactors, each consisting of 500 ml round bottom flask, were used for the experiment conducted in the Laboratory of the Department of Chemical/Petro-chemical Engineering, Rivers State University of Science and Technology, Port Harcourt, Nigeria. Twenty-five of the bioreactors were labeled 'bioaugmented' and each bioreactor was charged with 370 ml of the prepared liquid waste, while each of the remaining twenty-five bioreactors were labeled 'control' and charged with 400 ml of the prepared liquid waste. Thirty millilitres (30 ml) of the prepared broth culture was added to each of the bioaugmented bioreactors which increased the volume of the liquid in each of these bioreactors to 400 ml. The broth culture raised the initial microbial density in each of the bioaugmented bioreactors to 2.06×10^{11}cfu/l, while the initial microbial density in each of the twenty-five control-bioreactors with no innoculum added was 1.04×10^{11}cfu/l. The bioreactors and their contents were instrumented to monitor pressure, temperature, and airflow rate. Air was injected to the bottom of each flask for proper aerobic treatment, and the gas produced during the microbial degradation process was vented out from the open end of each flask. The flow rate of air was approximately 0.15 l/min per 400 ml of the organic waste solution, and this airflow rate was chosen to ensure proper mixing/bubbling of the solution in each flask without splashing on the walls of the flask. During the natural process of organic matter degradation in landfills, 'contaminated water' called leachate is formed. In the present case, the leachate produced during the biodegradation process was not withdrawn from the bioreactors, and the experimental setup was allowed to run for 50 days.

Every 2 days, one bioaugmented-flask and one control-flask were dismantled and a sample was taken from each flask and analysed for microbial density and chemical oxygen demand (COD) using standard methods in Ofunne [24] and Clesceri et al.

[25], noting that COD (taken here to represent substrate concentration) is normally used to determine the degree of degradation of waste [7]. The pH of the medium in each dismantled flask was also measured at the same time intervals as the other parameters (i.e. COD and microbial density) using a digital pH meter. The fractional conversion of substrate (X_s) based on the measured COD was calculated as

$$X_s = \frac{Initial\ COD - Final\ COD}{Initial\ COD}$$

The temperature in each bioreactor was measured twice daily at 0900 and 1600 hours using a thermometer.

3. KINETICS OF MICROBIAL GROWTH IN A BATCH REACTOR

The batch growth of microorganisms involves adding a small quantity of the microorganisms or their spores (the seed culture or inoculum) to a quantity of nutrient material (called substrate) in a suitable vessel. In the present case of aerobic digestion of biodegradable organic waste, the contents of the bioreactors were aerated to create aerobic condition for microbial growth. It is assumed that only oxygen from the air entering the vessel enhances growth of microorganisms, and the carbon dioxide in the inlet air is ignored. For a batch reactor in which the inflow and outflow terms are both zero, the material balance for growth of microorganisms yields

$$V\frac{d\rho_c}{dt} = r_g V = \mu\rho_c V \quad (1)$$

where V is the volume of the reactor, r_g is the growth rate of microorganisms (mass/(volume × time)), ρ_c is the microbial density or mass concentration of microorganisms (cells), t is time, and μ is the specific growth rate of microorganisms (time^{-1}) which is related to substrate concentration in the form [10]

$$\mu = \mu_m \frac{\rho_s}{K_s + \rho_s} \quad (2)$$

where ρ_s is the mass concentration of substrate, μ_m is the maximum specific growth rate of microorganisms, and K_s is the substrate saturation constant which is defined as the substrate concentration corresponding to $\mu = \mu_m / 2$. Combining eqs. (1) and (2) gives the batch culture rate equation for microbial growth as

$$\frac{d\rho_c}{dt} = \mu_m \frac{\rho_s \rho_c}{K_s + \rho_s} \quad (3)$$

If all the substrate is converted to cells, then the rate of substrate utilization is ideal. However, such an ideal condition does not occur in practice due to inefficiencies in the conversion process. Hence, a yield coefficient ($\gamma < 1$) is introduced such that the rate of substrate utilization is related to the rate of cells formation in the form

$$-\gamma\frac{d\rho_s}{dt} = \frac{d\rho_c}{dt} \quad (4)$$

where γ is the fraction of substrate converted to cells (mg/l of cells per mg/l of substrate) and ranges typically from 0.4 to 0.8 for aerobic systems, and 0.08 to 0.2 for anaerobic systems [2]. The yield coefficient may also be expressed as

$$\gamma = \frac{\rho_c - \rho_{co}}{\rho_{so} - \rho_s} \quad (5)$$

which can be rearranged to give

$$\rho_s = \rho_{so} - \frac{(\rho_c - \rho_{co})}{\gamma} \quad (6)$$

where ρ_{co} is the initial mass concentration of microorganisms, and ρ_{so} is the initial mass concentration of substrate. The mass concentration of microorganisms at any time in the batch reactor is obtained by solving eq. (3) in the form

$$\int\left(\frac{K_s + \rho_s}{\mu_m \rho_s}\right)\frac{d\rho_c}{\rho_c} = \int dt \quad (7)$$

Noting that ρ_s is a function of ρ_c, and substituting ρ_s from eq. (6) into eq. (7) and integrating the resulting expression yields

$$\frac{K_s\gamma + \rho_{so}\gamma + \rho_{co}}{\mu_m(\gamma\rho_{so} + \rho_{co})}\ln\left(\frac{\rho_c}{\rho_{co}}\right) + \frac{K_s\gamma}{\mu_m(\gamma\rho_{so} + \rho_{co})}\ln\left(\frac{\gamma\rho_{so}}{\gamma\rho_{so} + \rho_{co} - \rho_c}\right) = t \quad (8)$$

Equation (8) can be used to generate a graph showing changes in microbial density with time during batch biodegradation process. The main disadvantage of eq. (8) is that it is not explicit in ρ_c which requires solving for ρ_c at a particular value of t. We note in the present analysis that ρ_s is measured in mg/l; while $\hat{\rho}_c$ is measured in cfu/l, where the caret indicates the experimental units (cfu/l) of $\hat{\rho}_c$ and not mg/l. Hence, the appropriate forms of γ, ρ_c, and ρ_{co} to be used in eq. (8) are γ', $\hat{\rho}_c$, and $\hat{\rho}_{co}$ respectively, where the prime indicates that γ' is dimensional and expressed in cfu/mg.

3.1. Estimation of kinetic parameters during aerobic digestion of biodegradable organic waste

In this section, all kinetic parameters (μ_m, K_s, γ) in the Monod rate equations are estimated from experimental data [19] on microbial growth during aerobic digestion of biodegradable organic waste in bioaugmented and non-bioaugmented (i.e. control) batch reactors. It is shown in Yelebe [19] and Yelebe and Puyate [26] that microbial growth in the

bioaugmented and control bioreactors occurred during the first 20 days of the experiment, after which microorganisms in the bioreactors begin to die. The 'lag phase' of slow microbial growth in each type of bioreactor occurred during the first 10 days of the experiment, while the phase of very fast microbial growth (often called 'phase of exponential growth' of microorganisms) occurred between the 10^{th} and 20^{th} day of the experiment.

A dimensional yield coefficient (γ') is calculated from the experimental data [19] for the first 20 days using eq. (5) as 2.93×10^{10}cfu/mg for the control bioreactor, and 3.22×10^{11}cfu/mg for the bioaugmented bioreactors. Since the dimensionless yield coefficient (γ) is the fraction of substrate converted to cells, the value of γ for the aerobic digestion process considered in this study is 0.8 for the bioaugmented bioreactors, and 0.71 for the control bioreactors as shown in Figs. 1 and 2 respectively.

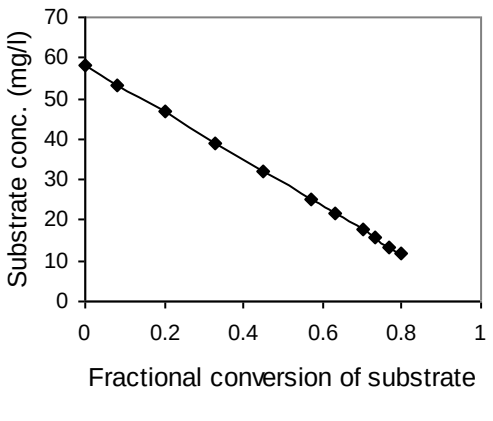

Fig. 1. Plot of substrate concentration against fractional conversion of substrate (bioaugmented).

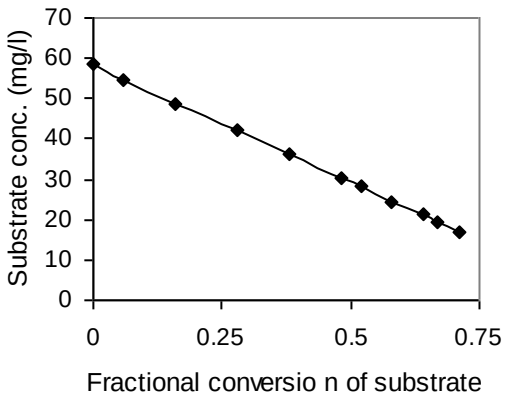

Fig. 2. Plot of substrate concentration against fractional conversion of substrate (control).

Thus the values of γ for the two types of bioreactors lie within the specified range (0.4 – 0.8) for aerobic systems [2]. It is obvious from Figs. 1 and 2 that the substrate concentration in the two types of bioreactors decreases as the fractional conversion of substrate increases.

The specific growth rate of microorganisms (μ) was calculated directly from the experimental data [19] using eq. (1) for the first 20 days of the experiment, and Fig. 3 shows plots of specific growth rate against substrate concentration in the bioaugmented and control bioreactors during the same period. It may be seen from Fig. 3 that the specific growth rate of microorganisms in the bioaugmented bioreactors is higher than in the control bioreactors and is attributable to the bioaugmentation of the system. Also, Fig. 3 indicates that the specific growth rate increases as the substrate concentration increases, which is due to abundant nutrients that promote and sustain microbial growth.

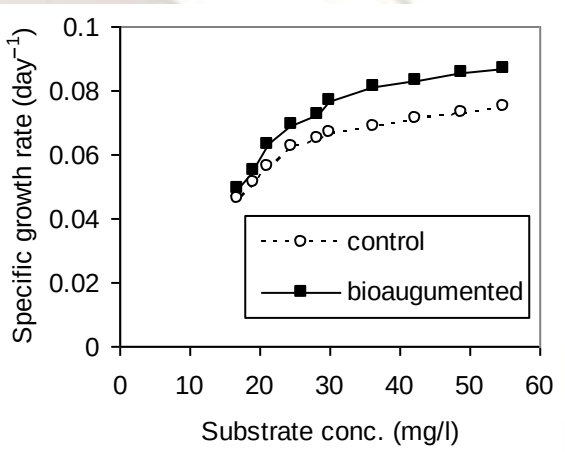

Fig.3. Plots of specific growth rate against substrate concentration

Yelebe and Puyate [17] estimated $\mu_m = 0.127\,\text{day}^{-1}$ and $0.215\ \text{day}^{-1}$ for the control and bioaugmented bioreactors respectively on the assumption that K_s is small compared to ρ_s, and K_s was neglected in the analysis. But predicted microbial densities in the two types of bioreactors based on this assumption did not compare well with experimental data. In the case where K_s is not negligible, a constant value of K_s is normally estimated as the substrate concentration corresponding to $\mu = \mu_m/2$ on a graph of specific growth rate against substrate concentration [11]. A constant value of $K_s \approx 24\,\text{mg/l}$ for the control bioreactors was estimated from Fig. 3, while a constant value of K_s for the bioaugmented bioreactors cannot be estimated from Fig. 3 since $\mu_m/2$ for this type of bioreactor lies outside the experimental range of μ. However, K_s may not be constant and a general procedure for estimating K_s

which is applied in the current analysis is presented as follows.

In order to investigate the effect of K_s on microbial growth during the aerobic digestion process, eq. (8) and experimental data [19] on microbial density during the period of microbial growth were used to generate values of K_s at specified intervals of time and corresponding values of $\hat{\rho}_c$ as shown in Table 1.

Table 1. Variation of K_s with microbial density and time

Time (days)	Control bioreactors		Bioaugmented bioreactors	
	K_s (mg/l)	$\hat{\rho}_c \times 10^{-11}$ (cfu/l)	K_s (mg/l)	$\hat{\rho}_c \times 10^{-11}$ (cfu/l)
0	4.0	1.04	4.0	2.06
2	32.46	1.22	73.92	2.49
4	26.98	1.47	60.54	3.14
6	22.24	1.8	49.622	4.13
8	15.42	2.31	39.597	5.72
10	8.64	3.12	27.66	8.8
12	0.35	4.73	11.38	17.66
14	-6.72	8.16	-7.69	70.2
16	-5.96	10.78	-6.44	108.5
18	-3.53	12.57	-3.60	138.12
20	-0.016	13.2	-0.012	152

It is obvious from Table 1 that K_s for each type of bioreactor varies with time and microbial density, indicating that K_s is not constant for the aerobic biodegradation process. The positive values of K_s in Table 1 correspond to a region of slow microbial growth such as the *lag phase*, while the negative values of K_s correspond to a region of fast microbial growth such as the *phase of exponential growth* [26]. Thus, the effect of K_s on microbial growth is considered in two stages: (i) a first stage of slow microbial growth with positive values of K_s, and (ii) a second stage of fast microbial growth with negative values of K_s. Such stage-wise treatment of engineering processes where the different stages have unique characteristics are reported in the literature. For example, drying of solids is often considered as a two-stage process where a *constant-rate period* during which the drying rate is constant is followed by a *falling-rate period* when the drying rate gradually decreases with time [27,28]. "Wick action" in concrete is also modeled as a two-stage transport process, where salt is transported in solution from a wet face of the concrete in contact with a marine environment to a dry face of the concrete in contact with air of relative humidity less than 100%, resulting in the buildup of salt at a liquid-gas interface within the concrete where evaporation of water occurs [29,30].

The initial microbial density in each type of bioreactor (Table 1) is not predicted in this study because it is constant and independent of any variable. This is justified in the application of *Newton's divided difference interpolation polynomial* to predict the flashpoints of bitumen blended with lighter petroleum products [31], and the flashpoints of kerosene blended with small quantities of alcohol [32], where the flashpoint of the pure (unblended) material was not predicted. Accordingly, the initial value of K_s in Table 1 is not predicted and the variations of K_s with time and microbial density in each type of bioreactor are investigated for $t > 0$, where t is the time in days.

3.1.1. Relationships between K_s, $\hat{\rho}_c$, and time for control bioreactors

It is obvious from eq. (8) that microbial density in the bioreactors depends on K_s and time, which is modeled in parts as follows: (i) K_s as a function of time, and (ii) microbial density as a function of K_s. Plotting the positive values of K_s for the control bioreactors in Table 1 against time for $2 \le t \le 12$ as shown in Fig. 4, gives

$$K_{s\,(ctrl)}^{+} = -0.0991t^2 - 1.7895t + 36.221 \qquad (9)$$

where the subscript '*ctrl*' refers to control bioreactors, and the positive superscript indicates the sign of K_s.

Plotting negative values of K_s for the control bioreactors in Table 1 against time for $14 \le t \le 20$ as shown in Fig. 5, yields

$$K_{s(ctrl)}^{-} = 0.1724t^2 - 4.7338t + 25.741 \qquad (10)$$

where the negative superscript indicates the sign of K_s. Thus, K_s decreases with time in the 'lag phase' (Fig. 4), but increases with time in the 'exponential growth phase' (Fig. 5).

Having known the functional relationship between K_s and time, the equations relating microbial density and K_s are obtained by plotting the microbial densities in Table 1 against the corresponding values of K_s for the control bioreactors in the range $t \ge 2$, to obtain

$$\hat{\rho}_{c\,(ctrl)}^{+} = 0.0029K_s^2 - 0.2016K_s + 4.7471 \qquad (11)$$

$$\hat{\rho}_{c(ctrl)}^{-} = -0.1854K_s^2 - 0.5824K_s + 13.131 \qquad (12)$$

which are shown graphically in Figs. 6 and 7, where the positive and negative superscripts of $\hat{\rho}_c$ indicate values of this parameter corresponding to positive and negative values of K_s respectively.

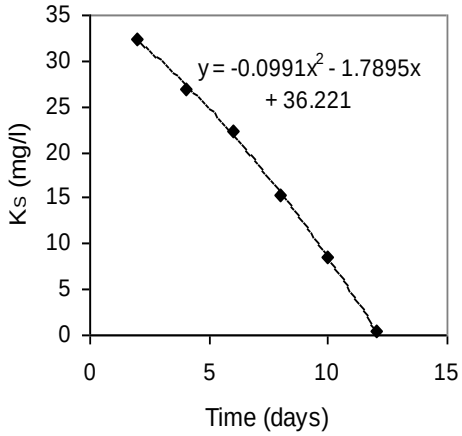

Fig. 4. Plot of positive values of K_s against time for control bioreactors in the range $2 \le t \le 12$.

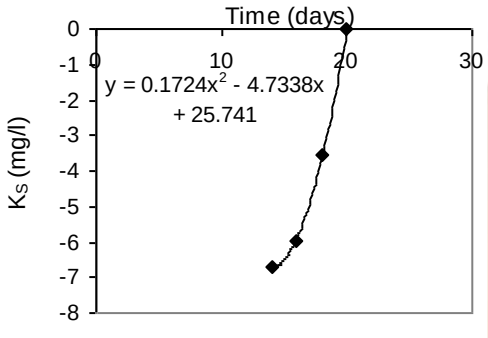

Fig. 5. Plot of negative values of K_s against time for control bioreactors in the range $14 \le t \le 20$.

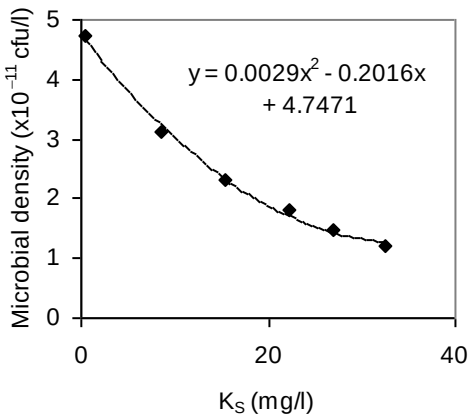

Fig. 6. Plot of microbial density against positive values of K_s for control bioreactors in the range $2 \le t \le 12$.

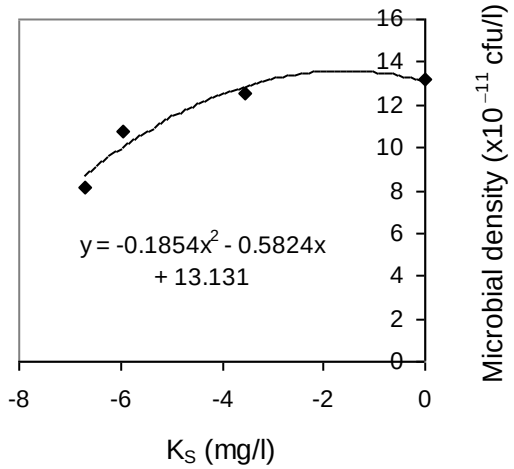

Fig. 7. Plot of microbial density against negative values of K_s for control bioreactors in the range $14 \le t \le 20$.

Fig. 6 indicates that microbial density in the 'lag phase' of the control bioreactors decreases as the value of K_s increases (or conversely, microbial density in the 'lag phase' increases as K_s decreases), while microbial density increases as K_s increases in the 'exponential growth phase' (Fig. 7). Since K_s decreases with time in the 'lag phase' and increases with time in the 'exponential growth phase,' it means microbial density increases with time in both the 'lag phase' and 'exponential growth phase' during microbial growth in the control bioreactors, which is consistent with the results of Yelebe and Puyate [26].

3.1.2. Relationships between K_s, $\hat{\rho}_c$, and time for bioaugmented bioreactors

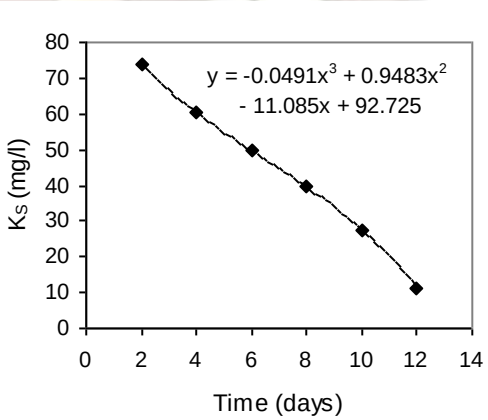

Fig. 8. Plot of positive values of K_s against time for bioaugmented bioreactors in the range $2 \le t \le 12$.

Plotting positive and negative values of K_s in Table 1 for the bioaugmented bioreactors against time in the range $2 \le t \le 12$, yields

$$K_{s\,(bioaug.)}^{+} = -0.0491t^3 + 0.9483t^2 - 11.085t + 92.725 \quad (13)$$

$$K_{s\,(bioaug.)}^{-} = 0.1461t^2 - 3.6745t + 15.071 \quad (14)$$

which are shown graphically in Figs. 8 and 9, where the subscript '*bioaug*' indicates bioaugmented bioreactors.

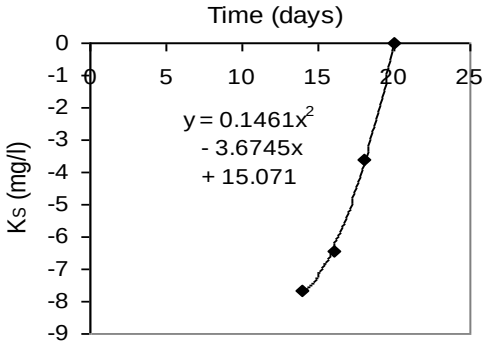

Fig. 9. Plot of negative values of K_s against time for bioaugmented bioreactors in the range $14 \le t \le 20$.

Like the control bioreactors, K_s in the 'lag phase of the bioaugmented bioreactors decreases with time,' but increases with time in the 'exponential growth phase.'

Accordingly, plotting the microbial densities in Table 1 against corresponding positive and negative values of K_s for the bioaugmented bioreactors in the range $2 \le t \le 20$, gives

$$\hat{\rho}_{c\,(bioaug.)}^{+} = -(8\times10^{-5})K_s^3 + 0.0152K_s^{\,2} - 1.0323K_s + 27.529 \quad (15)$$

$$\hat{\rho}_{c\,(bioaug.)}^{-} = -1.8244K_s^2 - 4.049K_s + 151.04 \quad (16)$$

which are shown graphically in Figs. 10 and 11.

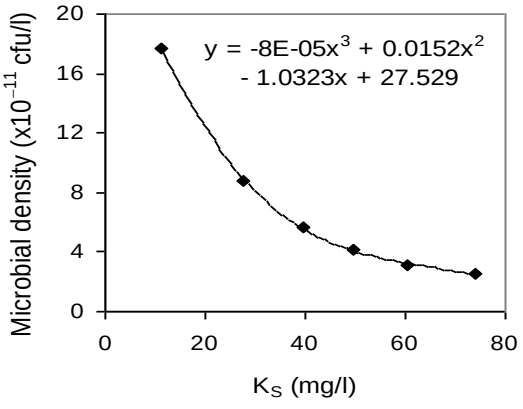

Fig. 10. Plot of microbial density against positive values of K_s for bioaugmented bioreactors in the range $2 \le t \le 12$.

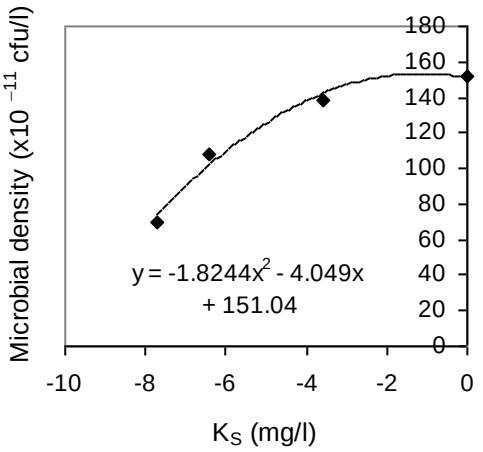

Fig. 11. Plot of microbial density against negative values of K_s for bioaugmented bioreactors in the range $14 \le t \le 20$.

As in the control bioreactors, microbial density in the bioaugmented bioreactors increases with time in both the 'lag phase' and 'exponential growth phase' during microbial growth.

4. RESULTS AND DISCUSSION

Figures 12 and 13 show the comparison between predicted microbial density using the current model (eqs. (8) – (16)), the approximate model by Yelebe and Puyate [17] when K_s is neglected, the normal method of predicting a constant value of K_s as the substrate concentration corresponding to $\mu = \mu_m/2$ on a graph of μ against substrate concentration (and represented in the plot for control bioreactors as 'normal method'), and experimental data.

(15)

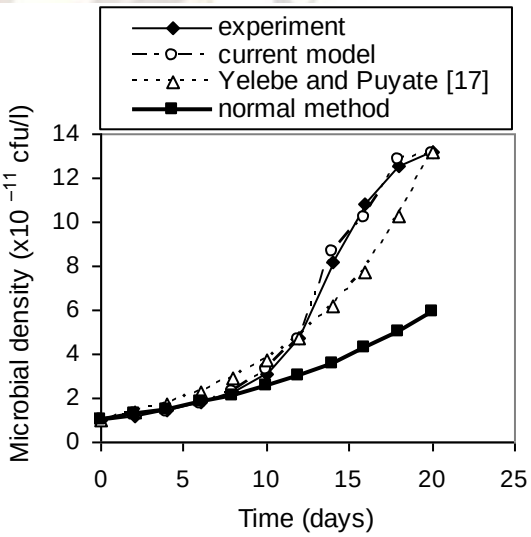

Fig. 12. Experimental and predicted microbial density in control bioreactors.

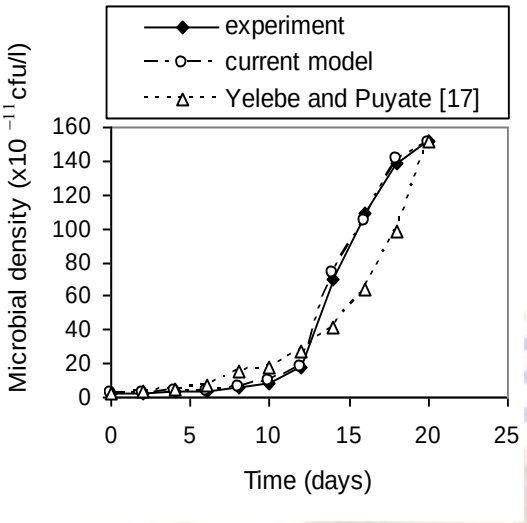

Fig. 13. Experimental and predicted microbial density in bioaugmented bioreactors

It may be seen from Fig. 12 that the current model compares very well with experimental data, the approximate model by Yelebe and Puyate [17] partly over-predicts and partly under-predicts the experimental data, while the 'normal method' compares fairly well only within the *lag phase*. In Fig. 13, the "normal method" is excluded because $\mu_m/2$ lies outside the experimental range of specific growth rate of microorganisms in the bioaugmented bioreactors (see Fig. 3). Figures 12 and 13 show clearly that the contribution of K_s to the aerobic biodegradation process is significant, and the 'normal method' of estimating a constant value of K_s does not apply in all cases especially when K_s is not constant as in the present analysis.

5. CONCLUSION

Estimation of all Monod kinetic parameters based on microbial growth during aerobic digestion of biodegradable organic waste in control and bioaugmented bioreactors has been presented. The growth rate and specific growth rate of microorganisms in the bioaugmented bioreactors are higher than in the control bioreactors. It is shown that K_s is not constant in the present analysis, neither is it equal to zero. The general procedure presented for estimating K_s as a function of time, and microbial density as a function of K_s, is adequate and may be applied to biodegradation of organic compounds.

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