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Modelling the Bioremediation Rate of Domestic Wastewater Supplemented with Urea and NPK 15:15:15 Fertilizers

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Abstract

The kinetic modelling of the bioremediation of domestic wastewater supplemented with a 1:1 combination of urea and NPK fertilizers was investigated in this study. The batch bioremediation data was obtained by conducting the bioremediation experiments using different concentrations of fertilizers 20, 40, 60 and 80 g/L. A mathematical model was proposed to describe the rate of bioremediation. The bioremediation parameters; biodegradation rate constant k and exponential order α were estimated as part of the model validation exercise. Model validation results show that the formulated model was able to predict the experimental results to a high level of confidence indicating that there was a good fit between experimental and model predicted results. The dynamic behaviour of the bioremediation process was assessed by simulating the validated model to obtain time trajectories of the BOD. The BOD decreased in the course of bioremediation with higher remediation rates recorded with increasing concentration of fertilizer.

Keywords: Bioremediation, domestic wastewater, urea, NPK, biochemical oxygen demand, Modelling

Nomenclature

BOD	Biochemical oxygen demand
α	Exponential order
k	Biodegradation rate constant
r	Biodegradation rate

1.0 Introduction

There are thousands of restaurants and fast-food shops in Nigeria and they use over a million tons of water everyday. The direct discharge of wastewater generated from these restaurants and shops down the drain without treatment represents a huge environmental burden. This threat to the environment is amplified by the growing population of urban centers in Nigeria and its attendant generation of huge amounts of wastewater [1,2].

The improper discharge of untreated wastewater especially those containing nitrates and phosphates typically leads to eutrophication and algal bloom as well as the accumulation of toxic substances in the receiving water bodies with potentially serious consequences on the immediate ecological environment [3-5].

A host of physical and chemical methods are currently employed in the treatment of wastewater. These methods are often costly and inefficient. A lot of attention has been given to the use of bioremediation as a means of treating wastewater and other industrial effluents. It is seen as an attractive option due to its cost effectiveness and the benefit of pollutant mineralization to simple substances such as CO_2 and H_2O through the process of biostimulation and bioaugmentation [5,6].

A lot of experimental effort [6,7-10] has been put into the use of biostimulants to enhance the rate of bioremediation, however, little work has been done in modelling the process. Dynamic modelling of the bioremediation process enables its representation in a mathematical sense. Simulation of the formulated model can be utilized in analyzing the behaviour of the process, provision of insights into the mechanisms that drive the process, understanding the response of the process to changes in operating conditions, design of controllers and design of entirely new processes [11]. This leads to vast improvements in process economics, design, operation and control [12]. Model predictions also make it possible to identify optimal design and operational parameters and this consequently leads to the maximisation of the system's performance [13].

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The current work deals with the use of inorganic fertilizers urea and NPK 15:15:15 for the biostimulation of indigenous microorganisms for the purpose of treating domestic wastewater. A mathematical model of the bioremediation process was formulated and validated for the purpose of predicting the performance of the process.

2. Materials and Methods

2.1 Sample collection and preparation

The domestic wastewater used for this study was obtained from fast food outlet at the University of Benin, Benin City, Edo State, Nigeria. Wastewater samples were collected in plastic containers previously cleaned by washing in non-ionic detergent, rinsed with tap water and later soaked in 10% HNO_3 for 24 hours and finally rinsed with deionised water prior to usage. The wastewater was collected at source to prevent any form of foreign contamination not associated with the process from which it was obtained. The wastewater was dispensed in 500mL quantities into six sets of 1000mL beakers. Beakers in each experimental set were then supplemented with different levels (20, 40, 60, and 80 g/L) of nutrient sources (1:1 combination of both urea and NPK 15:15:15). A control experiment which did not contain any nutrient supplements was set up to serve as comparison between biostimulation and natural attenuation (bioremediation) to determine the effectiveness of the nutrient supplements in treating domestic wastewater.

2.2 Analyses

The BOD of the wastewater was chosen as the bioremediation indicating variable and it was monitored weekly for a period of 5 weeks. Sampling was done on day zero (before biostimulation) and subsequently at intervals of seven days (one week). The azide modified winkler method was used in the estimation of the BOD of the wastewater samples [14].

3. Results and Discussion

3.1 Experimental Results

Table 1 shows the variation of BOD of wastewater samples with time at various concentrations of urea and NPK fertilizers combined in a 1:1 ratio. The general trend observed indicate that the BOD of the wastewater decreased with increase the concentration of the stimulants both at the start and at the end of bioremediation.

Table 1: Experimental values of BOD with time for domestic wastewater remediated with different concentration of urea and NPK fertilizer

Time (weeks)	Concentration of fertilizer (g/L)				
	Control 0	20	40	60	80
0	120.34	120.34	120.34	120.34	120.34
1	119.43	78.66	67.2	53.45	39.11
2	118.16	64.29	48.87	37.77	28.83
3	106.3	47.54	35.42	28.78	22.54
4	102.94	35.96	24.12	22.24	19.24
5	89.36	19.49	18.27	17.77	15.83

3.2. Model Development

For the current study, the bioremediation of domestic wastewater occurring in a batch system is represented as shown in Equation (1):

$$Wastewater\ (Complex\ organic\ compounds) \xrightarrow[Bioremediation]{Fertilizers} Simple\ Compounds\ (CO_2 \text{ and } H_2O) \quad (1)$$

In formulating the bioremediation model, the following assumptions were made:

- The volume of the reactor is fixed
- No nuclear reaction occurs; hence rate of material generation is zero
- The system is isothermal
- The biodegradation rate can be likened to the rate of reaction from chemical kinetics
- The reduction in the BOD of the wastewater was likened to the disappearance of reactant from chemical kinetics
- The biodegradation rate was monitored by following the reduction in the BOD of wastewater with time

The proposed model for describing the rate of bioremediation of domestic wastewater supplemented with urea and NPK fertilizers is BOD dependent and is presented as a power law as shown Equation (2).

$$-\frac{d[BOD]}{dt} = k\,[BOD]^{\alpha} \quad (2)$$

Equation (2) was written for the various remediation processes supplemented various concentrations of fertilizers as follows.

For 20 g/L of nutrient supplements: $$-\frac{d[BOD]}{dt} = k_{20}[BOD]^{\alpha_{20}} \quad (3)$$

For 40 g/L of nutrient supplements: $$-\frac{d[BOD]}{dt} = k_{40}[BOD]^{\alpha_{40}} \quad (4)$$

For 60 g/L of nutrient supplements: $$-\frac{d[BOD]}{dt} = k_{60}[BOD]^{\alpha_{60}} \quad (5)$$

For 80 g/L of nutrient supplements: $$-\frac{d[BOD]}{dt} = k_{80}[BOD]^{\alpha_{80}} \quad (6)$$

3.3. Model Validation

Model validation has to do with the estimation of model parameters by making use of the results of an experiment to validate the model. An experimental validation of the proposed bioremediation model was carried out by estimating the biodegradation rate constant *k* and the exponential order of the process *α*. The model was simulated and the result of the simulation was compared with experimental results to show validity. Equations (3) to (6) which make up the bioremediation model were linearized by making use of the data presented in Table 1 to obtain the values of the bioremediation parameters; biodegradation rate constant, *k* and exponential order, *α* for the wastewater remediated with 20, 40, 60 and 80 g/L of fertilizer respectively. Equations (3) to (6) were linearized by taking natural logarithms of both sides of the equations to obtain the following equations for 20, 40, 60 and 80 g/L of fertilizer respectively.

$$\ln(-r_{20}) = \ln(k_{20}) + \alpha_{20}\ln(BOD) \quad (7)$$

$$\ln(-r_{40}) = \ln(k_{40}) + \alpha_{40}\ln(BOD) \quad (8)$$

$$\ln(-r_{60}) = \ln(k_{60}) + \alpha_{60}\ln(BOD) \quad (9)$$

$$\ln(-r_{80}) = \ln(k_{80}) + \alpha_{80}\ln(BOD) \quad (10)$$

For equations (7) to (10), *r* represents the rate of biodegradation i.e.

$$r = \frac{d[BOD]}{dt} \quad (11)$$

The BOD of the wastewater was correlated with bioremediation time using a quadratic equation for each concentration of fertilizer. The rate of bioremediation as indicated in equations (7) to (10) were then calculated from each quadratic equation by simple differentiation. The logarithm of rate of bioremediation was plotted against the logarithm of BOD to obtain straight line from which the bioremediation parameters *k* and *α* were obtained from the intercept and slope respectively. The values of these parameters are presented in Table 2.

Table 2: Values of bioremediation parameters

Concentration of fertilizer (g/L)	Biodegradation rate constant, *k* ($week^{-1}$)	Exponential order *α*
20	1.117	0.701
40	0.703	0.877
60	0.725	0.911
80	1.085	0.854

Applying the values of the parameters presented in Table 2 to Equations (3) to (6) results in the following rate expressions for describing the bioremediation of domestic wastewater supplemented with urea and NPK fertilizers.

$$-\frac{d[BOD]}{dt} = 1.117[BOD]^{0.701} \quad (12)$$

$$-\frac{d[BOD]}{dt} = 0.703[BOD]^{0.877} \quad (13)$$

$$-\frac{d[BOD]}{dt} = 0.725[BOD]^{0.911} \quad (14)$$

$$-\frac{d[BOD]}{dt} = 1.085[BOD]^{0.854} \quad (15)$$

Figures 1 to 4 show the overlay plots of BOD of domestic wastewater remediated with 20, 40, 60 and 80 g/L of a 1:1 combination of urea and NPK fertilizer respectively. These plots display a comparison between the experimental results and the model predicted results in terms of trend and correlation. It is evident from the plots that the model was able to replicate the experimental values of the BOD of domestic wastewater to a high level of confidence. The standard deviation bars in the plots indicate the level of variation between the experimental results and those predicted by the model. The relatively small

magnitude of the standard deviation bars shows that there was little variation between the experimental results and the model predicted results indicating that the experimental results were very similar to the model predicted results. This means that the model exhibited a good fit with the experimental data as seen in the excellent correlation between the experimental and model predicted results.

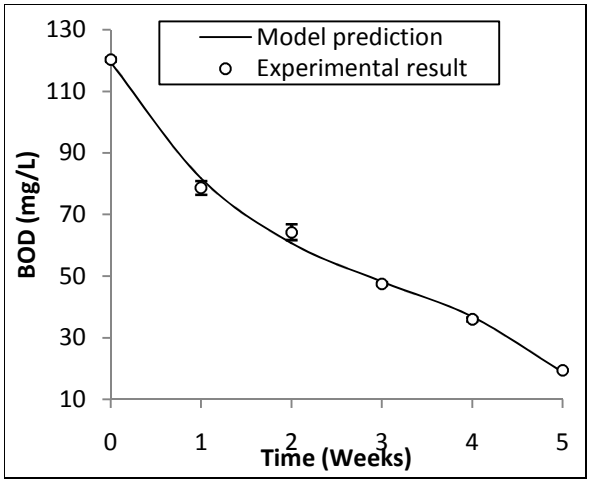

Figure 1: Comparison between experimental results and model prediction for wastewater remediated with 20 g/L fertilizer

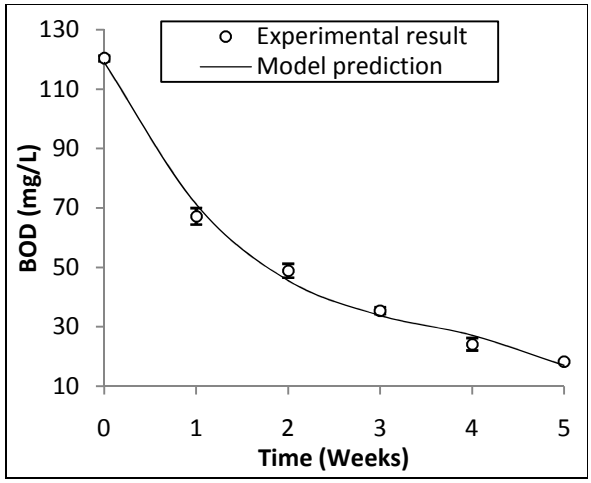

Figure 2: Comparison between experimental results and model prediction for wastewater remediated with 40 g/L fertilizer

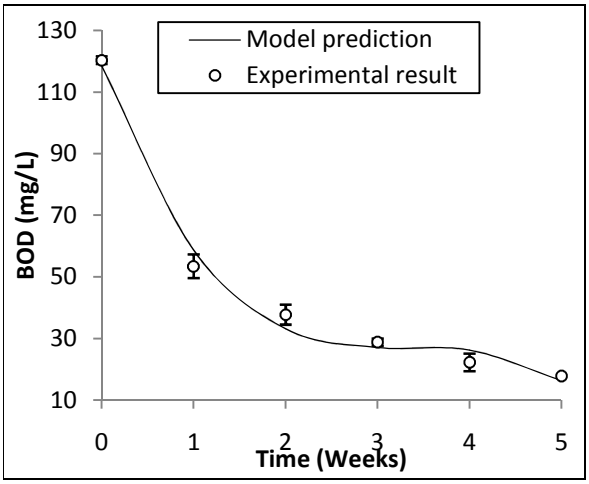

Figure 3: Comparison between experimental results and model prediction for wastewater remediated with 60 g/L fertilizer

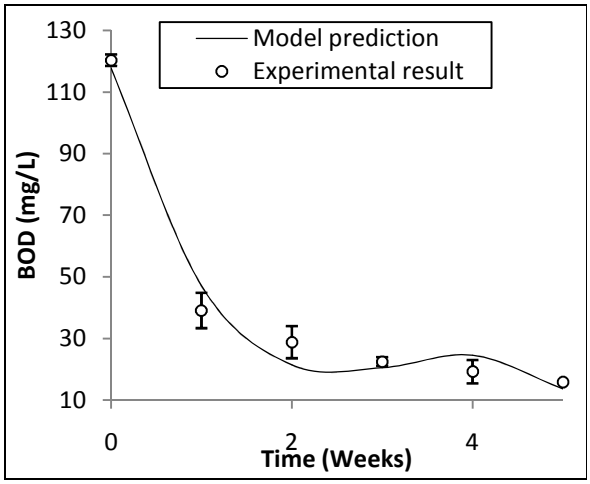

Figure 4: Comparison between experimental results and model prediction for wastewater remediated with 80 g/L fertilizer

3.4. Model Implementation and Simulation

In order to investigate the dynamic behaviour of the batch bioremediation of domestic wastewater, the formulated reactor model was implemented and simulated to obtain time trajectories of BOD of domestic wastewater under varying remediation conditions. The data utilized for the simulation of the model is presented in Table 2.

The profiles of the BOD of the wastewater at various concentrations of fertilizer are shown in Figure 5. The general trend observed indicate that the BOD of the wastewater decreased with increase the concentration of the stimulants both at the start and at the end of bioremediation. At a concentration of 0 g/L (no biostimulant added) there was still an observable reduction (though not significant) in the BOD of the wastewater with time as shown in the results presented in Table 1. The

reduction in BOD could be attributed to the activities of the indigenous microbes present in the wastewater which converts the contaminants into less toxic substances such as CO_2, H_2O and many intermediates like organic acids, lipids, esters, complex alcohols and microbial proteins in form of enzymes [10]. Higher reductions in BOD were recorded when stimulants were added indicating that the biodegrading ability of the indigenous microorganism had been enhanced. The BOD was reduced from 120.34 to 19.49 mg/L, 120.34 18.27 mg/L, 120.34 17.77 mg/L and 120.34 to 15.83 mg/L corresponding to 83.52, 84.82, 85.23 and 86.85% removal efficiencies for wastewater treated with combination of both fertilizers. Similar results were reported by Satyawali and Balakrishnan [15] for the treatment of wastewater from molasses-based alcohol distilleries. The better performance observed for urea relative to NPK can be explained by noting that biodegrading microorganisms need oxygen, carbon and hydrogen to function optimally. These are present in urea fertiliser and not in NPK fertiliser. It also stands to reason that the best result was obtained when both fertilisers were combined as the medium then contained all necessary nutrient needed by the microbes as shown in Figure 6. These values fell below the maximum value of 30 mg/L stipulated by the Federal Environmental Protection Agency [16].

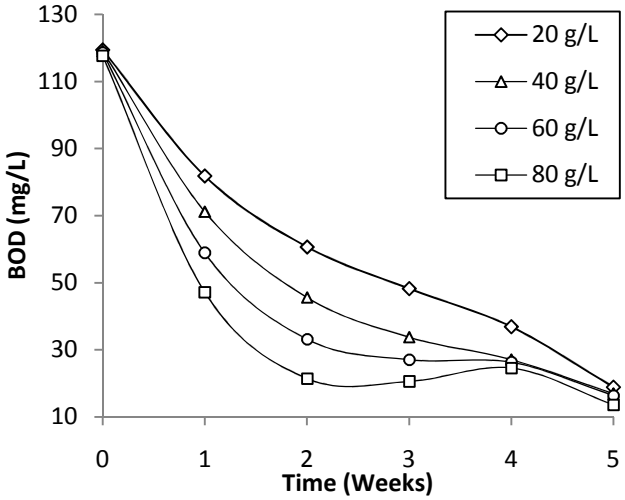

Figure 5: Variation of BOD with time for wastewater remediated with both urea and NPK fertiliser

4.0 Conclusion

The kinetic modelling of the bioremediation of domestic wastewater supplemented with a 1:1 combination of urea and NPK fertilizers was investigated in this study. The following conclusion can be drawn.

- The use of modelling tools to describe the trends in the bioremediation of domestic wastewater has been demonstrated.
- The rate of bioremediation was accurately represented by a validated mathematical model
- Kinetic parameters indicating the rate of bioremediation can be estimated accurately using experimentally generated data.
- The bioremediation model upon validation was able to replicate the results of the experiment to a high level of confidence as seen in the excellent correlation between model and experimental results.

References

[1] Arora, A. and Saxena, S. (2005). Cultivation of Azolla microphylla biomass on secondary treated Delhi municipal effluents. *Biomass and Bioenergy*, 29, pp. 60–64.

[2] de-Bashan, L.E, and Bashan, Y. (2010). Immobilized microalgae for removing pollutants: review of practical aspects. *Bioresource Technology*, 101, pp.1611–1627.

[3] Godos, I.D., Blanco, S., Garcia-Encina, P.A., Becares, E. and Munoz, R. (2009). Long-term operation of high rate algal ponds for the bioremediation of piggery wastewaters at high loading rates. *Bioresource Technology*, 100, pp. 4332–4339.

[4] Munoz, R. and Guieysse, B. (2008). Algal–bacterial processes for the treatment of hazardous contaminants: a review. *Water Research*, 40, pp. 2799–815.

[5] Otokunefor, T.V. and Obiukwu, C. (2010). Efficacy of inorganic nutrients in bioremediation of a refinery effluent. *Scientia Africana*, 9(1), pp 111-125.

[6] Agbor, R.B., Ekpo, I.A., Osuagwu, A.N., Udofia, U.U., Okpako, E.C. and Antai, S.P. (2012). Biostimulation of microbial degradation of crude oil polluted soil using cocoa pod husk and plantain peels. *Journal of Microbiology and Biotechnology Research*, 2(3), pp. 464-469.

[7] Chikere, C.B., Okpokwasili, G.C. and Chikere, B.O. (2009). Bacteria diversity in a tropical crude oil polluted soil undergoing bioremediation. *African Journal of Biotechnology*, 8 (11), pp. 2535-2540.

[8] Ebere, J.U., Wokoma, E.C. and Wokocha, C.C. (2011). Enhanced Remediation of a Hydrocarbon Polluted Soil. *Research Journal of Environmental and Earth Sciences*, 3(2), pp.70-74.

[9] Kim, S.J., Choi, D.H., Sim, D.S. and Oh, Y.S. (2005). Evaluation of bioremediation effectiveness on crude oil-contaminated sand. *Chemosphere*, 59, pp. 845-852.

[10] Obahiagbon, K.O. and Aluyor, E.O. (2009). Comparison of the efficiency of sodium nitrate and sodium nitrite as nutrients in the bioremediation of petroleum hydrocarbon polluted water. *Scientific Research and Essay*, 4(8), pp. 728-732.

[11] Suja M.R.M. and Thyagarajan, T. (2009). Modelling of continuous stirred tank reactor using artificial intelligence techniques. *International journal of simulation modelling, 8*(3), pp. 145–155.

[12] Lee, T. T., Wang, F. Y., and Newell, R. B. (1997). A generalised procedure for modelling and simulation of activated sludge plant using lumped-parameter approach. *Journal of Environmental Science and Health . Part A: Environmental Science and Engineering and Toxicology, 32*(1), pp. 83-104.

[13] Andres, H., Hu, Z., Snowling, S., and Schraa, O. (2006). Model-Based Optimum Design of Sequencing Batch Reactors for COD and Nitrogen Removal from a Slaughterhouse Wastewater. *Proceedings of the Water Environment Federation, 2006*(7), pp. 5100-5107.

[14] Woodring, S.L. and Clifford, D.A. (1988). A Comparison of the Graphical and Standard Methods for the Determination of Biochemical Oxygen Demand. *Journal (Water Pollution Control Federation)*, 60(4), pp. 537-542.

[15] Satyawali, Y. and Balakrishnan, M., (2008). Wastewater treatment in molasses-based alcohol distilleries for COD and color removal: a review. *Journal of Environmental Management*, 86(3), pp. 481-497.

[16] Federal Environmental Protection Agency (FEPA) (1997). Guidelines and `Standards for Environmental Impact Assessment in Nigeria, pp. 87-95.