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**Original Research Article**

## Investigation of Reaction Rates for Stabilization Pond Operation in Nigeria

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**ABSTRACT**

*Waste stabilization ponds are engineered and secondary treatment systems that are rapidly receiving global attention for wastewater treatment. Compared to conventional treatment plants, a waste stabilization pond is essentially an earth basin which retains wastewater within which natural stabilization process occurs. This highly effective and inexpensive method is favored by hot tropical climate but its use in Nigeria is not widespread as planned centralized sewage disposal schemes are not common. An attempt has been made in this study to determine the variation in reaction rate constants for model ponds system. By studying the existing wastewater quality, temperature of the environment; the influent and effluent were tested for chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO) etc among other parameters. This study went further to present a variation of reaction rates for stabilization ponds in Nigeria. A contour reaction rate constant (RRC) data map was generated. The study results show the reaction rate constant is estimated to be between 0.1815 and 0.2067 at average temperatures. It is expected that a slight deviation is possible for operation of life size ponds.*



## 1. INTRODUCTION

There are many ways of achieving wastewater secondary treatment and the use of stabilization ponds is one that offers several advantages over others. The use of stabilization ponds is the most widely applicable and advantageous method of waste treatment in a tropical climate like Nigeria (Varon and Mara 2004; Herath 2016). Treatment occurs through natural physical, chemical and biological processes and no machinery or energy input (except the sun) is required. They are the simplest and cheapest of all technologies and are capable of providing high quality effluents (Mara, 2004). However, its use in Nigeria is not yet widespread partly because there is little experience in its design, construction, operation and maintenance and there are very few centrally planned sewage systems. Shilton and Bailey (2006) noted that the only thing standing between raw sewage and the environment, into which it is ultimately discharged, is a waste stabilization pond (WSP). The WSP system typically consists of a series of continuous flow anaerobic, facultative, and maturation ponds. The anaerobic pond, which is the initial treatment reactor, is designed for eliminating suspended solids and some of the soluble organic matter. The residual organic matter is further removed through the activity of algae and heterotrophic bacteria in the facultative pond. The final stage of pathogens and nutrients removal takes place in the maturation pond. These three types of ponds when used in series, have demonstrated up to 95% removal of biochemical oxygen demand (BOD) and fecal coliform (Mara, 2004; Hamzeh and Ponce, 2007).

There is little information available on BOD removal reaction kinetics and the variation in reaction rate constants along the WSPs system (Gratziou and Chalatsi, 2015). Variability of BOD removal reaction rate constant is an important observation which has bearing on the design of these systems. It is believed that the processes that exist within ponds that, if understood better, could be used to enable the efficiency and effective treatment of wastewater with limited cost of construction and maintenance (Riaz et al., 2018). The dynamics of pollutants in these systems are not well understood and this can lead to improper design and poor removal efficiency of pollutants and also operational problems (Varon and Mara, 2004). The removal of organic matter is the primary goal of design systems in the most used wastewater treatment stabilization ponds; hence preliminary determination of BOD removal kinetics is often required.

Based on the situation already presented, it becomes important to investigate and improve further on the functioning and performance of waste stabilization pond currently in use. However, research on the hydraulic modeling and determination of reaction rate constants of the pond configuration is still limited. Pond hydraulics in Nigeria has been scantily researched because of climatic variation, low velocity and long residence time, and the systems are difficult to systemically study in the field (Olukanni, 2011). An alternative is to undertake further research on reaction rates for stabilization pond operation in Nigeria in order to establish these values for different parts of the country. This study aims to provide reaction rate constants for the design of waste stabilization ponds in different parts of Nigeria.

## 2. MATERIALS AND METHODS

The laboratory set-up for the investigation consisted of a model pond made of steel plates. The Set-up was done at Ilorin, Nigeria (Longitude: 4.58$^o$E, Latitude: 8.50$^o$N). Baffle obstruction was placed at about 0.1 m from the entrance of the pond to ensure that wastewater entering the system is fairly spread on entry. The constructed model was placed on a raised platform to ensure that storm runoff does not join the pond content (see Plates 1 & 2). The pond size was 243 litres. Since the pond is laboratory scale, the initial filling was done with water, nutrients (diluted evaporated milk) and algae seeds from a nearby natural pond. The pond was left for two weeks in which time the algal cells multiplied for the pond to be luxuriantly green for the experiments to begin. The pond was facultative and had a retention period of 15 days.

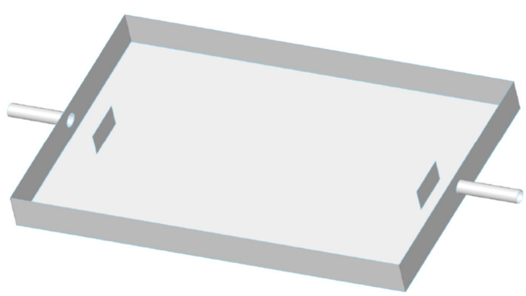

Plate 1: Pond construction

Plate 2: The pond in operation

Table 1: Descriptions of experiment and loadings

| Exp no. | Pond loading (litres/days) | Retention time (days) | Milk: Water ratio (tin to litre) |
|---|---|---|---|
| A | 16 | 15 | 1 tin per 25 litres |
| B | 16 | 15 | 2 tins per 25 litres |
| C | 16 | 15 | 3 tins per 25 litres |
| D | 48 | 5 | 1 tin per 25 litres |
| E | 48 | 5 | 2 tins per 25 litres |
| F | 48 | 5 | 3 tins per 25 litres |
| G | 48 | 5, 10, 15, 20 | 3 tins per 25 litres |

The experiment was performed in two parts. The first part involved the use of a constant retention time in the pond despite the varying of the strength of waste (organic loading) at the end of each round (Table 1).

In order to reduce the risk of blockage from suspended solids usually associated with raw sewage, avoid the risk associated with chemical or hazardous wastes, and to ensure that the quality of influent wastewater is kept constant and controlled, synthetic milk waste as a form of diary waste was used for the experiment. The milk waste was made by diluting a tin of unsweetened evaporated full cream milk, with water to make 25 litres of waste as actual milk waste has the tendency to vary widely in organic strength for a laboratory size models. The wastewater was applied daily at the established rates for a period of 10 days during which time both the influent and effluent quality would have stabilized. Samples were then collected at the entry and outlet points for 3 days and tested. The obtained results were averaged and used for analysis.

At the completion of the first round of tests, the organic loading of the ponds was increased by increasing the tin of milk to two. This was fed into the ponds for another ten days for the quality of influent and effluent to stabilize. The process of sampling and testing was repeated and the average values were used for analysis. The procedure was repeated again for an increased organic loading of three tins of milk and samples were taken as usual and analyzed.

The following parameters were tested for the sample according to standard methods (APHA, 2017): biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total solids (TS), suspended solids (SS), alkalinity, acidity, hydrogen ion concentration (pH), hydrogen sulphide ($H_2S$) and ammonia ($NH_3$). Meteorological data of Ilorin (location of the experiment) during the period of experimentation was also obtained from the Meteorological Station at the Ilorin Airport. The experiment was conducted in the months of February through April.

## 3. RESULTS AND DISCUSSION

The test results arising from the process of sampling and analysis of the influent and effluent of the model pond, loaded are presented in Tables 2 to 5. Each experiment was carried out thrice and the average was used for analysis. The treatment performance of the pond was assessed based on the following considerations: oxygen demand (Chemical and Biochemical), solids (total, suspended and dissolved) and nutrient removal (Ammonia).

Table 2: Experiment Results (equal hydraulic loading, different retention times)

| S/no | Parameter | 15 Days retention time | | | | | |
|---|---|---|---|---|---|---|---|
| | | Experiment A | | Experiment B | | Experiment C | |
| | | Influent | Effluent | Influent | Effluent | Influent | Effluent |
| 1 | COD (mg/l) | 23.0 | 3.9 | 40.0 | 4.0 | 49.6 | 4.6 |
| 2 | BOD (mg/l) | 16.0 | 2.6 | 26.0 | 2.7 | 34.0 | 3.0 |
| 3 | DO (mg/l) | 0.8 | 11.2 | 0.6 | 9.8 | 0.3 | 11.2 |
| 4 | Alkalinity (mg/l) | 60 | 115 | 90 | 63 | 100 | 105 |
| 5 | Acidity (mg/l) | 140 | 130 | 90 | 100 | 130 | 140 |
| 6 | TS (mg/l) | 368 | 230 | 412 | 266 | 460 | 312 |
| 7 | SS (mg/l) | 110 | 82 | 122 | 88 | 148 | 122 |
| 8 | DS (mg/l) | 258 | 148 | 290 | 178 | 312 | 190 |
| 9 | pH | 6.3 | 7.5 | 6.0 | 7.3 | 6.1 | 7.3 |
| 10 | $H_2S$ (mg/l) | 0.7 | 0.3 | 0.75 | 0.6 | 0.8 | 0.3 |
| 11 | $NH_3$ (mg/l) | 0.6 | 0.42 | 0.65 | 0.6 | 0.7 | 0.25 |

Table 3: Experiment Results (different hydraulic loading, equal retention times)

| S/no | Parameter | 5 Days retention time | | | | | |
|---|---|---|---|---|---|---|---|
| | | Experiment D | | Experiment E | | Experiment F | |
| | | Influent | Effluent | Influent | Effluent | Influent | Effluent |
| 1 | COD (mg/l) | 23.0 | 7.5 | 40.0 | 11.5 | 49.6 | 12.1 |
| 2 | BOD (mg/l) | 16.0 | 5.0 | 26.0 | 7.5 | 34.0 | 8.1 |
| 3 | DO (mg/l) | 0.8 | 10.5 | 0.6 | 9.9 | 0.3 | 9.2 |
| 4 | Alkalinity (mg/l) | 60 | 100 | 90 | 110 | 100 | 90 |
| 5 | Acidity (mg/l) | 140 | 140 | 90 | 140 | 130 | 140 |
| 6 | TS (mg/l) | 368 | 240 | 412 | 258 | 460 | 272 |
| 7 | SS (mg/l) | 110 | 78 | 122 | 82 | 148 | 84 |
| 8 | DS (mg/l) | 258 | 162 | 290 | 176 | 312 | 188 |
| 9 | pH | 6.3 | 7.1 | 6.0 | 7.4 | 6.1 | 7.6 |
| 10 | $H_2S$ (mg/l) | 0.7 | 0.7 | 0.75 | 0.6 | 0.8 | 0.4 |
| 11 | $NH_3$ (mg/l) | 0.6 | 0.36 | 0.65 | 0.28 | 0.7 | 0.30 |

Table 4: Experiment G Results

| S/no | Parameter | Influent | Pond Effluent | | | |
|---|---|---|---|---|---|---|
| | | | Day 5 | Day 10 | Day 15 | Day 20 |
| 1 | COD (mg/l) | 49.6 | 12.1 | 8.0 | 3.9 | 5.4 |
| 2 | BOD (mg/l) | 34.0 | 8.1 | 5.4 | 2.6 | 3.4 |
| 3 | DO (mg/l) | 0.3 | 9.2 | 11.2 | 12.8 | 11.9 |
| 4 | Alkalinity (mg/l) | 100 | 90 | 80 | 65 | 130 |
| 5 | Acidity (mg/l) | 130 | 140 | 110 | 100 | 80 |
| 6 | TS (mg/l) | 460 | 390 | 412 | 392 | 374 |
| 7 | SS (mg/l) | 148 | 136 | 124 | 156 | 142 |
| 8 | DS (mg/l) | 312 | 254 | 288 | 236 | 232 |
| 9 | pH | 6.1 | 7.6 | 7.6 | 7.3 | 6.9 |
| 10 | $H_2S$ (mg/l) | 0.8 | 0.4 | 0.5 | 0.6 | 0.5 |
| 11 | $NH_3$ (mg/l) | 0.7 | 0.30 | 0.48 | 0.6 | 0.38 |

### 3.1. Biochemical Oxygen Demand

The percentage BOD removal in each of the ponds is calculated using Equation 1 and shown in Table 5. Table 5 shows the percentage treatment achieved after the wastewater has passed through the pond. The pond achieved a significant reduction in the BOD content of the wastewater. The effluent in this case was better than the influent. However, the percentage removal varied. It was also observed from Table 5 that the efficiency of BOD removal increased with increased strength of loading applied. This may be due to the increased activities of algae and microbes as food becomes more available. It is also an indication that the organic load capacity of the model ponds was not exceeded. At a later stage in the experimental run (Experiment E and Experiment F), the pond was loaded to a point of declining BOD removal rate. The rate of change of removal efficiency reduced with increase in loadings. This was used to estimate the possible range of loading for model WSP to obtain optimum performance in a geographical location as Ilorin.

$$BOD\ Removal\ Efficiency = \frac{Influent\ BOD - Effluent\ BOD}{Influent\ BOD} \text{ x } 100 \tag{1}$$

Table 5: BOD removal efficiencies (%)

| | Equal waste volume, varied detention times | | | Varied waste volume, equal detention times (5 days) | | |
|---|---|---|---|---|---|---|
| | Expt. A | Expt. B | Expt. C | Expt. D | Expt. E | Expt. F |
| Pond | 83.75 | 89.61 | 91.17 | 68.75 | 71.15 | 76.17 |

Meteorological data for Ilorin during the period of the experimentation was obtained from the Meteorological Department at Ilorin Airport. The evaporation losses in the pond was considered not enough to significantly affect the outcome of the results as the average temperature was 27.4 $^oC$.

Biodegradation in WSPs is greatly favored by sunshine and high temperature. These experiments were conducted between February and April. Data available for the Ilorin weather indicates that the hottest months in the year falls within this period which in turn makes the ponds more efficient. In colder months, removal efficiency will thus be less than the results obtained here.

An attempt was also made to establish a reaction rate constant for the model ponds using the BOD equation as follows:

$$L_e = L_o e^{-kt} \tag{2}$$

Where $L_e$ = BOD of effluent (mg/l), $L_o$ = BOD of influent (mg/l), K = rate constant, which varies with temperature according to Equation 3.

$$K_T = K_{20}\ 1.047^{T-20} \tag{3}$$

Using results from Tables 2 to 5 in Equations 2 and 3, the rate constants obtained are given in Table 6.

Table 6: Ponds rate constants for treatment based on waste strength

| | Equal waste volume, varied detention times | | | Varied waste volume, equal detention times (5 days) | | |
|---|---|---|---|---|---|---|
| | Expt. A | Expt. B | Expt. C | Expt. D | Expt. E | Expt. F |
| Reaction rate constant | 0.121 | 0.151 | 0.162 | 0.232 | 0.248 | 0.286 |

Average = 0.2

Table 7: Ponds rate constants for treatment based on retention time

| Retention time (days) | 5 | 10 | 15 | 20 |
|---|---|---|---|---|
| Rate Constant | 0.286 | 0.183 | 0.171 | 0.115 |

Average = 0.189

The average reaction rate constant for Ilorin is:

Average = 0.195 $d^{-1}$

And the BOD removal equation is:

$$L_e = L_o e^{-0.195t} \tag{4}$$

The standard BOD test is conducted at 20 °C. From Equation (3), the BOD rate constant determined at 20° C, $day^{-1}$.

$$K_{20} = \frac{K_T}{1.047^{T-20}}$$

For Ilorin:

$$K_{20} = \frac{0.195}{1.047^{27.4-20}} \tag{5}$$

$$K_{20} = \frac{0.195}{1.405} = 0.14$$

The standard temperature at which BOD is determined is 20 °C.

1.047 = Temperature co-efficient

$K_{20}$ at Ilorin = 0.14 for an average temperature of 27.4 °C.

The general equation to describe the reaction rate constants for Nigeria may be written as:

$$K_T = 0.14\ (1.047)^{T-20} \tag{6}$$

Where T = Average temperature at the location of interest.

The average temperature of various locations in Nigeria were obtained and used in Equation (6) to produce Table 7 and Figure 1. Figure 1 represents a map showing the variation of reaction rate constants across Nigeria for the design and operation of waste stabilization ponds.

From Tables 2 to 5, it was observed that increase in waste strength at the laboratory range led to increase in reaction rate constant but increase in detention time without corresponding increase in organic loading, led to decrease in rate. This can be explained by increased biological activity of bacteria and algae with the availability of nutrient. But as the nutrient reduces with time, bioactivity also reduces.

The activity of various microorganisms in the treatment process depends on the pH of the wastewater. Influent pH for this work was between 6.0 and 6.3 while for the effluent, it was between 6.8 and 7.6. The pH of all the samples were within the standard value (5.5 to 8.5) (EPA, 2011). Thus, the ponds operated quite normally and the effluent can be disposed into a stream without causing any harm to the outfall. The pH of the pond started to fall after day 10. It is possible that after this time, nutrients have been greatly diminished as to cause the death of algae and some other microbial presence, whose decay has the tendency to worsen the quality of the effluent or during algal respiration, carbon dioxide is produced which lowers the pH (Ceci, 2015) and hydroxide levels decrease. This among other things, suggest that the pond detention time should not be too long as to completely exhaust the nutrient supplies in the pond, which will lead to a significant death rate of the algae. Dead algae will decay and reduce the effluent quality. This is because at this point, the bacteria become more dominant and start to decompose the algae. As there is much food for them, they also experience a sort of bloom, and they literally suck the oxygen out of the water (APEC Water, 2019).

Table 8: Description of weather stations and average temperature used

| Station No | Station Name | Latitude (°N) | Longitude (°E) | Elevation (m) | Average Temp. | Reaction rate constant (K) |
|---|---|---|---|---|---|---|
| 1 | Yelwa | 10.53 | 4.45 | 244 | 27.9055 | 0.2013 |
| 2 | Sokoto | 12.55 | 5.12 | 351 | 28.471 | 0.2067 |
| 3 | Kaduna | 10.42 | 7.19 | 645 | 25.6568 | 0.1815 |
| 4 | Kano | 12.03 | 8.32 | 476 | 26.5004 | 0.1887 |
| 5 | Bauchi | 10.17 | 9.49 | 591 | 25.8918 | 0.1835 |
| 6 | Maiduguri | 11.51 | 13.05 | 354 | 27.5667 | 0.1982 |
| 7 | Ilorin | 8.26 | 4.3 | 308 | 26.7084 | 0.1905 |
| 8 | Yola | 9.16 | 12.26 | 191 | 28.2878 | 0.2049 |
| 9 | Ikeja | 6.35 | 3.2 | 40 | 26.9196 | 0.1924 |
| 10 | Ibadan | 7.22 | 3.59 | 234 | 26.6931 | 0.1904 |
| 11 | Oshogbo | 7.47 | 4.29 | 305 | 26.2707 | 0.1867 |
| 12 | Benin | 6.19 | 5.36 | 77.8 | 26.9937 | 0.1930 |
| 13 | Warri | 5.31 | 5.44 | 6 | 27.2065 | 0.1949 |
| 14 | Lokoja | 7.48 | 6.44 | 113 | 27.8667 | 0.2009 |
| 15 | Port Harcourt | 5.01 | 6.57 | 18 | 26.7216 | 0.1906 |
| 16 | Owerri | 5.25 | 7.13 | 91 | 27.6176 | 0.1986 |
| 17 | Enugu | 6.28 | 7.34 | 142 | 27.1143 | 0.1941 |
| 18 | Calabar | 4.58 | 8.21 | 62 | 26.6884 | 0.1903 |
| 19 | Makurdi | 7.42 | 3.37 | 113 | 27.6400 | 0.1988 |
| 20 | Ogoja | 6.4 | 8.48 | 117 | 27.5500 | 0.1980 |

After the measurement of BOD, the suspended solids (SS) content is probably the next most important test for raw wastewater and treated effluent. The range of solid removal in Table 2 is 35 to 50% as compared to 32 to 40% in Table 3. This is for unfiltered samples. The bulk of the effluent solids consist of algal cells, thus this value will increase for filtered samples. Solid content also increased with increase in detention time of ponds. This indicates increase in algal cell population, since the BOD quality of the effluent did not significantly deteriorate. However, this cannot be used as a general rule since the growth pattern is expected to peak and begins to decay after some time. The conclusion here is that the growth and multiplication of algal cells has not peaked, and that the pond is capable of treating a higher hydraulic and organic loading to the one it is subjected to.

Monthly mean values of daily minimum and maximum temperatures for the period 1950- 2012 at 20 synoptic stations spread across Nigeria were obtained from the Nigerian Meteorological Agency, (NIMET) Oshodi, Lagos, Nigeria. Table 8 shows the details of the station locations, average temperature used and the reaction rates obtained. The average temperature used in calculating the reaction rate constants for waste stabilization ponds across Nigeria was derived from descriptive statistics for minimum and maximum temperature data. Table 8 has been used to plot the variation of reaction rate constants for various parts of Nigeria as shown in Figure 1. The obtained figure provides information on the reaction rate constant which can be used in the design of stabilization ponds for any chosen location in Nigeria. These rates were usually previously assumed or chosen based on information of pond operations elsewhere.

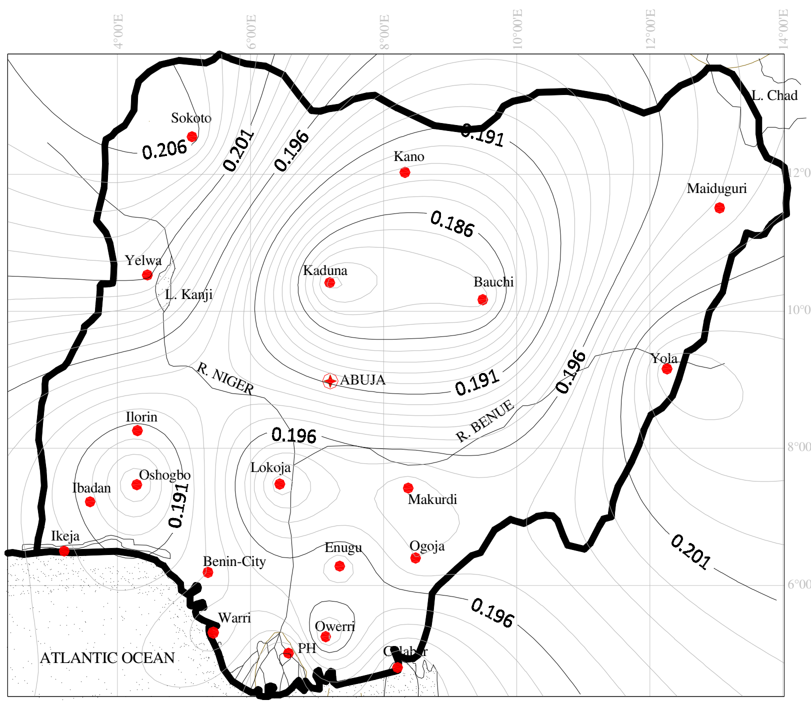


Figure 1: Contour of reaction rates for stabilization pond design in Nigeria

## 4. CONCLUSION

The use of stabilization ponds in wastewater treatment is well suited to the Nigerian environment even though its use is not as widespread as it should be. This may be attributed to the low occurrence of central sewage systems in the country. The data for its design and operation are quite scanty and this study is meant to advance the case for more use of ponds in wastewater treatment. A major design requirement is the reaction rate constant which is estimated to be between 0.1815 and 0.2067 at average temperatures. These values were obtained from laboratory experiments where conditions are controlled. It is expected that a slight deviation is possible for operation of life size ponds and thus a slightly lower value of reaction rate than the ones obtained should be used in design.

## 5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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