EREM 73/2

Journal of Environmental Research, Engineering and Management
Vol. 73 / No. 2 / 2017
pp. 52-61
DOI 10.5755/j01.erem.73.2.17696

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Received 2017/03 Accepted after revision 2017/07

http://dx.doi.org/10.5755/j01.erem.73.2.17696

Optimisation of Waste Stabilisation Pond Performance for Piggery Waste Treatment Using Response Surface Methodology

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The treatment of piggery wastewater using the waste stabilisation pond was studied in a semi- continuous process. Optimisation of chemical oxygen demand (COD) removal was conducted using response surface methodology where pH, temperature and retention time were independent variables. The Box-Behnken design approach, an experimental design was used for creating a set of experimental runs needed for optimising COD removal. An attempt was also made to optimise COD removal by reducing hydraulic retention time while maintaining pH and temperature of a defined range. Analysis of variance (ANOVA) was conducted on model terms and the results revealed that the coefficient of determination value (R^2) of % COD removal was 0.86, 0.88, and 0.86 for the anaerobic, the facultative and the maturation pond, respectively. The highest desirability was obtained for optimum COD % removal and this was 0.89, 0.89 and 1.0 for the ponds. The waste stabilisation pond treatment process can effectively be improved on for piggery wastewater treatment.

Keywords: wastewater, Box-Behnken, optimum, treatment, waste stabilisation pond.

Introduction

Wastewater is basically water supply that has been fouled by various users, and it is potable water that now contains pollutants (Canter and Negid, 2000). Wastewater generated from piggery is usually utilised for agriculture because of the high nutrient content. This water requires a properly planned and engineered system to enable immediate conveyance, storage and application in irrigation schemes. Piggery waste is comprised of faeces and urine. Faeces include organic carbon (90% of the total discharge), and about 30% of the nitrogen and 80% of the phosphorus are usually discharged (Choi, 2007). Macronutrients needed by plants include carbon, nitrogen and phosphorus. However, the organics in the faeces need to be stabilised before utilisation.

Waste stabilisation ponds (WSP) are large shallow basins enclosed by earthen embankments, which utilise natural processes involving pond algae and bacteria, for the biological treatment of wastewater. Typical hydraulic retention times range from 10 days to 100 days depending on the temperature of a particular region. According to Mara (1976), WSP are considered as the most effective and efficient method of wastewater treatment in warm climates where sufficient land is available and where the temperature is most favourable for their operation. A waste stabilisation pond consists of anaerobic, facultative and maturation ponds, which may be singularized (facultative) or combined in series (anaerobic, facultative, and maturation).

The extent of treatment in a waste stabilisation pond to a great extent depends on the hydraulic retention time of the pond. The hydraulic retention time (HRT) denotes the residence period of water molecules in the pond, which has been proven to impact on the quality of effluent (Denbigh and Turner, 1984, Sincero and Sincero, 1996, Meisheng et al., 1992). Therefore, factors such as short circuiting and baffles that affect the retention time will also influence the COD removal efficiency. Muttamara and Puetpaiboon (1997) reported an increase in removal of COD, with the introduction of baffles. The rational for this increase was given as follows: the baffle arrangement lengthens the flow path of the wastewater stream, thus increasing the organic carbon removal efficiency.

The chemical oxygen demand (COD) reflects the extent to which oxygen is depleted in receiving water by discharging wastewater. Pisarevsky et al. (2005) defined chemical oxygen demand as a measurement of pollution in terms of the total concentration of substances that can be chemically oxidised in the water. It gives a measure of the total organic matter without distinguishing between compounds that are biodegradable and those that are not (Liptak, 2000).

The response surface methodology (RSM) as an empirical statistical tool employs the use of multiple regression analysis in analysing quantitative data obtained from statistically designed experiments for evaluating the multivariate equations simultaneously. The graphical representations of these equations are called as response surfaces, and could be used to describe the individual and cumulative effect of the test variables on the response and to determine the mutual interaction between the test variables and their subsequent effect on the response (Khuri and Cornell, 1989, Montgomery, 1991). This statistical technique evaluates the interactions/relationships between the working variables, thereby reducing experimental runs that ordinarily would have been cumbersome to obtain by experimentation (Khuri and Cornell, 1989). This technique can also be used in the determination of the optimum operational condition of a process or a system. This study investigated the removal of COD from piggery wastewater in a waste stabilisation pond by employing the use of the Box-Behnken design of response surface methodology. The application of RSM in wastewater treatment using several techniques such as coagulation amongst others exists; however, there is paucity of information on the optimisation of waste stabilisation pond performance for piggery waste treatment using response surface methodology. This study evaluates the various influences of pH, temperature and detention time (independent variables) on COD of piggery wastewater (dependent variable).

Materials and methods

Piggery waste for piloting research work was collected from a piggery located in Awka, Anambra state, Nigeria. The temperature of study area is high throughout the year averaging from 27°C to 34°C. The wastes collected are comprised of raw influent which is the solid/semi-solid waste obtained from the piggery and spillage water from drinkers, veterinary activities impacted waste, etc. Initial characterisation performed on wastewater samples were pH = 6.8, turbidity = 849NTU, COD = 917.33mg/L.

A field scale prototype of a WSP was designed and rescaled to a laboratory-scale model using Froude number and dimensional analysis. The ponds are 3 in number, namely: anaerobic (1 No.), facultative (1 No.) and maturation ponds (1 No.). A laboratory-scale unit was operated in a semi-continuous mode by adding manure effluent daily under prescribed flow rates. The experiment was performed at the Civil Engineering Department laboratory, Parasitology and Entomology laboratory, Microbiology and Applied Brewing laboratory, Nnamdi Azikiwe University Awka, and Springboard laboratory located at Udoka housing estate, Awka, Anambra State, Nigeria.

For the COD analysis, 15 mL of the wastewater sample was added to a 250 mL beaker, was refluxed with an accurate unknown amount of a potassium dichromate (2.5 mL standard 5% $KCrO_4$ digestion reagent), and slowly mixed in a large excess of sulphuric acid (3.5 mL of conc. sulphuric acid reagent was introduced slowly through sides of the beaker) for a definite time to oxidise most of organic substances. The remaining dichromate was determined by titration with ferrous ammonium sulphate. The beaker was capped and the content was mixed before transfer into a water bath alongside a blank. Distilled water was added to make up the volume to 50 mL, 2–3 drops of the ferroin indicator was added and titrated with 0.05 M ferrous ammonium sulphate (FAS) solution (mohr salt). Chemicals utilised for experimentation were analytically pure. Removal efficiency of COD (%) was obtained from the Equation (1):

$$R = \frac{C_0 - C}{C_0} X\,100 \qquad (1)$$

where

C_0 and C represent the initial and the final value of COD.

Experimental design

In this present study, a standard response surface methodology (RSM) design called Box-Behnken design (BBD) was employed to study the variables, evaluate relationships and optimise the removal of COD from piggery wastewater using a semi-continuous process. Model independent variables of defined ranges were pH (6.5–7.1), temperature (28–31°C), detention time (10–20 days). Box-Behnken response surface experimental design (BBD) consisting of 3 variables, 2 levels, i.e. low (-1) and high (+1), and 17 experiments alongside results were subjected to multiple regression analysis to analyse adequacy of the adopted model. Experimental runs and responses are shown in Table 1.

The mathematical model showing the relationship between independent and dependent variables was developed. The mathematical model (full quadratic equation) used in responses (COD) for the various ponds was described by the relationship in Equation (2):

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ij} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} X_i X_j \qquad (2)$$

where

β_o, β_i, and β_{ij} represent the regression coefficient for intercepts, linear, quadratic and interactive terms of the model; X_i and X_{ij} are the independent variables while Y_1 (anaerobic pond), Y_2 (facultative pond) and Y_3 (maturation pond) represent the predicted response, COD removal. The Stat-Ease Design Expert 7.0. statistical software package (Stat-Ease Inc., Minneapolis, USA) was employed for statistical analysis of variance (ANOVA) and the optimisation studies.

Table 1

Box-Behnken experimental design and observed response for the anaerobic, the facultative and the maturation ponds

Run	Detention Time (A)	pH (B)	Temp. (C)	Responses (COD), %		
				Ana. pond	Fac. pond	Mat. pond
1	2	3	4	5	6	7
1	0.000	-1.000	1.000	62.81	98.95	99.10
2	0.000	-1.000	-1.000	63.36	98.96	99.11
3	0.000	1.000	1.000	62.49	98.99	99.12
4	0.000	0.000	0.000	64.23	99.03	99.13
5	1.000	1.000	0.000	64.78	99.04	99.15
6	-1.000	0.000	-1.000	53.76	98.67	98.83
7	1.000	0.000	-1.000	65.43	99.04	99.15
8	1.000	0.000	1.000	65.21	99.04	99.15
9	-1.000	1.000	0.000	59.00	98.76	98.94
10	0.000	0.000	0.000	63.90	99.03	99.13
11	-1.000	0.000	1.000	60.74	98.88	99.06
12	0.000	0.000	0.000	64.56	99.04	99.13
13	0.000	0.000	0.000	64.56	99.04	99.15
14	0.000	1.000	-1.000	64.56	99.04	99.14
15	1.000	-1.000	0.000	65.10	99.05	99.15
16	0.000	0.000	0.000	64.55	99.04	99.15
17	-1.000	-1.000	0.000	61.61	98.93	99.09

Results and discussion

Statistical analysis and model development

Statistical designed experiments were performed to study the effect of variables (independent and dependent) on percentage removal of COD. The data were fitted into linear, interactive, 2FI, quadratic and cubic mathematical models. The results obtained from the analysis for adequacy and fitness adopted the quadratic model as best for analysis; the quadratic regression models for removal percentage of COD in the anaerobic, the facultative and the maturation ponds are depicted as Y_1, Y_2 and Y_3 in Equation (3), Equation(4) and Equation(5), respectively.

$$Y_1 = 64.360 + 3.176A - 0.259B + 0.518C + 0.573AB - 1.799AC - 0.382BC - 1.878A^2 + 0.140B^2 - 1.196C^2 \quad (3)$$

$$Y_2 = 99.035 + 0.119A - 0.006B + 0.020C + 0.039AB - 0.053AC - 0.011BC - 0.083A^2 - 0.008B^2 - 0.043C^2 \quad (4)$$

$$Y_3 = 99.139 + 0.085A - 0.011B + 0.024C + 0.034AB - 0.056AC - 0.003BC - 0.064A^2 + 0.007B^2 - 0.027C^2 \quad (5)$$

Table 2 depicts the ANOVA test results for removal efficiencies of COD in the waste stabilisation ponds. The model F value obtained was 4.90, 5.88 and 4.76 for the anaerobic, the facultative and the maturation ponds, respectively, which implies that the model is significant. Values of "Prob> F" less than 0.05 indicate that the model terms are also significant.

Statistically significant lack of fit value of 0.0006, 0.0001 and 0.0002 for the anaerobic, the facultative and the maturation pond, respectively, may be attributed to variations in the waste stabilisation ponds hypothesised model (Virkutyte et al., 2010). The interaction between modelled and observed values reflects the influences of the independent factor on the models. The level of statistical significance was obtained by analysing the variance. The tested model terms were linear terms (A, B, C), square terms (A^2, B^2, and C^2), and interaction terms (AB, BC, and AC), which shows variability in the significance level at the 5% level. Younis et al. (2014) reported that variations might be due to exact replicate values of the independent variables in the model that indicate an estimate of pure error. Adoption of the quadratic model allowed for a better estimation for the COD removal in the waste stabilisation pond, as noted in Table 2.

Table 2

ANOVA test for the COD removal efficiency for the anaerobic, the facultative and the maturation ponds

Model term	Anaer. pond		Fac. pond		Mat. pond	
	F value	p value Prob> F	F value	p value Prob> F	F value	p value Prob> F
1	2	3	4	5	6	7
Model	4.90	0.0239	5.88	0.0146	4.76	0.0258
A	29.64	0.0010	34.33	0.0006	24.39	0.0017
B	0.20	0.6707	0.10	0.7609	0.41	0.5424
C	0.79	0.4042	0.98	0.3547	1.91	0.2099
AB	0.48	0.5101	1.82	0.2191	1.95	0.2054
AC	4.76	0.0656	3.48	0.1043	5.33	0.0543
BC	0.21	0.6573	0.14	0.7230	0.012	0.9146
A^2	5.45	0.0522	8.87	0.0206	7.22	0.0312
B^2	0.030	0.8667	0.08	0.7917	0.09	0.7729
C^2	2.21	0.1806	2.38	0.1668	1.30	0.2911
Lack of fit	73.57	0.0006	170.51	0.0001	129.16	0.0002

The coefficient of correlation (R^2) and the validity of the fitted model as earlier noted were major tools utilised for the validation of the adopted model. These were obtained from the analysis of variance (ANOVA). Table 3 shows the value for the determination coefficient (R^2) for the quadratic polynomial models shown in Equations (3), (4) and (5), which were noted to be 0.86, 0.88, 0.86, respectively. From the results, it can be noted that 86%, 88% and 86% of the variance can be attributed to the model terms with R^2 having the highest value. A good agreement existed between the actual and the predicted values as seen in Table 4. This reflects the adequacy of the regression model of response variables. It can be noted that COD removal efficiency for actual experimentation ranged between from 53.76% to 65.43%, and its corresponding predicted values were 55.79% and 66.11% for the anaerobic pond, 98.67% to 99.05% and 98.72% to 99.09% for the actual and the predicted values in the facultative pond, and 98.83% to 99.15% and 98.88% to 99.19% for the actual and the predicted values in the maturation pond, respectively.

Table 3

Summary statistics for the model for COD removal efficiency for the anaerobic, the facultative and the maturation ponds

Variable	COD removal, %		
	Anaer. pond	Fac. pond	Mat. pond
1	2	3	4
Std. dev.	1.65	0.06	0.05
Mean	62.98	98.97	99.10
C.V. %	2.62	0.06	0.05
R-squared	0.86	0.88	0.86
Adj R-squared	0.69	0.73	0.68

Response surface plots were obtained from the developed models (Equations (3) – (5)) to portray a 3D graphical representation of variation between operating variables utilised for the study of COD removal efficiencies to aid better understanding of their interactions. A total of 2 factors were used for each plot, leaving one as constant. From Fig. 1 (a) and (b) and Fig. 2 (a) and (b), it can be generally noted that the efficiency of removal of COD increased with an increase in the retention time. Experimental results reflected the same trend of gradual COD depletion with a prolonged retention period. Organic matter contained in the waste stabilisation ponds got depleted with time, hence the corresponding increase in removal percentage. The efficiency of treatment in the ponds can be said to differ significantly, removal percentage attained in the anaerobic pond is lesser (Fig. 1 (a) – (c)) than that of the facultative pond (Fig. 1 (d) – (f)) and the maturation pond (Fig. 2 (a) – (c)).

Table 4

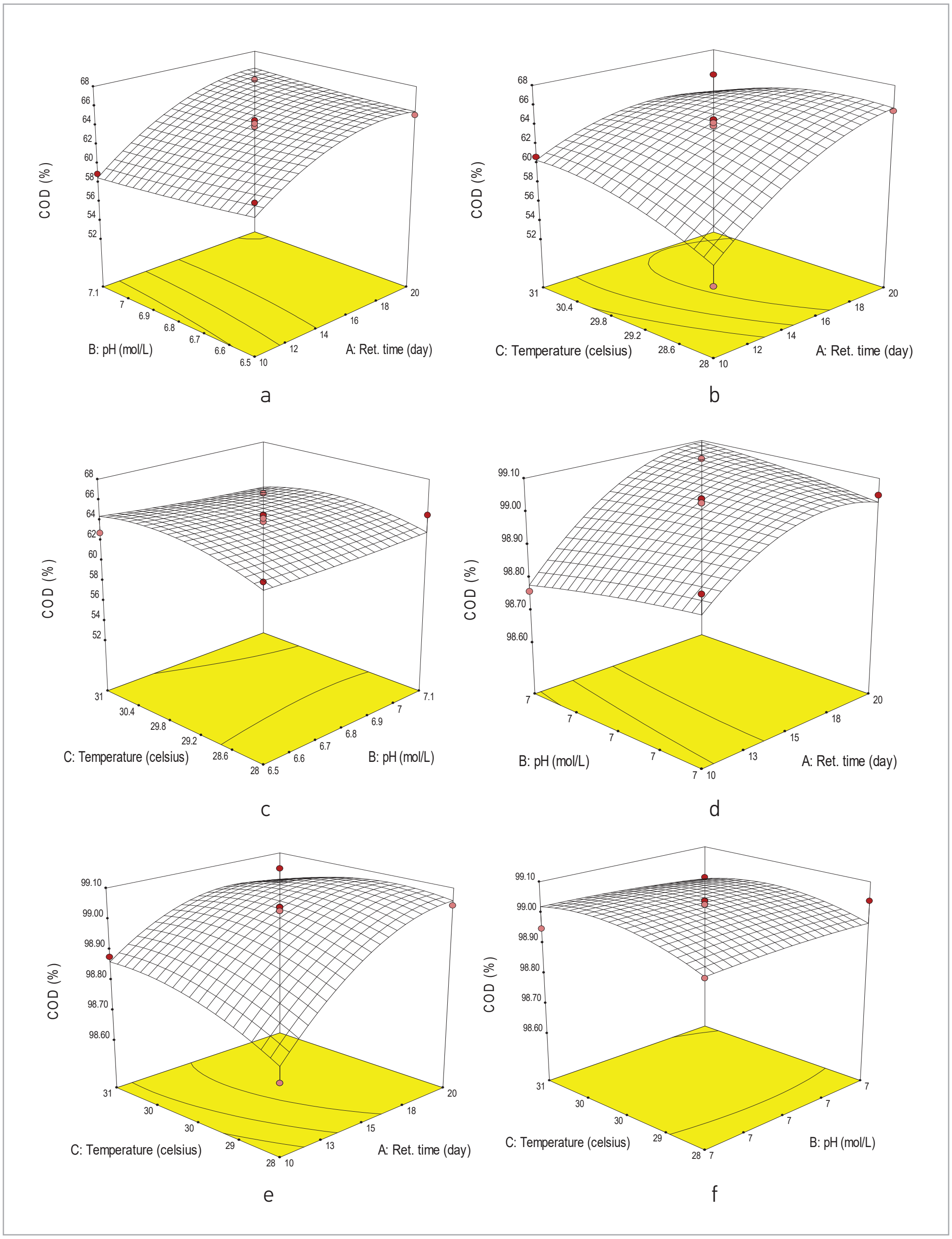
Actual and predicted responses for COD removal efficiency for the anaerobic, the facultative and the maturation ponds

Run	Anaer. pond		Fac. pond		Mat. pond	
	Actual	Pred.	Actual	Pred.	Actual	Pred.
1	2	3	4	5	6	7
1	62.81	64.46	98.95	99.02	99.10	99.16
2	63.36	62.66	98.96	98.96	99.11	99.10
3	62.49	63.18	98.99	98.99	99.12	99.13
4	64.23	64.36	99.03	99.03	99.13	99.14
5	64.78	66.11	99.04	99.09	99.15	99.19
6	53.76	55.79	98.67	98.72	98.83	98.88
7	65.43	65.74	99.04	99.06	99.15	99.17
8	65.21	63.18	99.04	98.99	99.15	99.10
9	59.00	58.62	98.76	98.78	98.94	98.95
10	63.90	64.36	99.03	99.03	99.13	99.14
11	60.74	60.43	98.88	98.86	99.06	99.04
12	64.56	64.36	99.04	99.03	99.13	99.14
13	64.56	64.36	99.04	99.03	99.15	99.14
14	64.56	62.91	99.04	98.97	99.14	99.09
15	65.10	65.49	99.05	99.03	99.15	99.14
16	64.55	64.36	99.04	99.03	99.15	99.14
17	61.61	60.28	98.93	98.87	99.09	99.04

Fig. 1 (c) shows the effects of varying temperature and pH on removal efficiency of COD (%). It can be observed that variation in model terms is almost normalised compared with the retention time. pH and temperature are important variables in wastewater treatment, as they both can aggravate the rate of degradation of organics or cause a decline in the rate of treatment. The results show that at temperature range of 28–31°C and pH range of 6.8–7.1, considerable treatment was attained. A low temperature seems not to favour high COD removal as seen in Fig. 1 (b) and 2 (b). This can be said to be due to the fact that temperature influences algal growth in aerobic ponds and algae majorly aid COD removal.

Fig. 1

The surface plot showing the effect of operating variables on COD removal in the anaerobic and the facultative ponds



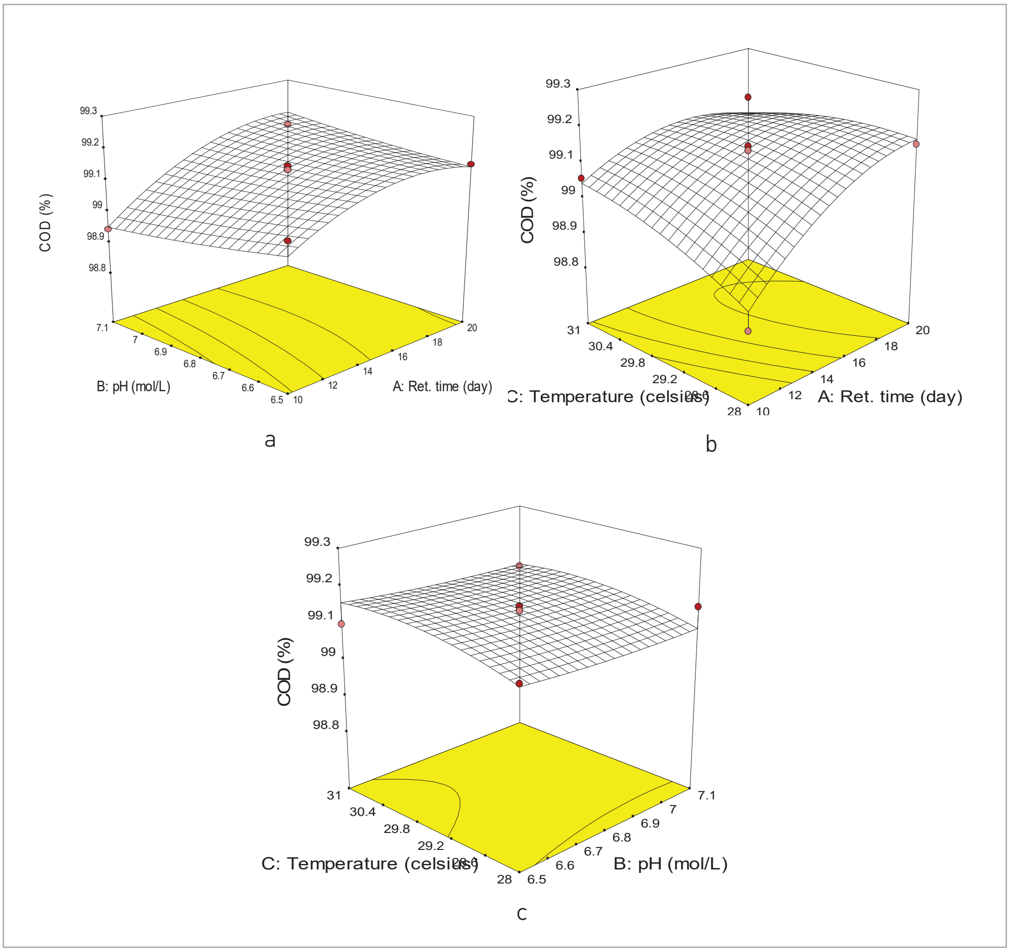


Fig. 2

The surface plot showing the effect of operating variables on COD removal in the maturation pond

Optimisation analysis

Furthermore, the optimisation process was performed mainly to evaluate the optimum value needed for the maximum removal efficiency of COD. Table 5 shows the optimum COD removal percentage for wastewater treatment in the waste stabilisation ponds. The predicted maximum removal percentage for COD was ≈ 66.11%, 99.09% and 99.19% for the anaerobic, the facultative and the maturation ponds effectively at pH of 7.1, temperature of 31°C, and retention time of 20 days. Further analysis was carried out to determine the most optimum range of variables; the optimum range for the detention time was gotten as 15 days for the anaerobic pond and 20 days for the facultative and the maturation ponds, pH as 7.1, and temperature as 30°C and 31°C, respectively. This agrees considerably well with the results obtained from the response surface plot of Fig. 1 and 2.

Considering the variation in the optimum retention time and temperature between the various ponds, an attempt was made to unify the retention period as given in Table 5. A target flow hydraulic retention time of 15 days was chosen while keeping constant ranges of other independent variables. The results obtained showed that on adoption of the target retention time and a % COD removal efficiency of 64.91%, 99.04% and 99.16% would be obtained in the anaerobic, the facultative and the maturation ponds, respectively. The obtained values are near surface plot optimum values and their reliance can further be attested to by the desirability index of 0.89, 0.89 and 1.0 for the three ponds.

Table 5

Optimum values of model variables utilised for maximum COD removal efficiency in the anaerobic, the facultative and the maturation ponds

Name		Anaer. pond	Fac. pond	Mat. pond
1	2	3	4	5
Ret. time (day)	target	15	15	15
pH (mol/ L)	range	7.1	7.1	7.1
Temperature (°C)	range	31	31	31
Optimum COD (mg/L)(%)		64.91	99.04	99.16
Desirability		0.89	0.89	1.00

Conclusions

This research study employs the use of BBD for evaluation and optimisation of model terms. Different operating conditions such as pH, temperature and hydraulic retention time for the treatment of piggery wastewater in a waste stabilisation pond were evaluated in a semi-continuous mode. The removal efficiency of COD in a waste stabilisation pond greatly increases with an increase in retention time and temperature. COD removal at pH ranges adopted for the experiment (6.8–7.1) had little variableness. Development of quadratic mathematical models for predicting COD removal in a waste stabilisation pond was determined using Derringer's desired function methodology. The 3-dimension response plot was adopted for the study of the effect of model variables on the response. Optimum conditions for removal of COD were found to be as follows: pH of 7.1, temperature of 31°C and detention time of 15 days. It can be concluded that a waste stabilisation pond is an effective method for removal of COD in piggery wastewater.

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Gauta:
2017 m. kovas
Priimta spaudai:
2017 m. liepa

Kiaulidžių atliekų stabilizavimo tvenkinių optimizavimas naudojant atsako paviršiaus metodiką

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Kiaulidžių nuotekų valymas naudojant atliekų stabilizavimo tvenkinį buvo tiriamas pusiau pertraukiamame procese. Cheminio deguonies suvartojimo (ChDS) optimizavimo tyrimai buvo atlikti naudojant atsako paviršiaus metodiką, kur pH, temperatūra ir išbuvimo laikas yra nepriklausomi kintamieji. ChDS rodiklio optimizavimui buvo naudojamas Box-Behnken eksperimento dizaino metodas, kurio pagalba sudarytas eksperiemento planas, t.y. reikalingų atlikti tyrimų serija. Taip pat buvo mėginta optimizuoti ChDS rodiklį mažinant hidraulinio išbuvimo trukmę, bet išlaikant pH ir nustatyto diapazono temperatūrą. Nuokrypio analizė (NA) buvo atlikta pagal modelio sąlygas ir rezultatai atskleidė, kad procentinis ChDS sumažinimo vertės koeficientas (R^2) buvo 0.86, 0.88 ir 0.86 atatinkamai anaerobiniam, fakultatyviniam ir brandinimo tvenkiniui. Buvo pasiektas didžiausias pageidaujamas sumažinimas ChDS %, kuris atatinkamai siekė 0.89, 0.89 ir 1.0. Atliekų stabilizavimo tvenkinių valymo procesas gali būti veiksmingai pagerintas kiaulidžių nuotekų valyme.

Raktiniai žodžiai: nuotekos, Box-Behnken, optimumas, valymas, atliekų stabilizavimo tvenkinys.