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Journal of Hazardous Materials 153 (2008) 532–543

Journal of Hazardous Materials

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# Development of empirical models for performance evaluation of UASB reactors treating poultry manure wastewater under different operational conditions

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Received 14 June 2007; received in revised form 8 August 2007; accepted 29 August 2007
Available online 1 September 2007

## Abstract

A nonlinear modeling study was carried out to evaluate the performance of UASB reactors treating poultry manure wastewater under different organic and hydraulic loading conditions. Two identical pilot scale up-flow anaerobic sludge blanket (UASB) reactors (15.7 L) were run at mesophilic conditions (30–35 °C) in a temperature-controlled environment with three hydraulic retention times ($\theta$) of 15.7, 12 and 8.0 days. Imposed volumetric organic loading rates ($L_V$) ranged from 0.65 to 4.257 kg COD/(m$^3$ day). The pH of the feed varied between 6.68 and 7.82. The hydraulic loading rates ($L_H$) were controlled between 0.105 and 0.21 m$^3$/(m$^2$ day). The daily biogas production rates ranged between 4.2 and 29.4 L/day. High volumetric COD removal rates ($R_V$) ranging from 0.546 to 3.779 kg COD$_{\text{removed}}$/(m$^3$ day) were achieved. On the basis of experimental results, two empirical models having a satisfactory correlation coefficient of about 0.9954 and 0.9416 were developed to predict daily biogas production ($Q_g$) and effluent COD concentration ($S_e$), respectively. Findings of this modeling study showed that optimal COD removals ranging from 86.3% to 90.6% were predicted with HRTs of 7.9, 9.5, 11.2, 12.6, 13.7 and 14.3 days, and $L_V$ of 1.27, 1.58, 1.78, 1.99, 2.20 and 2.45 kg COD/(m$^3$ day) for the corresponding influent substrate concentrations ($S_i$) of 10,000, 15,000, 20,000, 25,000, 30,000 and 35,000 mg/L, respectively.

*Keywords:* Poultry manure wastewater; COD removal; Biogas production; Modeling; Nonlinear regression

## 1. Introduction

The problem of poultry waste management has been of increasing concern in many parts of the world. Pollutants from improperly managed poultry waste can cause serious environment problems in terms of water, air, and health quality. Particularly the huge amount of waste produced in a concentrated area requires urgent treatment and disposal solutions because ammonia and greenhouse gases, $CH_4$ and $CO_2$, emitted from the waste storage units may cause air pollution problems. Moreover, improper application of nitrogen and phosphorus to land in animal manure can result in eutrophication of surface water resources and pollution of soil and groundwater [1].

Animal densities continue to increase at the farm level, and the consolidation of animal agriculture has created manure-related problems. These problems are leading to more regulations concerning where and how poultry producers may dispose of wastes [2]. Although many options have been proposed for the utilization, treatment and disposal of poultry manure, most disposal strategies are not found to be feasible for poultry manure due to unfavorable economics.

Continued sustainability of animal agriculture and its allied industries will be largely dependent on the waste management technology. Considering the dual benefits of environmental pollution control and meeting national energy needs, anaerobic digestion technology has been chosen as an attractive option in recent years [3].

Until now, many investigations have been conducted on applicability of anaerobic processing of poultry wastes. Adderley et al. [4] carried out studies on anaerobic fermentation of poultry manure. They reported that the optimal temperature and dilution

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doi:10.1016/j.jhazmat.2007.08.087

for fermenting chicken manure to volatile acids were found to be 25 °C and 2.5% total solids (TS) by weight, respectively. They also concluded that the rates of methane production and waste stabilization could be improved by considering the sensitiveness of methane bacteria for temperature changes. Converse et al. [5] investigated the performance of a large size anaerobic digester (96.5 $m^3$) in treatment of poultry manure at 35 °C. They reported a biogas production between 55 and 74 $m^3$/day, with a methane content of 55–63% for a feeding range of 1.6–2.0 kg volatile solids (VS)/($m^3$ day) with hydraulic retention times from 30 to 52 days. Webb and Hawkes [6] conducted an experimental study on anaerobic digestion of poultry manure to observe the variation of gas yield with influent concentration and ammonium nitrogen levels. They found that the gas yields for poultry litter were from 0.245 to 0.372 $m^3$ biogas/kg VS at hydraulic retention times of 29 and 12 days and influent VS concentrations of 4% and 1%, respectively. Kalyuzhnyi et al. [7] carried out investigations in two laboratory 2.6-L UASB reactors to examine the suitability of the reactors for the pre-treatment of the liquid fraction of hen manure in terms of its treatment efficiency on total chemical oxygen demand (COD) reduction and methane production at 35 °C. They reported a biogas production rate of about 3.5–3.6 L/(L day) with a methane content of 79–81% at the organic loading rate (OLR) of 11–12 g COD/(L day) and hydraulic retention time (HRT) of 1–2 days. With these OLR and HRT, both reactors demostrated optimal operation stability with a treatment efficiency of 70–75% on total COD reduction. Atuanya and Aigbirior [8] examined the feasibility of applying the UASB reactor for treatment of poultry wastewaters. They carried out studies for 95 days in a 3.5-L continuos flow UASB at 26–34 °C to assess the treatability of poultry wastewater. They reported that the maximum COD removal was found to be 78% for an OLR of 2.9 kg COD/($m^3$ day) at 13.2 h HRT. They also concluded that the average biogas recovery was obtained to be 0.26 $m^3$ $CH_4$/kg COD with an average methane content of 57% at 30 °C. Another experimental study was conducted by Gungor-Demirci and Demirer [1] to investigate anaerobic treatability and biogas generation potential of broiler and cattle manure in seven sets of anaerobic batch reactors. They reported biogas yields of 180–270 and 223–368 mL/g $COD_{added}$ for initial COD concentrations of 12,000 and 53,500 mg/L, respectively. They achieved total COD removals of 37.9–50%, for the same initial COD concentrations, respectively. Finally, Anozie et al. [9] carried out studies for 40 days to investigate the anaerobic digestion of four types of agricultural wastes including poultry droppings, cow dung, corn stalk and mixed substrate in a 0.28 $m^3$ batch pilot-scale reactor at 25–29 °C. They reported that the average daily gas production from poultry droppings was the highest with a gas volume of 137.16 L.

Although much attention is given to the bio-chemistry and physical characteristics of anaerobic digestion, very little knowledge is available in the literature regarding on the mathematical modeling of anaerobic reactors treating poultry and livestock waste [10]. Some of the recent applications based on the modeling of anaerobic digesters treating animal manure can be found in some studies such as modeling of low-temperature methane production from cattle manure [11], development of a kinetic model for anaerobic digestion of livestock manure [12], determination of a kinetic model for anaerobic digestion of the solid fraction of piggery slurries [13], improvement of a comprehensive model for anaerobic digestion of swine manure slurry [14], development of a kinetic model for an intermittent-flow, continuous-mix anaerobic reactor [15], and a kinetic modeling for anaerobic processing of cattle manure [16].

Even though the hydraulic characteristics of the anaerobic process is very complicated, a number of attempts in developing different representative mathematical models may help to develop a better understanding of the process. Therefore, model results may be evaluated for different operating data before transferring the concepts to a full scale plant. Furthermore, choosing the most appropriate model may help to recognize possible technical faults and to reduce operating costs of plants in the planning stage.

The main objectives of this study were: (1) to investigate the performance of UASB reactors treating poultry manure wastewater under various organic and hydraulic loading conditions; (2) to conduct a nonlinear regression analysis to develop mathematical models for the prediction of biogas production rate and effluent COD concentration; and, (3) to evaluate the model performance to determine optimal operating conditions for different hydraulic retention times and imposed susbtrate concentrations.

## 2. Materials and methods

### 2.1. Origin of poultry manure and feed preparation

Fresh poultry manure was collected from a moderate size commercial poultry farm (Hakan's Poultry Farm) located at Buyukkilicli Village in Silivri, Istanbul and stored in the refrigerator at 4 °C to minimize substrate decomposition before the experiment. The water content and density of the fresh poultry manure were determined to be 77.5 (±0.59)% and 1102.16 (±114.5) kg/$m^3$, respectively. Prior to feeding, VS was about 64.5 (±1.13)% of TS.

The feed for UASB reactors was prepared by diluting fresh poultry manure with tap water. Three feed ratios (kg of fresh poultry manure to litre of tap water respectively) of 1:8, 1:6 and 1:4 were conducted to investigate the effects of different feed strengths on the digestion performance of the reactors. The diluted manure was mixed with a vertical stirrer (Makita HP1500) for 5–10 min to obtain a uniform environment in feeding material. The homogenised feed material was then filtered through a screen of 1.18 mm mesh size (Endecotts Ltd.) to reduce potential clogging of tubing and operational problems may be caused by broken egg shells, hair or feathers and inert bedding materials such as sand, sawdust and wood shavings which were present in the fresh manure. Prior to feeding, stored feed was warmed to the reactor operating temperature using Chiltern Hotplate Magnetic Stirrer, HS31. Stability of the treatment process and components of wastewater samples were monitored in Environmental Engineering Laboratory at Yildiz Technical University in Istanbul, Turkey.

### 2.2. Seed sludge

All reactors were seeded with 4.5 L of actively digesting granular sludge (28.6% of the reactor working volume) from an ongoing mesophilic UASB reactor of Pasabahce Distillery Inc. (Istanbul, Turkey). Then, the systems were filled to their respective volumes of 15.7 L (79.1% of the total tank capacity) with poultry manure wastewater having a feed ratio of 1:10 (kg of fresh poultry manure to litre of tap water respectively) to acclimate the anaerobic biomass to the feed.

Prior to seeding, TS content of the granular sludge was about 90.8 g TS/L. The VS content of the sludge was found to be 82.3% of TS. The contents of the reactors were maintained at the respective temperatures (32 ± 2 °C) for a week to allow temperature equilibration and utilization of the substrate by the anaerobic microorganisms.

The initial average diameter of the granules ($d_p$) was found to be about 1.18 mm. The density of the granular sludge ($\rho_p$) was measured to be 1075 kg/m$^3$. The mean settling velocity ($u_t$) and Reynolds number at terminal settling velocity ($Re_t$) of the granules having a diameter of 1.18 mm were determined to be 74.16 m/h and 24.31 for the viscosity of water at room temperature ($\mu \cong 10^{-3}$ kg m/s or Pa s), respectively. The mean settling velocity was determined using the well-known force balance equation. In determination of $u_t$, the drag coefficient ($\xi$) being a function of $Re_t$ was obtained using Perry's and Green's equation. Images of sample granules showing their initial and final morphologies were taken with a digital camera (Sony Cyber-shot DSC-N1) combined with a stereomicroscope (Prior, James Swift).

### 2.3. Basal medium

Gungor-Demirci and Demirer [1] reported that nutrients present in the manure were sufficient for anaerobic microbial growth if sufficient amount of water was present to dissolve them. Therefore, addition of extra nutrient may not be necessary at low COD and TS concentrations. However, they observed an increase in the total methane production by nutrient and trace metal supplementation at relatively high substrate concentrations. This showed the positive effect of nutrient supplementation on digestion of manure at high initial COD and TS concentrations.

In this study, a nutrient solution/basal media containing all necessary micro and macro nutrients for an optimum anaerobic microbial growth was prepared with the following components, and added 1 mL/L of the daily fed subtrate at relatively high initial COD and TS concentrations [17]: 5 g/L $MgSO_4{\cdot}7H_2O$, 6 g/L $FeCl_2{\cdot}6H_2O$, 10 g/L $CoCl_2{\cdot}6H_2O$, 1 mg/L $H_3BO_3$, 1 mg/L $ZnSO_4{\cdot}7H_2O$, 1 mg/L $CuSO_4{\cdot}5H_2O$, 100 mg/L $MnCl_2{\cdot}6H_2O$, 1 mg/L $(NH_4)_6Mo_{24}{\cdot}4H_2O$, 585 mg/L $Al_2(SO_4)_3{\cdot}18H_2O$, and 1 g/L $Na_2SiO_3{\cdot}9H_2O$.

### 2.4. Analytical methods

In the daily operation of UASB system, influent and effluent pH values were measured by a pH meter (Jenway 3040 Ion Analyser) and a pH probe (HI1230, Hanna Instruments). Soluble COD (SCOD) was determined by filtering sample through 0.45 μm filter paper. All analyses were performed according to the Standard Methods for the Examination of Water and Wastewater [18]. These parameters were determined by the procedures described in method numbers of 5220 B (open reflux method for COD), 2540 B (total solids dried at 103–105 °C), 2540 D (total suspended solids dried at 103–105 °C), 2540 E (fixed and volatile solids ignited at 550 °C), 5210 B (5 day BOD test), 2320 B (titration method for alkalinity), 4500 $NH_3$-N E (titrimetric method for ammonia), 4500 Norg B (Macro-Kjeldahl method for total Kjeldahl nitrogen), and 4500 P (persulfate digestion method for total phosphorus). Samples were ignited at 550 °C using an ashing furnace (Lenton) for volatile solids (VS) and volatile suspended solids (VSS) analyses. Absorbance values were recorded at 690 nm using a spectrophotometer (Pharmacia Biotech LKB Novaspec II) for total phosphorus (TP) analysis. Biogas composition was determined using a portable multi-channel environmental gas analyser (Gas Data LMSxi G3 Landfill Gas Analyser). All standard deviations reported here were calculated using the statistical functions in Microsoft Excel used as an ODBC (Open Database Connectivity) data source. The nonlinear modeling study carried out using DataFit® scientific software (version 8.1.69, Copyright © 1995–2005 Oakdale Engineering, RC167).

### 2.5. Experimental set-up

Two identical 15.7-L pilot scale up-flow anaerobic sludge blanket (UASB) reactors (R1 and R2) were run to investigate the effects of different organic and hydraulic loading conditions on the performance of reactors treating poultry manure wastewater. The diameter, total height, total tank capacity of the reactors were 12 cm, 160 cm and 19.85 L, respectively. The reactors were made of transparent plexiglass material with a wall thickness of 5 mm. The reactors had a conical bottom of 20 cm length and a feed inlet pipe of 1.5 cm diameter to avoid chocking during operation. An outlet weir was provided at the top (1.51 m), which is connected to an outlet gutter and outlet pipe to the effluent collection tank. The reactors had ports for sampling, feeding, effluent and gas collecting. Gas was collected from the headspace on the top of the reactor and gas production was measured by the liquid displacement method. The gas collecting and measuring systems consisted of a gas–solid–liquid (GSL) separator (made from an inverted plastic funnel of 11 cm diameter), a gas collecting pipe, a water trap, a graduated gas measuring tube and a water tank for keeping of the gas measuring tube. The reactors were equipped with six sampling ports, localized at 0.35, 0.50, 0.65, 0.80, 0.90 and 1.10 m from the bottom of the reactors. A detailed schematic of the experimental set-up is depicted in Fig. 1.

### 2.6. UASB operation

Both R1 and R2 were operated simultaneously in a daily-continuous mode feeding by pumping of the fresh feed into the reactors and collecting effluent samples daily. In feeding, different target HRTs were achieved using a peristaltic

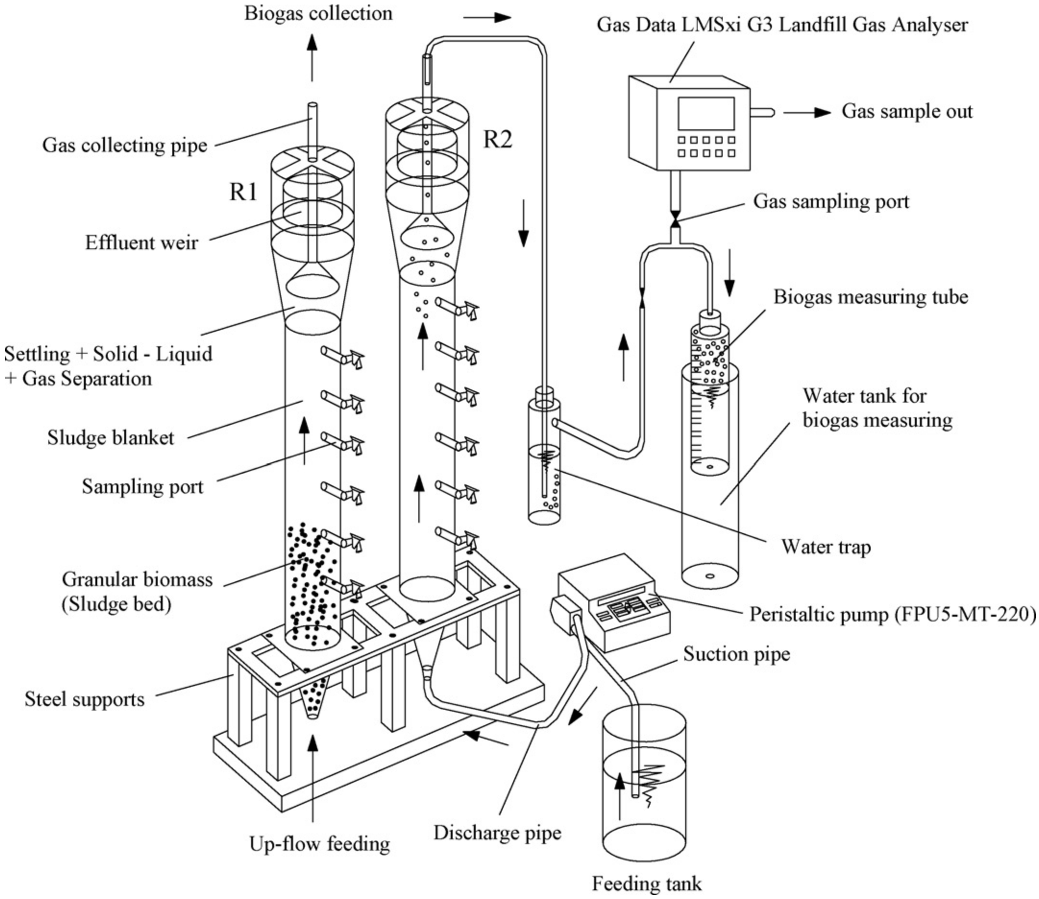

Fig. 1. A detailed schematic of the experimental set-up.

pump (FPU5-MT-220, OmegaFlex®). No recirculation of effluents or mixing were carried out in either reactor. During the feeding of the reactors, the feeding tank was continuously agitated to prevent sedimentation of suspended solids. Feed wastewater samples were prepared daily and pumped to the reactor from the feeding tank with a stable up-flow velocity of about 0.70 m/h by operating the peristaltic pump in a feeding mode of 50 rpm for the corresponding flow rate of 133 mL/min. The pH of the raw wastewater was adjusted between 6.6 and 7.8 by the gradual addition of $H_2SO_4$ and NaOH reagents (Merck Chemical Corp.). Both reactors were operated at mesophilic conditions ($32 \pm 2\,^{\circ}C$) in a temperature-controlled environment maintained by two adjustable radiators with thermostat (Demirdokum DEYR 7B CM).

### *2.7. Nonlinear modeling study*

On the basis of experimental results, a nonlinear modeling study was carried out to evaluate the performance of UASB reactors treating poultry manure wastewater under different organic and hydraulic loading conditions. In this study, experimental data was evaluated by DataFit® scientific software (version 8.1.69, Copyright © 1995–2005 Oakdale Engineering, RC167). The nonlinear regression was conducted based on the Levenberg–Marquardt method with double precision. As regression models were solved, they were automatically sorted according to the goodness-of-fit criteria.

In modeling study, two empirical models were developed to predict daily biogas production rate ($Q_g$) and effluent COD concentration ($S_e$), respectively. In order to obtain the best-fit models, numerous tests were carried out. In training of the proposed models, various forms of input variables were tested to obtain the highest correlation between the experimental data and predicted values. In selection of input variables, the aim was also investigate the effects of them on target values. Hence, *t*-ratios and the corresponding *p* values were determined to better evaluate the significance of the regression coefficient. Moreover, the descriptive statistics of the residual errors were provided to better evaluate the model performance.

## 3. Results and discussion

### *3.1. UASB reactors*

The experiments in this study were divided into three operational phases. The two of these were performed in R1 and the other in R2. Both reactors were conducted with three HRTs of 15.7, 12.0 and 8.0 days. Three feed ratios (kg of fresh poultry manure to litre of tap water respectively) of 1:8, 1:6 and 1:4 were carried out to investigate the effects of various organic loading rates (OLR) on anaerobic treatability and biogas production.

Table 1
Characteristics of R1 influent and R1 effluent in Phase 1

| Constituent | R1 Influent (mean ± S.D.) | R1 Effluent (mean ± S.D.) | Efficiency (%) (mean ± S.D.) |
|---|---|---|---|
| Total chemical oxygen demand, TCOD (mg/L) | 12052 ± 911 | 1753 ± 203 | 85 ± 1.9 |
| Biological oxygen demand, $BOD_5$ (mg/L) | 5900 ± 390 | 420 ± 50 | 93 ± 1.2 |
| Soluble chemical oxygen demand, SCOD (mg/L) | 2085 ± 171 | 1113 ± 93 | 46.3 ± 6.5 |
| Total solids, TS (mg/L) | 8275 ± 699 | 1975 ± 197 | 75.8 ± 3.6 |
| Volatile solids, VS (mg/L) | 5371 ± 450 | 1380 ± 126 | 74 ± 3.7 |
| Total suspended solids, TSS (mg/L) | 5018 ± 374 | 1130 ± 65 | 77.4 ± 2.5 |
| Volatile suspended solids, VSS (mg/L) | 4015 ± 336 | 969 ± 124 | 75.5 ± 4.3 |
| Total Kjeldahl nitrogen, TKN (mg/L) | 1825 ± 134 | 1381 ± 122 | 23 ± 10.1 |
| Ammonia nitrogen, $NH_3$-N (mg/L) | 987 ± 72 | 1178 ± 71 | −21 ± 11.8[a] |
| Total phosphorus, TP (mg/L) | 446 ± 35 | 382 ± 28 | 13.4 ± 9.1 |
| pH | 7.30 ± 0.22 | 8.28 ± 0.26 | – |
| Alkalinity (mg $CaCO_3$/L) | 3210 ± 200 | 2686 ± 193 | 15.8 ± 8.8 |

[a] The negative value of ammonia corresponds to an increase in the reactor.

### 3.1.1. Phase 1

Following the start-up, a daily-continuous operation was conducted in R1 with three HRTs of 15.7, 12.0 and 8.0 days. A feed ratio of 1:8 was carried out during Phase 1. Characteristics of the prepared poultry manure wastewater and R1 effluent in Phase 1 are given in Table 1.

On the basis of the cross-sectional area of the reactor (95.03 $cm^2$) and applied feed flow rates (1–2 L/day), hydraulic loading rates ($L_H$) were controlled between 0.105 and 0.21 $m^3/(m^2$ day). Imposed volumetric OLR ranged from 0.65 to 1.783 kg COD/($m^3$ day). The pH of the feed varied between 6.96 and 7.82, with an average value of 7.3 (±0.2). Biogas production rates ranged from 4.2 to 13 L/day and averaged 6.87 (±2.46) L/day. The observed total COD, SCOD, $BOD_5$, TS, TSS, VS, VSS, TKN and TP removal efficiencies averaged 85 (±1.9)%, 46.3 (±6.5)%, 93 (±1.2)%, 75.8 (±3.6)%, 77.4 (±2.5)%, 74 (±3.7)%, 75.5 (±4.3)%, 23 (±10.1)%, and 13.4 (±9.1)%, respectively. The removals in TP and also the loss of N in the UASB should be due to both new biomass production, as well as settling in the reactor [19]. Relatively low treatment efficiencies may be expected for TKN and TP, since anaerobic reactors are known to reduce negligible amounts of nutrients [20]. The $NH_3$-N concentration on average was increased by about 21 (±11.8)% during Phase 1 because of the anaerobic bioconversion of proteins contained in manure into amino acids and then to ammonia [20]. This also resulted in an increase of effluent pH, as given in Table 1. The negative value of ammonia nitrogen removal in Table 1 corresponds to an increase in the reactor. This is an observation also reported by other researchers [20–22]. The alkalinity was reduced by 15.8 (±8.8)% on average. This reduction can be attributed to the buffering of the VFA during the digestion process. High volumetric COD removal rates ($R_V$) ranging from 0.55 to 1.61 kg $COD_{removed}/(m^3$ day) were achieved. The result of COD mass balance showed that 72.7 (±2.1)% of influent organic matter on average was transformed to biogas with a methane content over 70%.

### 3.1.2. Phase 2

Following Phase 1, daily-continuous operation was maintained in R1 with a feed ratio of 1:6 at same HRTs of 15.7, 12.0 and 8.0 days, respectively. Characteristics of the prepared poultry manure wastewater and R1 effluent in Phase 2 are given in Table 2.

In Phase 2, imposed volumetric OLR ranged from 1.165 to 2.664 kg COD/($m^3$ day). The pH of the feed varied between 6.95 and 7.45, with an average value of 7.2 (±0.11). Depending on the gradual increase in OLR and $L_H$, biogas production rates ranged from 7.5 to 17.2 L/day and averaged 10.93 (±2.88) L/day. The observed total COD, SCOD, $BOD_5$, TS, TSS, VS,

Table 2
Characteristics of R1 influent and R1 effluent in Phase 2

| Constituent | R1 Influent (mean ± S.D.) | R1 Effluent (mean ± S.D.) | Efficiency (%) (mean ± S.D.) |
|---|---|---|---|
| Total chemical oxygen demand, TCOD (mg/L) | 19551 ± 732 | 1928 ± 173 | 90.1 ± 0.9 |
| Biological oxygen demand, $BOD_5$ (mg/L) | 9100 ± 250 | 380 ± 40 | 96 ± 0.4 |
| Soluble chemical oxygen demand, SCOD (mg/L) | 3417 ± 137 | 1217 ± 101 | 64.5 ± 2.7 |
| Total solids, TS (mg/L) | 12580 ± 497 | 1770 ± 154 | 87 ± 1.1 |
| Volatile solids, VS (mg/L) | 8678 ± 262 | 1129 ± 100 | 86.7 ± 1.2 |
| Total suspended solids, TSS (mg/L) | 8018 ± 303 | 1061 ± 95 | 86.7 ± 1.3 |
| Volatile suspended solids, VSS (mg/L) | 6758 ± 217 | 886 ± 74 | 86.7 ± 1.1 |
| Total Kjeldahl nitrogen, TKN (mg/L) | 2977 ± 100 | 2314 ± 166 | 23 ± 6.1 |
| Ammonia nitrogen, $NH_3$-N (mg/L) | 1757 ± 67 | 1970 ± 92 | −12 ± 6.3[a] |
| Total phosphorus, TP (mg/L) | 733 ± 29 | 454 ± 35 | 37.9 ± 4.9 |
| pH | 7.20 ± 0.11 | 8.11 ± 0.23 | – |
| Alkalinity (mg $CaCO_3$/L) | 5254 ± 204 | 3283 ± 273 | 37.4 ± 5.4 |

[a] The negative value of ammonia corresponds to an increase in the reactor.

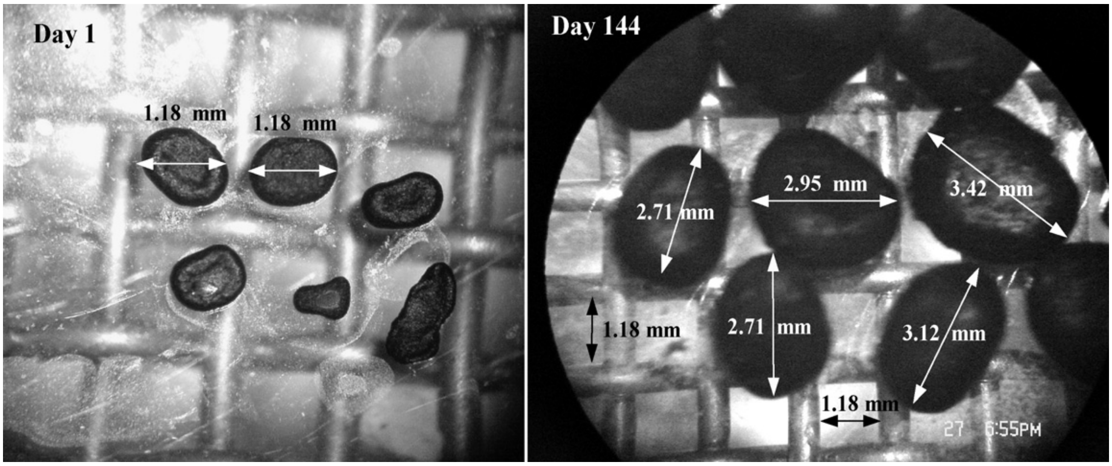

Fig. 2. Initial and final morphologies of some sample granules taken with a digital camera (Sony Cyber-shot DSC-N1) combined with a stereomicroscope (Prior, James Swift) on Day 1 and 144.

VSS, TKN and TP removal efficiencies averaged 90.1 (±0.9)%, 64.5 (±2.7)%, 96 (±0.4)%, 87 (±1.1)%, 86.7 (±1.3)%, 86.7 (±1.2)%, 86.7 (±1.1)%, 23 (±6.1)%, and 37.9 (±4.9)%, respectively. The observed increase in COD, $BOD_5$, and solids removal in the system in Phase 2 can be explained by acclimation of the anaerobic biomass to operating conditions. The $NH_3$-N concentration on average was increased by about 12 (±6.3)% during Phase 2. The alkalinity was reduced by 37.4 (±5.4)% on average. $R_V$ values were obtained between 1.04 and 2.42 kg $COD_{removed}/(m^3$ day). A COD mass balance revealed that 73.5 (±5.3)% of influent organic matter on average was transformed to biogas by anaerobic digestion. At the end of Phase 2, the volume of sludge bed was increased about 37%. Final morphologies of granules showed that diameter of the granules ($d_p$) was increased about 2.5 times as compared to the initial morphologies. Fig. 2 depicts initial and final morphologies of some sample granules on Day 1 and 144.

### 3.1.3. Phase 3

Phase 3 was carried out in R2 with a feed ratio of 1:4 at same HRTs of 15.7, 12.0 and 8.0 days, respectively. Phase 3 was simultaneously started with Phase 1 conducted in R1. Characteristics of the prepared poultry manure wastewater and R2 effluent in Phase 3 are given in Table 3.

Imposed volumetric OLR ranged from 1.74 to 4.26 kg COD/($m^3$ day). The pH of the feed varied between 6.68 and 7.40, with an average value of 7.1 (±0.19). Biogas production rates ranged from 10.2 to 29.4 L/day and averaged 17.1 (±5.3) L/day. The observed total COD, SCOD, $BOD_5$, TS, TSS, VS, VSS, TKN and TP removal efficiencies averaged 90 (±1.9)%, 52.7 (±9.0)%, 94 (±0.99)%, 73.5 (±5.0)%, 74.4 (±5.5)%, 70 (±6.6)%, 72.5 (±4.0)%, 20 (±7.1)%, and 20.3 (±13.5)%, respectively. Although, high incoming COD, $BOD_5$, and solids concentrations were imposed to the system, R2 demonstrated a stable performance on anaerobic treatability of poultry manure wastewater and biogas production. The $NH_3$-N concentration on average was increased by about 18 (±7.3)% during Phase 2. The alkalinity was reduced by 21.4 (±8.83)% on average. High $R_V$ values were obtained between 1.55 and 3.78 kg $COD_{removed}/(m^3$ day). The COD mass balance demonstrated that 73.9 (±5.1)% of influent organic matter on average was transformed to biogas.

Table 3
Characteristics of R2 influent and R2 effluent in Phase 3

| Constituent | R2 Influent (mean ± S.D.) | R2 Effluent (mean ± S.D.) | Efficiency (%) (mean ± S.D.) |
|---|---|---|---|
| Total chemical oxygen demand, TCOD (mg/L) | 29966 ± 1557 | 3028 ± 601 | 90 ± 1.9 |
| Biological oxygen demand, $BOD_5$ (mg/L) | 14800 ± 440 | 950 ± 150 | 94 ± 0.99 |
| Soluble chemical oxygen demand, SCOD (mg/L) | 5220 ± 362 | 2487 ± 492 | 52.7 ± 9.0 |
| Total solids, TS (mg/L) | 21112 ± 971 | 5552 ± 946 | 73.5 ± 5.0 |
| Volatile solids, VS (mg/L) | 13214 ± 531 | 3940 ± 840 | 70 ± 6.6 |
| Total suspended solids, TSS (mg/L) | 12290 ± 561 | 3148 ± 661 | 74.4 ± 5.5 |
| Volatile suspended solids, VSS (mg/L) | 10057 ± 594 | 2732 ± 320 | 72.5 ± 4.0 |
| Total Kjeldahl nitrogen, TKN (mg/L) | 4431 ± 212 | 3562 ± 318 | 20 ± 7.1 |
| Ammonia nitrogen, $NH_3$-N (mg/L) | 2201 ± 93 | 2608 ± 168 | −18 ± 7.3[a] |
| Total phosphorus, TP (mg/L) | 1120 ± 56 | 886 ± 145 | 20.3 ± 13.5 |
| pH | 7.10 ± 0.19 | 8.01 ± 0.18 | – |
| Alkalinity (mg $CaCO_3$/L) | 7550 ± 333 | 5918 ± 703 | 21.4 ± 8.83 |

[a] The negative value of ammonia corresponds to an increase in the reactor.

Table 4
Average values of input and output variables obtained at the end of three operating phases

| Reactor | Days operated | HRT (days) | Influent COD range (mg/L) | Average influent COD (mg/L) | Biogas production range (L/day) | Average biogas production rate (L/day) |
|---|---|---|---|---|---|---|
| R1 | 1–32 | 15.7 | 10200–13398 | 11459 | 4.2–5.6 | 4.8 |
| R1 | 33–56 | 12.0 | 11076–14504 | 12469 | 5.9–7.9 | 6.9 |
| R1 | 57–72 | 8.0 | 11300–13999 | 12594 | 9.5–13 | 11.1 |
| R1 | 73–104 | 15.7 | 18294–20929 | 19380 | 7.5–10.2 | 8.7 |
| R1 | 105–128 | 12.0 | 18454–20816 | 19729 | 9.6–12.9 | 10.7 |
| R1 | 129–144 | 8.0 | 18276–20914 | 19579 | 14.4–17.2 | 15.9 |
| R2 | 1–32 | 15.7 | 27284–32418 | 29452 | 10.2–15.3 | 13 |
| R2 | 33–56 | 12.0 | 26880–33600 | 30408 | 14–21.0 | 16.7 |
| R2 | 57–72 | 8.0 | 26614–33414 | 30297 | 23–29.4 | 26.2 |

## 3.2. Nonlinear modeling study

### 3.2.1. Prediction of biogas production rate ($Q_g$)

In this work, HRT values ($\theta$) and the corresponding average influent COD concentrations ($S_i$) were selected as input variables to predict the daily biogas production rate ($Q_g$). Experimental results obtained from three different operating phases were directly imported from Microsoft® Excel used as an ODBC data source and nonlinear regression analysis was performed. Average values of input and output variables obtained at the end of three operating phases are summarized in Table 4. Descriptive statistics of the data set considered in the regression analysis are presented in Table 5.

In nonlinear study, 179 different mathematical models were solved and automatically sorted according to the goodness-of-fit criteria. The first seven of them are summarized in Table 6. As shown in Table 6, the first seven of solved models had a remarkable correlation with the experimental data. However, model-6 which had more simple structure than the others was preferred and selected as the best-fit model.

Regression variable results including standard error, the $t$-statistics and the corresponding $p$ values for the best-fit model are summarized in Table 7. The proposed model defined as a function of two operating variables [$Q_g = f(\theta, S_i)$] is given in following equation:

$$Q_g = 0.005775(\theta)^{-1.013} S_i^{1.019} = 0.005775\left(\frac{V_R}{Q_f}\right)^{-1.013} S_i^{1.019} \quad (1)$$

Table 5
Descriptive statistics of the data set considered in the regression analysis

| Data statistics | $x_1$ | $x_2$ | $Y$ |
|---|---|---|---|
| Variables | $\theta$ | $S_i$ | $Q_g$ |
| Units | day | mg/L | L/day |
| Number of points | 9 | 9 | 9 |
| Missing points | 0 | 0 | 0 |
| Maximum value | 15.7 | 30407.5 | 26.2 |
| Minimum value | 8 | 11459.1 | 4.8 |
| Range | 7.7 | 18948.4 | 21.4 |
| Average | 11.9 | 20596.23 | 12.667 |
| Standard deviation | 3.335 | 7791.27 | 6.3951 |

where $Q_g$ is the biogas production rate (L/day), $\theta$ is the hydraulic retention time (day), $S_i$ is the influent COD concentration (mg/L), $V_R$ is the working volume of the reactor and $Q_f$ is the feed flow rate (L/day).

To evaluate the model performance, descriptive statistics of the residual errors are given in Table 8. Predicted $Q_g$ values and residual errors are summarized in Table 9. Fig. 3 illustrates the agreement between the proposed model outputs and the experimental data.

### 3.2.2. Prediction of effluent COD concentration ($S_e$)

In this modeling work; HRT values ($\theta$), the corresponding average influent COD concentrations ($S_i$), volumetric OLR values ($L_V$), and biogas production rate ($Q_g$) were selected as input variables to predict the effluent COD concentration ($S_e$). Average values of input and output variables regarding the second modeling study are summarized in Table 10. Descriptive statistics of the data set considered in prediction of effluent COD concentration are presented in Table 11.

According to results obtained from the nonlinear study, an exponential function giving the highest correlation coefficient was selected as the best-fit equation for the prediction of effluent COD concentration. Results are summarized in Table 12.

Regression variable results including standard error, the $t$-statistics and the corresponding $p$ values for the best-fit exponential function are presented in Table 13. The proposed model defined as a function of four operating variables [$S_e = f(\theta, L_V$,

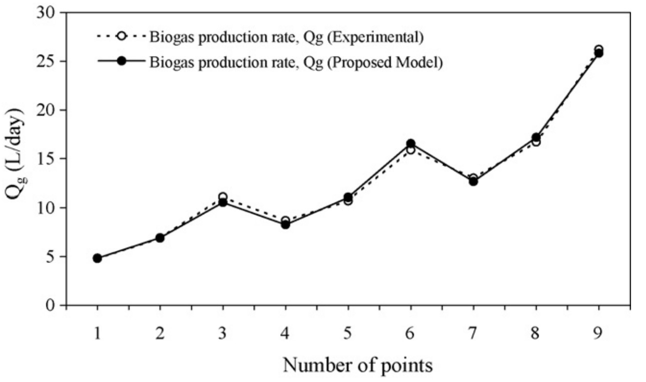

Fig. 3. Agreement between the proposed model outputs and the experimental data ($R^2 = 0.9954$).

Table 6
Summary of regression results for the first modeling study

| Rank | Model | SEE | SR | AR | RSS | $R^2$ | $R^2_a$ |
|---|---|---|---|---|---|---|---|
| 1 | $a+b/x_1+cx_2+d/x_1^2+ex_2^2+fx_2/x_1$ | 0.559 | 2.92E−10 | 325E−11 | 0.938 | 0.997 | 0.992 |
| 2 | $a+b/x_1+c/x_1^2+d\log(x_2)+e\log(x_2)^2+f\log(x_2)^3+g\log(x_2)^4+h\log(x_2)^5$ | 1.035 | −1.14E−05 | −1.27E−06 | 1.070 | 0.997 | 0.974 |
| 3 | $a+b\log(x_1)+c\log(x_1)^2+d\log(x_2)+e\log(x_2)^2+f\log(x_2)^3+g\log(x_2)^4+h\log(x_2)^5$ | 1.035 | 2.15E−05 | 2.38E−06 | 1.070 | 0.997 | 0.974 |
| 4 | $a+bx_1+cx_1^2+d\log(x_2)+e\log(x_2)^2+f\log(x_2)^3+g\log(x_2)^4+h\log(x_2)^5$ | 1.035 | −4.77E−07 | −5.30E−08 | 1.072 | 0.997 | 0.974 |
| 5 | $a+b\log(x_1)+cx_2+d\log(x_1)^2+ex_2^2+f\log(x_1)x_2$ | 0.667 | −4.11E−09 | −4.57E−10 | 1.333 | 0.996 | 0.989 |
| 6 | $ax_1^bx_2^c$ | 0.504 | 1.24E−01 | 1.37E−02 | 1.522 | 0.995 | 0.994 |
| 7 | $a+bx_1+cx_2+dx_1^2+ex_2^2+fx_1x_2$ | 0.812 | 0.000 | 0.000 | 1.978 | 0.994 | 0.984 |

SEE, standard error of the estimate; SR, sum of residuals; AR, average residual; RSS, residual sum of squares; $R^2$, coefficient of multiple determination; $R^2_a$, adjusted coefficient of multiple determination.

Table 7
Regression variable results including standard error, the *t*-statistics and the corresponding *p* values for the best-fit model

| Regression variable | Value | Standard error | *t*-Ratio | *p*-Value |
|---|---|---|---|---|
| *a* | $+5.775\times10^{-3}$ | $2.4333\times10^{-3}$ | 2.3733 | 0.05527 |
| *b* | −1.013 | $4.6273\times10^{-2}$ | −21.8892 | 0.0 |
| *c* | +1.019 | $4.0156\times10^{-2}$ | 25.3678 | 0.0 |

Table 8
Descriptive statistics of the residuals errors in prediction of $Q_g$ values

| Residual statistics | Calculation | Regression results |
|---|---|---|
| Residual tolerance | $Y_a-Y_p$ | $1\times10^{-10}$ |
| Sum of residuals | $\sum_{i=1}^{n}(Y_a-Y_p)$ | 0.1237 |
| Average residual | $\frac{1}{n}\sum_{i=1}^{n}(Y_a-Y_p)$ | $1.3744\times10^{-2}$ |
| Residual sum of squares (absolute) | $\mathrm{SSE}=\sum_{i=1}^{n}(Y_a-Y_p)^2$ | 1.5216 |
| Residual sum of squares (relative) | $\mathrm{SSE_R}=\sum_{i=1}^{n}\left[\frac{(Y_a-Y_p)^2}{\sigma^2}\right]$ | 1.5216 |
| Standard error of the estimate | $\sqrt{\frac{\sum_{i=1}^{n}(Y_a-Y_p)^2}{n-p}}=\sqrt{\frac{\mathrm{SSE}}{n-p}}$ | 0.503586 |

$Y_a$, actual data point; $Y_p$, predicted values; *n*, number of data points or observations; $\sigma$, standard deviation of data point; *p*, number of parameters or variables in the regression model.

$S_i$, $Q_g$)] is given in Eq. (2).

$$S_e=\exp[0.04(\theta)+0.722(L_V)+0.00001341(S_i)-0.0695(Q_g)+6.4455] \quad (2)$$

where $S_e$ is the effluent COD concentration (mg/L), $\theta$ is the hydraulic retention time (day), $L_V$ is the volumetric OLR (kg COD/(m$^3$ day)), $S_i$ is the influent COD concentration (mg/L) and $Q_g$ is the biogas production rate (L/day).

To evaluate the second model performance, descriptive statistics of the residual errors are presented in Table 14. Predicted $S_e$ values and residual errors are given in Table 15. Fig. 4 depicts

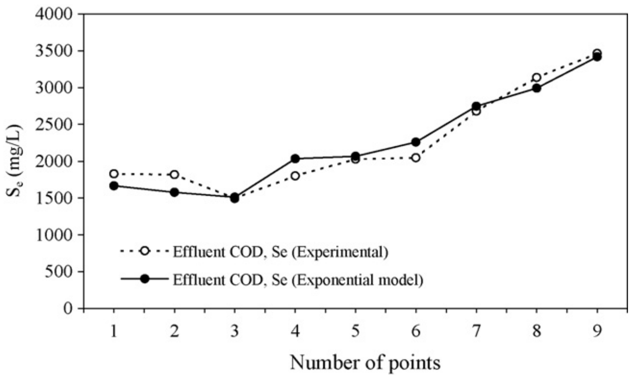

Fig. 4. Agreement between the exponential model outputs and the experimental data ($R^2$ = 0.9416).

Table 9
Predicted $Q_g$ values and residual errors

| $\theta$ | $S_i$ | $Q_g$ (experimental) | $Q_g$ (model) | Residuals | Error (%) | Absolute residual |
|---|---|---|---|---|---|---|
| Power-law nonlinear regression model: $Q_g = 0.005775(\theta)^{-1.013} S_i^{1.019}$ | | | | | | |
| 15.7 | 11459.1 | 4.8 | 4.84342 | −0.0434 | −0.9047 | 0.043424287 |
| 12 | 12468.7 | 6.9 | 6.92995 | −0.03 | −0.4341 | 0.029952091 |
| 8 | 12593.7 | 11.1 | 10.5561 | 0.54389 | 4.89993 | 0.543892478 |
| 15.7 | 19380 | 8.7 | 8.27209 | 0.42791 | 4.91846 | 0.427906317 |
| 12 | 19729.3 | 10.7 | 11.0596 | −0.3596 | −3.3611 | 0.359632859 |
| 8 | 19579.3 | 15.9 | 16.5472 | −0.6472 | −4.0705 | 0.647213323 |
| 15.7 | 29451.6 | 13 | 12.6696 | 0.33039 | 2.54147 | 0.330390631 |
| 12 | 30407.5 | 16.7 | 17.1837 | −0.4837 | −2.8964 | 0.483694058 |
| 8 | 30296.9 | 26.2 | 25.8146 | 0.38542 | 1.47108 | 0.385423128 |

the agreement between the exponential model outputs and the experimental data.

### 3.3. UASB performance evaluation using proposed models

Following the nonlinear regression study, a performance evaluation was conducted to determine optimal operating conditions for different HRTs and imposed susbtrate concentrations. $\theta$ and $S_i$ values were evaluated in the ranges of 8.0–15.7 days, and 10,000–35,000 mg/L, respectively. Proposed models given in Eqs. (1) and (2) were combined as follows:

$$S_e = \exp[0.04(\theta) + 0.722\left(\frac{S_i}{\theta}\right) + 0.00001341(S_i) - 0.0695(0.005775(\theta)^{-1.013} S_i^{1.019}) + 6.4455] \quad (3)$$

$$S_e = \exp\left[0.04\left(\frac{V_R}{Q_f}\right) + 0.722\left(\frac{Q_f S_i}{V_R}\right) + 0.00001341(S_i) - 0.0004014\left(\frac{V_R}{Q_f}\right)^{-1.013} S_i^{1.019} + 6.4455\right] \quad (4)$$

By using the combined model, effluent COD concentrations were determined for varying values of HRT and influent COD concentrations. Next, COD removal efficiencies were calculated and performance curves were developed. Fig. 5 depicts the performance curves obtained for six different influent COD concentrations. On the basis of performance curves, optimal operating conditions to obtain highest COD removal efficiencies are summarized in Table 16 for different $S_i$ values.

The performance evaluation revealed that COD removal efficiency increased with the gradual decrease of HRT at relatively low substrate concentrations. At the substrate concentration of 20,000 mg/L, COD removal efficiency was predicted to increase up to feed flow rate of about 1.4 L/day. Similarly, COD removal efficiency was estimated to increase up to feed flow rate of 1.25 L/day at the substrate concentration of 25,000 mg/L. However, a further increase in $L_H$ at relatively medium strength feedings resulted a gradual decrease in COD removal efficiency. This initial low efficiency at each gradual decrease in HRT can be attributed to the fact that the acidogens and methanogens bacterial populations had to be acclimated to the new flow regime and the increase in organic loading rate. At relatively high substrate concentrations of 30,000 and 35,000 mg/L, performance

Table 11
Descriptive statistics of the data set considered in prediction of effluent COD concentration

| data statistics | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $Y$ |
|---|---|---|---|---|---|
| Variables | $\theta$ | $L_V$ | $S_i$ | $Q_g$ | $S_e$ |
| Units | day | kg COD/(m$^3$ day) | mg/L | L/day | mg/L |
| Number of points | 9 | 9 | 9 | 9 | 9 |
| Missing points | 0 | 0 | 0 | 0 | 0 |
| Maximum value | 15.7 | 3.8 | 30407.5 | 26.2 | 3465.1 |
| Minimum value | 8 | 0.7 | 11459.1 | 4.8 | 1494 |
| Range | 7.7 | 3.1 | 18948.4 | 21.4 | 1971.1 |
| Average | 11.9 | 1.856 | 20596.23 | 12.667 | 2255.93 |
| Standard deviation | 3.335 | 0.944 | 7791.27 | 6.3951 | 678.05 |

Table 10
Average values of input and output variables regarding the second modeling study

| Reactor | Days operated | HRT (day) | Average OLR (kg COD/(m$^3$ day) | Average influent COD (mg/L) | Average biogas production rate (L/day) | Effluent COD range (mg/L) | Average effluent COD (mg/L) |
|---|---|---|---|---|---|---|---|
| R1 | 1–32 | 15.7 | 0.73 | 11459 | 4.8 | 1596–2180 | 1829 |
| R1 | 33–56 | 12.0 | 1.04 | 12469 | 6.9 | 1609–2064 | 1819 |
| R1 | 57–72 | 8.0 | 1.60 | 12594 | 11.1 | 1112–1916 | 1494 |
| R1 | 73–104 | 15.7 | 1.23 | 19380 | 8.7 | 1615–2130 | 1801 |
| R1 | 105–128 | 12.0 | 1.65 | 19729 | 10.7 | 1856–2214 | 2029 |
| R1 | 129–144 | 8.0 | 2.49 | 19579 | 15.9 | 1834–2214 | 2046 |
| R2 | 1–32 | 15.7 | 1.88 | 29452 | 13 | 1794–3412 | 2682 |
| R2 | 33–56 | 12.0 | 2.54 | 30408 | 16.7 | 1747–4000 | 3138 |
| R2 | 57–72 | 8.0 | 3.86 | 30297 | 26.2 | 2836–4122 | 3465 |

Table 12
Summary of regression results for the second modeling study

| Rank | Model | SEE | SR | AR | RSS | $R^2$ | $R_a^2$ |
|---|---|---|---|---|---|---|---|
| 1 | $\exp(ax_1 + bx_2 + cx_3 + dx_4 + e)$ | 231.777 | 26.8123 | 2.97914 | 214881 | 0.94158 | 0.88315 |
| 2 | $ax_1 + bx_2 + cx_3 + dx_4 + e$ | 298.607 | 4.03E−09 | 4.48E−10 | 356666 | 0.90303 | 0.80605 |
| 3 | $ax_1 + bx_2 + cx_3 + dx_4$ | 274.704 | −40.09 | −4.4544 | 377311 | 0.89741 | 0.83586 |

SEE, standard error of the estimate; SR, sum of residuals; AR, average residual; RSS, residual sum of squares; $R^2$, coefficient of multiple determination; $R_a^2$, adjusted coefficient of multiple determination.

curves showed a declining trend with increasing $L_H$. This can be ascribed to a longer adaptation stage.

On the basis of the COD removal efficiency, results indicated that there was no significant difference in operating the reactor at HRTs of 7.9 and 14.3 days for the corresponding influent substrate concentrations of 10,000 and 35,000 mg/L, respectively. However, the optimum HRT and initial feeding concentrations to be applied depend on the desired results and whether a post treatment is needed. If the UASB reactor is employed as the only or main treatment unit, the optimum HRT should be sufficiently

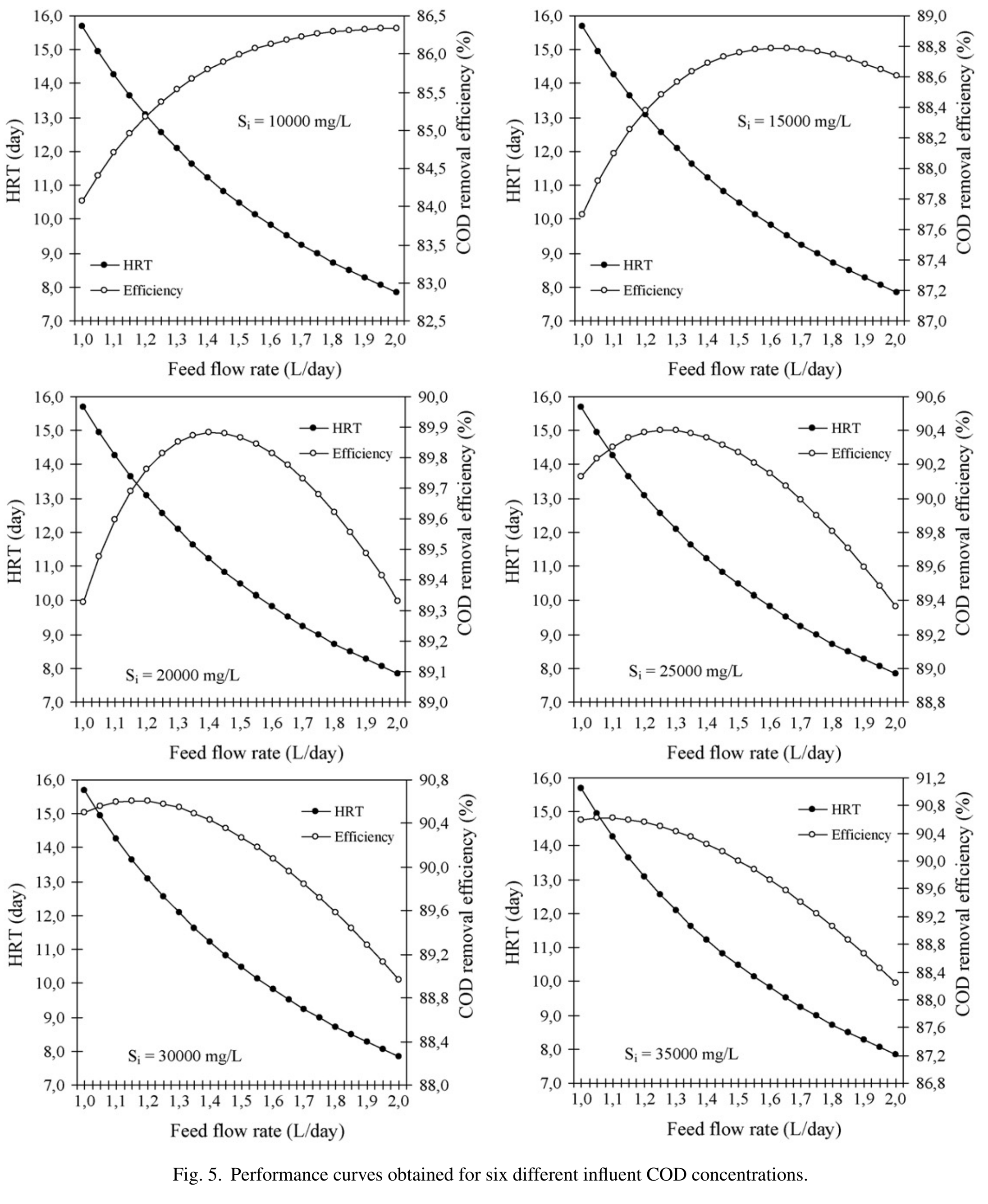

Fig. 5. Performance curves obtained for six different influent COD concentrations.

Table 13
Regression variable results including standard error, the *t*-statistics and the corresponding *p* values for the best-fit exponential function

| Regression variable | Value | Standard Error | *t*-Ratio | *p*-Value |
|---|---|---|---|---|
| *a* | +0.040 | $3.75 \times 10^{-2}$ | 1.06279498 | 0.3478 |
| *b* | +0.722 | 0.768663853 | 0.93952474 | 0.4007 |
| *c* | +0.00001341 | $1.52 \times 10^{-5}$ | 0.88282545 | 0.4272 |
| *d* | −0.0695 | 0.1 | −0.6936749 | 0.5261 |
| *e* | +6.4455 | 0.489885955 | 13.1570952 | 0.0002 |

Table 14
Descriptive statistics of the residuals errors in prediction of $S_e$ values

| Residual statistics | Calculation | Regression results |
|---|---|---|
| Residual tolerance | $(Y_a - Y_p)$ | $1 \times 10^{-10}$ |
| Sum of residuals | $\sum_{i=1}^{n}(Y_a - Y_p)$ | 26.8123 |
| Average residual | $\frac{1}{n}\sum_{i=1}^{n}(Y_a - Y_p)$ | 2.97914 |
| Residual sum of squares (absolute) | $\mathrm{SSE} = \sum_{i=1}^{n}(Y_a - Y_p)^2$ | 214881.4452 |
| Residual sum of squares (relative) | $\mathrm{SSE_R} = \sum_{i=1}^{n}\left[(Y_a - Y_p)^2 \frac{1}{\sigma^2}\right]$ | 214881.4452 |
| Standard error of the estimate | $\sqrt{\frac{\sum_{i=1}^{n}(Y_a-Y_p)^2}{n-p}} = \sqrt{\frac{SSE}{n-p}}$ | 231.7765 |

$Y_a$, actual data point; $Y_p$, predicted values; *n*, number of data points or observations; $\sigma$, standard deviation of data point; *p*, number of parameters or variables in the regression model.

high to guarantee a high removal efficiency and consequently a longer HRT is required. In case the UASB reactor is used as a pre-treatment unit, shorter HRT can be applied [23].

Although the efficiency decreased with shorter HRT, particularly at medium to high strength substrate concentrations, no process failure was observed. It can be stated that both UASB reactors showed a remarkable performance under varying organic and hydraulic loading conditions applied in the systems.

## 4. Conclusions

The poultry manure wastewater was satisfactorily treated by means of high-rate anaerobic processes, specifically with the use of UASB reactors. Both R1 and R2 showed a remarkable performance on total COD reductions with treatment efficiencies between 82% and 94% under varying organic and hydraulic loading conditions. High volumetric COD removal rates ($R_V$) ranging from 0.55 to 3.78 kg $\mathrm{COD_{removed}}/(\mathrm{m^3}$ day) were achieved. The maximum organic loading achieved with the system was observed to be 4.26 kg COD/($\mathrm{m^3}$ day) with a corresponding COD removal efficiency of about 88.2% and a removal rate of 3.78 kg $\mathrm{COD_{removed}}/(\mathrm{m^3}$ day). Good performance of the reactors may be explained by the contribution of the good quality of the seed sludge. The initial volume of actively digesting granular biomass, about 30% of the reactor working volume, was found to be sufficient for an effective start-up process. Depending on various organic and hydraulic loading conditions, daily biogas production rates ranged between 4.2 and 29.4 L/day (or 0.27–1.87 L/(L day)). Result of COD mass balances showed that over 72% of influent organic matters imposed to the systems

Table 15
Predicted $S_e$ values and residual errors

| $\theta$ | $L_V$ | $S_i$ | $Q_g$ | $S_e$ -experimental | $S_e$ -model | Residuals | Error (%) | Absolute Residual |
|---|---|---|---|---|---|---|---|---|
| Exponential model : $S_e = \exp[0.04(\theta)+0.722(L_V)+0.00001341(S_i)-0.0695(Q_g)+6.4455]$ | | | | | | | | |
| 15.7 | 0.73 | 11459.1 | 4.8 | 1829.4 | 1667.48 | 161.916 | 8.85075 | 161.9156311 |
| 12 | 1.04 | 12468.7 | 6.9 | 1818.5 | 1576.53 | 241.972 | 13.3061 | 241.9721893 |
| 8 | 1.60 | 12593.7 | 11.1 | 1494 | 1511.08 | −17.079 | −1.1432 | 17.0794695 |
| 15.7 | 1.23 | 19380 | 8.7 | 1801 | 2035.06 | −234.06 | −12.996 | 234.059546 |
| 12 | 1.65 | 19729.3 | 10.7 | 2029 | 2067.19 | −38.19 | −1.8822 | 38.18985516 |
| 8 | 2.49 | 19579.3 | 15.9 | 2046.3 | 2260.8 | −214.5 | −10.482 | 214.498143 |
| 15.7 | 1.88 | 29451.6 | 13 | 2682.1 | 2746.81 | −64.712 | −2.4127 | 64.71210352 |
| 12 | 2.54 | 30407.5 | 16.7 | 3138 | 2992 | 146.001 | 4.65267 | 146.0007052 |
| 8 | 3.86 | 30296.9 | 26.2 | 3465.1 | 3419.64 | 45.4629 | 1.31202 | 45.46287818 |

Table 16
Optimal operating conditions for different $S_i$ values

| Variables | Influent COD concentration, $S_i$ (mg/L) | | | | | |
|---|---|---|---|---|---|---|
| | 10,000 | 15,000 | 20,000 | 25,000 | 30,000 | 35,000 |
| Reactor working volume, $V_R$ (L) | 15.7 | 15.7 | 15.7 | 15.7 | 15.7 | 15.7 |
| Hydraulic retention time, $\theta$ (day) | 7.9 | 9.5 | 11.2 | 12.6 | 13.7 | 14.3 |
| Feed flow rate, $Q_f$ (L/day) | 2.00 | 1.65 | 1.40 | 1.25 | 1.15 | 1.10 |
| Volumetric OLR, $L_V$ (kg COD/($\mathrm{m^3}$ day)) | 1.27 | 1.58 | 1.78 | 1.99 | 2.20 | 2.45 |
| COD removal efficiency (%) | 86.33 | 88.79 | 89.88 | 90.40 | 90.61 | 90.62 |
| Effluent COD concentration, $S_e$ (mg/L) | 1367 | 1682 | 2024 | 2400 | 2817 | 3282 |

were transformed to biogas with a methane content over 70%. On the basis of experimental results, a power-law nonlinear regression model with two variables ($\theta$, $S_i$) and a correlation coefficient of 0.9954, and an exponential nonlinear regression model with four variables ($\theta$, $L_V$, $S_i$, $Q_g$) and a correlation coefficient of 0.9416 were developed as the best-fit models for the prediction of $Q_g$ and $S_e$ values, respectively. Nonlinear modeling study showed that $\theta$ and $S_i$ were found to be main operational variables which directly affect biogas production rate ($Q_g$) and COD removal efficiency. The optimum HRT was predicted to be between 7.9 and 14.3 days for the corresponding OLR values ranged from 1.27 to 2.45 kg COD/(m$^3$ day). The choice depends on the desired effluent quality and whether post-treatment is needed. It should be noted that the effluent quality in terms of COD obtained means that compliance with the effluent discharge standards would not be met. Therefore, a post-treatment will be required when treating poultry manure wastewater with the UASB reactor.

## Acknowledgements

The authors wish to thank to Mr. Hasan Mutlu who is the owner of Hakan's Poultry Farm for providing the poultry manure used as feed material in the experiments. The authors would like to thank to Pasabahce Distillery Inc. for supplying the granular biomass used in this study. The authors also wish to thank to Prof. Dr. Ahmet Demir and Prof. Dr. Cumali Kinaci for their helpful comments.

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