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Water Practice & Technology Vol 14 No 2
doi: 10.2166/wpt.2019.010

Performance evaluation and kinetic parameter analysis for static granular bed reactor (SGBR) for treating poultry slaughterhouse wastewater at mesophilic condition

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Abstract

Poultry slaughterhouses consume a substantial quantity of potable water during processing of live birds. Subsequently, high strength poultry slaughterhouse wastewater (PSW) is generated at different stages during poultry product processing. In this study, a Static Granular Bed Reactor (SGBR) was used to treat the PSW from a poultry processing facility in the Western Cape, South Africa. The performance of the SGBR was primarily evaluated for chemical oxygen demand (tCOD) removal with the kinetics of the treatment process for PSW being evaluated using both the Grau second-order and the modified Stover-Kincannon models to predict the effluent COD. The overall treatment efficiency averaged >80% when the SGBR was operated at steady state for 110 days' experimental trial. On the basis of the experimental results, the predicted values of the tCOD concentration using the Grau second-order and modified Stover Kincannon model were inconsistent with the experimental data indicating an insignificant correlation with predicted tCOD concentration being higher than the experimental data. The high variation between the modelled and experimental data based on both the Grau second order and modified Stover-Kincannon model was observed at higher organic loading rates when the reactor was fed with undiluted influent, phenomena attributed to tCOD entrapped inside the SGBR, especially during periods of clogging caused by the accumulation of suspended solids in the underdrain.

Key words: grau second order, modified-stover-kincannon, poultry slaughterhouse, static granular bed reactor

INTRODUCTION

In South Africa, the poultry product industry consumes a significant quantity of potable water ranging from 4.2 to 16.7 m^3 per tonne of live carcass weight for slaughtering and processing of birds, including for cleaning and sanitising of equipment (Basitere *et al.* 2016). The wastewater volumes generated from the poultry slaughterhouse ranges from 2.0 to 5.1 L per tonne of live weight kill (LWK) with an average of 3.9 m^3 per tonne LWK (Oh 2012). This results in the generation of a large volume of wastewater, which contains a high concentration of organic matter quantifiable as biochemical oxygen demand (BOD_5) and/or total chemical oxygen demand (tCOD). The poultry slaughterhouse wastewater (PSW) contains phosphorous and nitrogenous compounds, including blood, fats, oil, grease (FOG) and proteins (Debik & Coskun 2009; Basitere *et al.* 2017). The presence of suspended and colloidal matter such as proteins, fats and cellulosic matter may result in poor performance of an anaerobic digester, which is attributed to the undegradability and insolubility of such organic matter (Johns 1995; Torkian *et al.* 2003). To circumvent severe environmental pollution and subsequent

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municipal disposal charges/levies, the PSW must be efficiently treated prior to discharge into the local municipal sewage system or receiving fresh water sources.

For suitable treatment, anaerobic digestion (AD) technology is described as one of the most favourable methods utilised for the treatment of high strength agricultural wastewater due to its reduced footprint, high influent treatment rates, low sludge production and operating costs (Jijai *et al.* 2015). Due to AD's dual benefit of reducing environmental pollution and generating biogas for energy needs, it is considered to be an attractive treatment option (Harikishan & Sung 2003). The advantages of AD include its ability to function independent of electricity supply, thus its suitability for some developing countries, such as South Africa (Turkdogan-Aydinol *et al.* 2011). Furthermore, the application AD technology in environmental engineering applications is motivated by the need for energy efficiency and CO_2 emission reduction to mitigate against global warming effects (Van Lier 2008). The first generation AD to be widely used in the wastewater treatment environment is the septic tank system, with its application mainly used as a pre-treatment system for sewage (Al-Jamal & Mahmoud 2009). Over the last decade, advances in AD process technology development has led to improvements in new AD technologies, culminating in their ability to treat low to high strength wastewater. The newly developed AD bioreactors include the anaerobic filters, anaerobic contact process, up-flow anaerobic sludge blanket (UASB) bioreactor, and expanded granular bed (EGSB) bioreactors. A newly developed bioreactor known as the Static Granular Bed Reactor (SGBR), developed by Ellis & Mach (2004) at the Iowa State University Environmental Laboratory, has shown potential to treat high strength wastewater with a high efficiency. The SGBR design incorporates highly active, dense microbial granules, in a simple down-flow configuration. Due to its down-flow configuration, the SGBR allows for an improved retention of anaerobic biomass and a simpler influent distribution system while recovering biogas easily, separating the anaerobic granules from treated wastewater due to the counter-current flow between the gas generated and liquid phases (Park *et al.* 2009). Furthermore, the down-flow operation allows suspended solids in the influent to be filtered through the granular bed (Oh 2012), with minimal mechanical agitation requirements and a mixing system or recirculation system, as it relies on biogas-induced mixing, which reduces short circuiting and dead-zones within the reactor. As such, the SGBR can treat a variety of wastewater at high organic loading rates (OLRs) and short hydraulic retention time (HRT(s)); inadequacies observed in numerous studies using laboratory scale bioreactors. Debik & Coskun (2009) reported on the performance of the SGBR and its suitability in treating PSW, achieving 90% tCOD reduction. Similarly, Ellis & Mach (2004) reported tCOD removal of 91% treating synthetic wastewater composed of sucrose and non-fat dry milk, an improved system performance when compared to an UASB reactor. Roth *et al.* (2004) reported tCOD removal efficiency of 90% at OLRs of 1.9 to 4.55 kg tCOD/m^3.d, when treating pork slaughterhouse wastewater, with Park *et al.* (2012) concurring to such performance at OLRs of 0.77 to 12.76 kg/m^3.day, achieving tCOD removal efficiency >95%.

Generally, modelling plays a valuable role in the design of biological treatment plants. Furthermore, modelling of wastewater treatment plants assists in the development of better treatment processes, as it provides a potential to lower operation cost through optimization, while solving operational problems (Turkdogan-Aydinol *et al.* 2011). Additionally, modelling provides a rational basis for process analysis and control strategies to meet the effluent quality requirements at reasonable cost (Yu *et al.* 1998; Turkdogan-Aydinol *et al.* 2011). The model generated to describe bioreactors' operation under different operating conditions can be used to scale-up processes from pilot to full-scale plant operations, reducing the generation of complex and laborious experimental data using simplified mathematical expressions (Yetilmezsoy & Sapci-Zengin 2009). Models developed for AD must incorporate a variety of bioremediation mechanisms such as: hydrolysis, acidogenesis, acetogenesis and methanogenesis; processes which are involved in the biodegradability and transformation of organic matter. This will give an insight into reaction mechanisms, thus assisting in describing specific

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kinetic parameters, which can be used to compare theoretical values with experimental data obtained from monitoring the bioreactor performance (Jijai *et al.* 2016), including prediction of treatment efficiencies for a full-scale bioreactor (Debik & Coskun 2009), such as a system used for the treatment of PSW using a SGBR at ambient temperature.

Kinetic models that have been successfully used to simulate substrate utilization rates, i.e. organic matter biodegradation rates for AD processes, include Monod's (Lyberatos & Skiadas 1999) second-order Grau (Grau *et al.* 1975) and the modified Stover-Kincannon kinetic models (Abtahi *et al.* 2013). These models are used for the prediction of tCOD concentrations as a process output, with known input data, at steady-state conditions. The second-order Grau and the modified Stover-Kincannon models have been widely used for determining kinetic parameters in wastewater treatment processes involving biological mechanisms. These models have been successfully used in studies involving the treatment of wastewater from the food processing, including, e.g. starch, soybeans and PSW, for which anaerobic contact bioreactors were used (Yu *et al.* 1998; Ahn & Forster 2000; Debik & Coskun 2009; Şentürk *et al.* 2010). This study used an analytical approach to determine kinetic parameters, which describes the substrate utilization rates for SGBR treating PSW at mesophilic conditions, in order to effectively evaluate process efficiency and formulate design relationships for the system designed.

MATERIALS AND METHODS

Inoculum preparation, PSW characteristics, SGBR set-up and operation

The PSW was collected from a poultry product process facility in Cape Town, Western Cape Province. The characteristics of the PSW (Table 1) shows a typical high strength wastewater, i.e. PSW in South Africa. The collected wastewater samples were kept refrigerated (4 °C) prior to use in the experiments. The granular sludge inoculum was collected from a full-scale up-flow anaerobic-sludge bed (UASB) reactor treating brewery effluent at a South African brewery (SAB Miller Plc, Newlands, South Africa). A laboratory bench-scale polyvinyl chloride (PVC) SGBR AD was used for this study. The experimental set-up is illustrated in Figure 1. The bioreactor had a total working volume of 2 L

Table 1 | Specification of poultry slaughterhouse wastewater (unfiltered)

Parameter	Unit	Minimum	Maximum	Average ± SD
pH	–	6.13	7.24	–
Conductivity	μS/cm	973	2,405	1,604 ± 414
TDS	Ppm	691	1,693	1,138 ± 294
Salinity	Ppm	529	1,413	916 ± 179
Turbidity	NTU	237	997	719 ± 201
TSS	mg/L	313	8,200	1,654 ± 1,695
VSS	mg/L	239	8,920	1,906 ± 1,498
COD	mg/L	2,517	12,490	5,216 ± 2,534
NH_4^+-N	mg/L	135	447	216 ± 56
NO_3^-N	mg/L	0.63	22.7	3.33 ± 4.45
PO_4^{3-}P	mg/L	29	54	38 ± 6
VFA	mg/L	105	898	375 ± 213
Alkalinity	mg/L	322	923	499 ± 158
BOD_5	mg/L	925	5,000	2,477 ± 1,347
FOG	mg/L	156	1,710	715 ± 506

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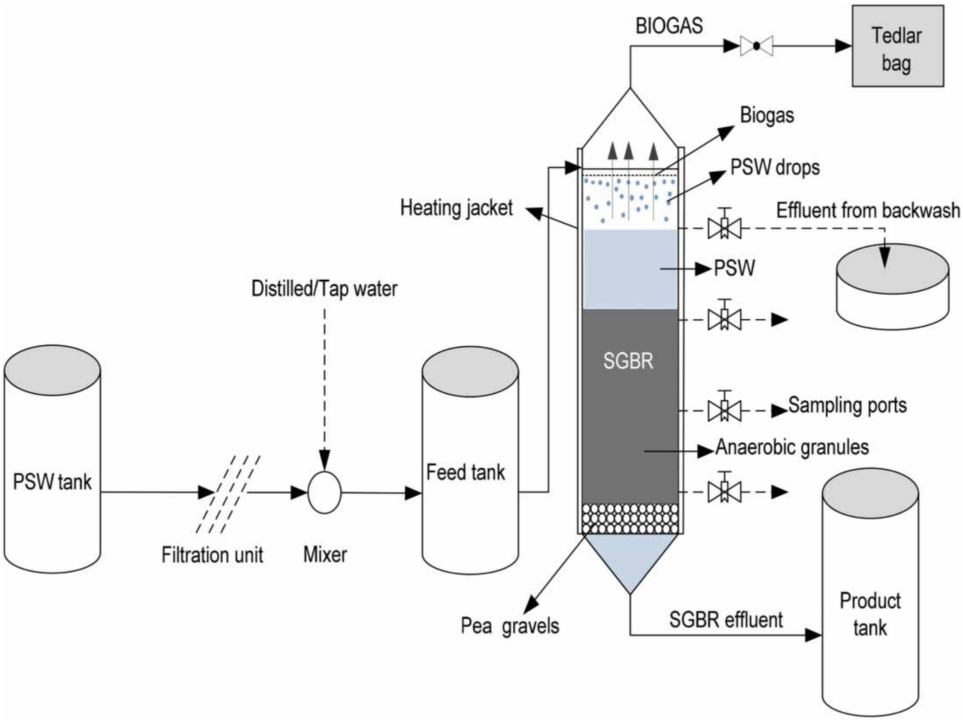

Figure 1 | Layout of the Static Granular Bed Reactor with basic parameters of the PSW used.

with an inner diameter and height of 0.062 and 0.065 m, respectively. The bioreactor was inoculated with 0.4 L of anaerobic granular sludge (to which 1.6 L of PSW and 0.01 L of dry milk solution were added as growth medium during acclimatization stage). The PSW was passed through a grit sieve (2 mm) and pumice stones (average diameter of 5–20 mm) were used as the underdrain bed to prevent anaerobic granular sludge washout due to pumping effects, i.e. pulsation. A multi-head Gilson (Limburg-Offheim, Germany) peristaltic pump was used to pump the influent to the top of the bioreactor. A similar pump was used to pump the effluent from the reactor in order to maintain a steady-state operation. The bioreactor was operated under mesophilic temperature (35 to 37 °C) with the influent temperature being regulated using a heated water jacket connected to a thermostatic water bath. To avoid clogging and head losses caused by suspended solids (SS) including FOG in the PSW, a backwash-stream containing the treated PSW effluent was used. The HRT of the bioreactor was kept at 55 hr over a period 28 days during the start-up period, which was increased to 96 hr for a period of 29 days, then subsequently reduced to 48 hr and 36 hr, respectively, after 25 days' interval. After the acclimatization period, the bioreactor was supplied with a 50% diluted influent at both HRTs of 55 hr and 96 hr, which was then reduced to 25% for a further 25 days at an HRT of 48 hr to prevent shock loading. Raw PSW was only supplied after day 84, maintaining such influent feed up to day 110, at HRT of 36 hr. All values reported are averaged values for the bioreactor used.

RESULTS AND DISCUSSION

Performance of the SGBR system: tCOD removal rate

During the first 28 days of the start-up period at 50% (v/v) dilution, the average tCOD removal efficiency of 71% was observed at an HRT of 55 hr and average OLRs 1.17 gCOD/L.day. The high SGBR tCOD removal rate achieved within a short period of time (28 days) was due to anaerobic granules obtained from an operating UASB reactor treating brewery wastewater, which was used

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to seed the SGBR. Thereafter, the HRT was increased to 96 hr, maintaining a 50% dilution for 29 days and the average tCOD removal efficiency was 77% at an average OLRs of 0.78 gCOD/L.day. The reactor was then fed with 25% PSW for a period of 25 days and HRT of 48 hr at an average OLR of 1.97 gCOD/L.day with an average tCOD removal efficiency of 79% achieved. The system was then fed with undiluted PSW for a period of 25 days at an average OLR of 4.10 gCOD/L.day and HRT of 36 hr achieving an average COD removal rate of 85%. The system experienced head losses resulting in clogging of the pea gravel in the underdrain due to high average OLRs between 1.97 and 4.10 gCOD/L.day. Furthermore, a scheduled periodic backwash was initiated for declogging the system to alleviate the operational deficiencies. Despite the operational deficiency experienced, the SGBR maintained higher overall performance with regard to COD removal over a period of 110 days.

Figure 2 shows the effect of OLRs on the performance of the SGBR reactor based on tCOD removal efficiency. The SGBR attained an overall average tCOD removal rate of 82% at an average OLR range of 0.78 to 4.10 gCOD/L.day. The variation of the organic loading rate was due to high fluctuation of the influent quality characteristics of the PSW ranged from 1,427 to 11,708 mg/L. The SGBR was able to cope with hydraulic overloading by reduction of the HRT and the increasing organic shock load caused by an increase in wastewater strength when the reactor was fed with undiluted PSW. Furthermore, high organic removal efficiency was maintained at high OLRs when the reactor was fed with undiluted PSW, indicating the system ability to adapt within a period of 24 hr as indicated by Ellis & Mach (2004). The average tCOD removal efficiency of the SGBR reactor was not decreased with an increase in OLRs despite clogging of the underdrain, which was alleviated by a periodic backwash.

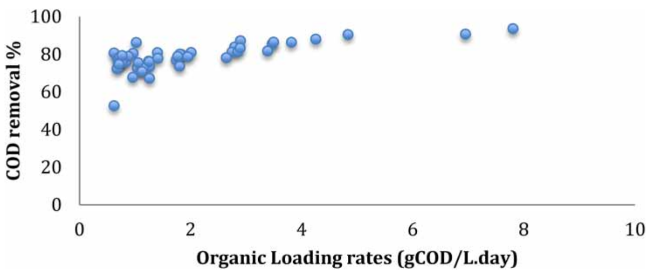

Figure 2 | tCOD removal efficiency in the SGBR with different OLR.

KINETIC MODEL EVALUATION

Grau second-order multicomponent substrate removal model

The general model, described as a second-order Grau model, is illustrated in Equation (1):

$$-\frac{ds}{dt} = k_s X \left(\frac{S_e}{S_0}\right)^2 \tag{1}$$

where $-\frac{ds}{dt}$ is the COD removal rate (g/L.day), k_s is the substrate removal rate kinetic constant (1/day), X is the average biomass concentration in the bioreactor (g VSS/L), S_e is the effluent substrate concentration and S_0 is the influent substrate concentration (g/L) and $t = \theta_H$ as the hydraulic retention time (HRT).

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The subsequent linearized format of Equation (6.1), within defined boundary conditions, i.e. to and to is – see Equation (2):

$$\frac{S_0\theta_H}{S_0 - S_e} = \theta_H + \frac{S_0}{k_s X} \tag{2}$$

Which can be further simplified to (Equation (3)),

$$\frac{S_0\theta_H}{S_0 - S_e} = a + b\theta_H \tag{3}$$

where the substrate kinetics $\left(\frac{S_0}{k_s X}\right)$ represented by letter a and the coefficient of the HRT b representing a value close to zero reflecting an impossibility of attaining a zero tCOD. By substituting and/or replacing the tCOD removal efficiency $\left(\frac{S_0 - S_e}{S_0}\right)$ with E, the model can be further simplified to– see Equation (4):

$$\frac{\theta_H}{E} = a + b\theta_H \tag{4}$$

The kinetic parameters used in the Grau second order model, i.e. a and b in Equation (3), can be determined using a linear trend line in order to quantify the intercept (a) and the slope (b) by assessing the interrelatedness between HRT/E, and HRT as shown in Figure 3.

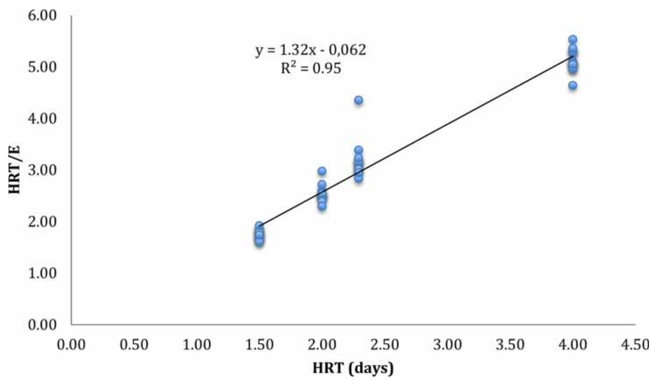

Figure 3 | Evaluation of Grau second-order model kinetic parameters.

The obtained values for a , and b, were 0.062 and 1.32, respectively, with a correlation coefficient of $R^2 = 0.95$ being achieved. These values, i.e. for a and b, can be used to predict process efficiency, with the tCOD effluent concentration (S_e) from the SGBR being adequately described by Equation (5):

$$S_e = S_0\left(1 - \frac{\theta_H}{0.062 + 1.32\theta_H}\right) \tag{5}$$

The predicted tCOD concentration in the effluent was calculated using Equation (5) based on the Grau second order kinetic model. Figure 4 shows the relationship between the experimental and the predicted tCOD concentration. The predicted values were slightly inconsistent with the experimental data from day 1 to day 80, with the predicted data being higher than the experimental data. Furthermore, a major variation was observed between the predicted and experimental data during day 80 to day 110, which might have been caused by high and fluctuating influent tCOD concentration as undiluted PSW was fed into the reactor culminating into an operational deficiency, including an increase

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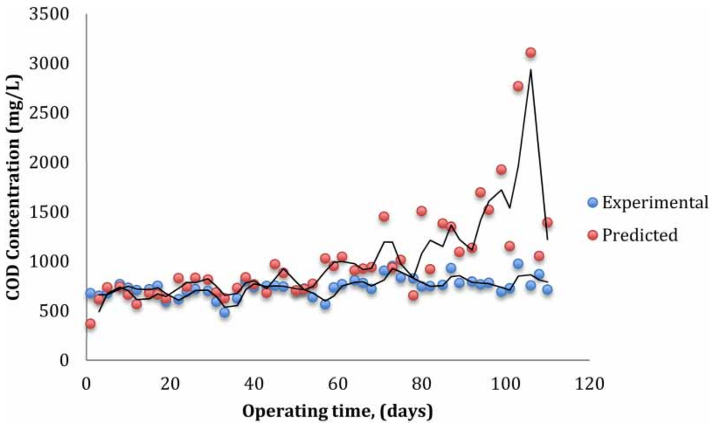

Figure 4 | Predicted and experimental COD concentration using Grau second order model.

in head losses to the system, which was alleviated by the initiation of a backwash stream. Additionally, the Grau second order model did not account for theses operational deficiencies such as an increase in head losses to the system due to high OLRs of the influent, which might have resulted in the observed high variation between the predicted and experimental data tCOD values. The head losses to the system are due to accumulation of the solids on the pea gravel, which has a potential to result in clogging of the underdrain system.

Table 2 summarises Grau second order kinetic constants obtained in this study in comparison to other related studies using the SGBR reactor. The difference in the values of kinetic constants obtained might be due to wastewater characteristics and the type of microorganisms dominant in the granular sludge.

Table 2 | Comparison of kinetic constant of Grau second-order model

Feed substrate	Type of reactor	(per day)		R^2	References
Poultry slaughter house	SGBR	0.062	1.32	0.95	This study
Meat slaughterhouse	SGBR	0.017	1.05	0.99	Oh (2012)
Poultry slaughterhouse	SGBR	0.173	1.155	0.95	Debik & Coskun (2009)

Modified Stover-Kincannon model

The Stover-Kincannon model was developed in the 1970 as a design model used for modelling tCOD removal rate in AD. The tCOD utilisation rate in this model is expressed as a function of the organic loading rate (Yu *et al.* 1998). This kinetic model was previously used to describe tCOD and total organic carbon (TOC) reduction, including biological oxygen demand (BOD_5) in the treated PSW from the digesters (Yu *et al.* 1998). The rate, at which the change in tCOD concentration is quantified requires a steady-state bioreactor operation. Equation (6) represents the model:

$$-\frac{ds}{dt} = \frac{U_{max}\left(\frac{S_0}{\theta_H}\right)}{k_B + \left(\frac{S_0}{\theta_H}\right)} \tag{6}$$

where $-\frac{ds}{dt}$ is defined as the tCOD removal rate (g/L.day), U_{max} is the maximum tCOD removal rate constant (g/L.day), k_B is the saturation constant (g/L.day), Q is the flow rate (L/day), V is the working

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volume of the reactor (L), while S_0 and S_e are the influent and effluent tCOD concentrations (g COD/L) respectively.

Equation (6) can also be used to represent the periodical change in tCOD concentration, i.e. $-\frac{ds}{dt}$.

$$-\frac{ds}{dt} = \frac{Q}{V}\,(S_0 - S_e) \tag{7}$$

To evaluate kinetic parameters, the combination and subsequent linearization of both Equations (6) and (7), is useful – see Equation (8):

$$\left(\frac{ds}{dt}\right)^{-1} = \frac{\theta_H}{S_0 - S_e} = \frac{K_B}{U_{max}}\left(\frac{\theta_H}{S_0}\right) + \frac{1}{U_{max}} \tag{8}$$

Comparative analysis between the inverse of substrate utilisation rate against the inverse of the total loading rates shows a linear relationship as depicted in Figure 5. The value of the maximum tCOD removal rate constant, U_{max}, including the saturation (affinity) constant, K_B, as depicted in Equation (8), can be obtained from both the slope and the intercept of Equation (8). In Figure 4, the slope and the intercept were found to be 1.43 and 0.079, respectively, leading to the determination of U_{max} and K_B of 12.70 gCOD/L/day and 18.2 gCOD/L.day respectively. The predicted value of the maximum tCOD removal U_{max} was higher than the maximum OLR of 7.81 gCOD/L.day used during the study. This showed the potential of the SGBR to be able to treat high strength PSW.

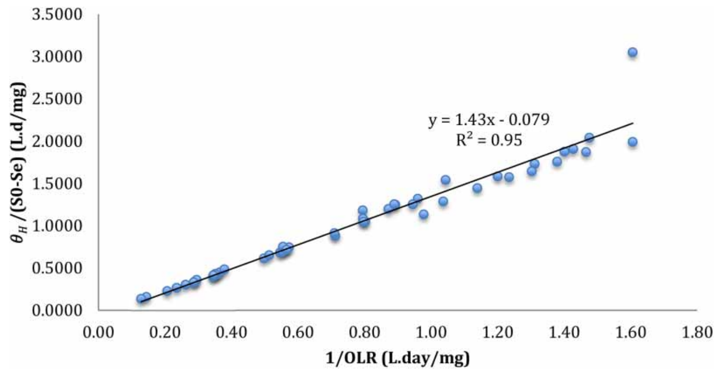

Figure 5 | Evaluation of modified Stover-Kincannon model kinetic parameters.

A substrate balance at a defined reactor volume can be expressed as follows;

$$QS_0 = QS_e + V\left(\frac{ds}{dt}\right) \tag{9}$$

Substituting Equation (6.8) for the relationship of $\left(\frac{ds}{dt}\right)$ result in Equations (6.10) and (6.11) as follows;

$$QS_0 = QS_e + V\left(\frac{U_{max}\left(\frac{S_0}{\theta_H}\right)}{k_B + \left(\frac{S_0}{\theta_H}\right)}\right) \tag{10}$$

By rearranging to make the effluent concentration, the subject of the formula, Equation (11), can be obtained.

$$S_e = S_0 - \frac{U_{max} S_0}{k_B + \left(\frac{S_0}{\theta_H}\right)} \tag{11}$$

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Using the value of U_{max} and K_B of 12.70 gCOD/L.day and 18.2 gCOD/L.day, Equation (11) can be used to determine predicted values of the effluent tCOD concentration as seen in Figure 6. Figure 6 shows the relationship between the experimental and the predicted tCOD concentration in the effluent. However, the predicted values were slightly inconsistent with the experimental data with the predicted data usually being higher than experimental values. A high variation similar to the one observed from the Grau second order model was also observed between day 80 to day 110 when undiluted PSW influent was fed, which could be a result of operational deficiencies caused by an increased OLR and head losses. This variation might have been due to tCOD entrapped within the SBGR system due to periodic clogging of the pea gravel by ss and sloughed-off biomass. A similar variation was observed by Oh (2012) in a study modelling the treatment of meat-processing wastewater, when using the modified Stover-Kincannon model.

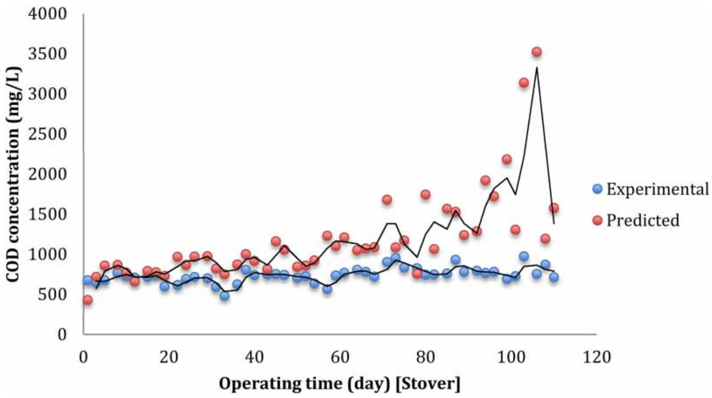

Figure 6 | Modified Stover-Kincannon model application.

Table 3 indicate kinetic coefficients U_{max} and K_B of the modified Stover Kincannon obtained in this study in comparison with other studies with different substrates and reactors at mesophilic conditions. As seen from Table 3, the value of U_{max} and K_B obtained from this study were lower than those observed from other study conducted using the SGBR treating both meat and PSW.

Table 3 | Comparison of the kinetic coefficient in the modified Stover Kincannon model

Feed Substrates	Type of reactor	U_{max} (gCOD/L.day)	K_B (gCOD/L.day)	R^2	References
Poultry slaughterhouse	SGBR	12.70	18.2	0.95	This study
Meat slaughterhouse	SGBR	192.3	206.6	0.99	Oh (2012)
Poultry slaughterhouse	SGBR	164.48	177.21	0.99	Debik & Coskun (2009)

CONCLUSIONS

Since process modelling can be used to predict performance outcomes, the SGBR's kinetic parameters, were quantified for the SGBR experiments for a system operated for 110 days at an HRT of 96 to 36 hr and average OLRs of 0.78 to 4.10 gCOD/L.day for predicting substrate removal from the PSW using the Grau and modified Stover Kincannon models. There was no significant correlation between the predicted and experimental data for both the Grau and modified Stover Kincannon models, with a high variation observed at higher OLRs of 4.10 gCOD/L.day, when the SGBR influent was the undiluted PSW. The variation between predicted and experimental data was hypothetically assumed to be influenced by head losses through the granular bed due to accumulated excess biomass and solids retained by the underdrain, a phenomenon unaccounted by models used. The SGBR

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sustained a high COD removal, 82%, despite these operational deficiencies and changes in OLRs including HRTs, an indication of the ability of the system to adapt, even under strenuous operational conditions, requiring a backwash system to fluidize the sludge-bed and periodically purge the system-off fine particles and sloughed-off inactive biomass, which was easier to flocculate out of the system.

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