Modified kinetic-hydraulic UASB reactor model for treatment of wastewater containing biodegradable organic substrates

Mostafa M. El-Seddik, Mona M. Galal, A. G. Radwan and Hisham S. Abdel-Halim

ABSTRACT

This paper addresses a modified kinetic-hydraulic model for up-flow anaerobic sludge blanket (UASB) reactor aimed to treat wastewater of biodegradable organic substrates as acetic acid based on Van der Meer model incorporated with biological granules inclusion. This dynamic model illustrates the biomass kinetic reaction rate for both direct and indirect growth of microorganisms coupled with the amount of biogas produced by methanogenic bacteria in bed and blanket zones of reactor. Moreover, the pH value required for substrate degradation at the peak specific growth rate of bacteria is discussed for Andrews’ kinetics. The sensitivity analyses of biomass concentration with respect to fraction of volume of reactor occupied by granules and up-flow velocity are also demonstrated. Furthermore, the modified mass balance equations of reactor are applied during steady state using Newton Raphson technique to obtain a suitable degree of freedom for the modified model matching with the measured results of UASB Sanhour wastewater treatment plant in Fayoum, Egypt.

Key words | acetic acid degradation, bacterial growth, biogas modeling, modified UASB

NOMENCLATURE

\( C_{S1}, C_{S2} \) substrate concentration in reactor bed and blanket zones (kg/m\(^3\))
\( C_{X1}, C_{X2} \) biomass concentration in reactor bed and blanket zones (kg/m\(^3\))
\( C_g, C_{CH_4} \) gas and methane gas concentrations in reactor bed zone (kg/m\(^3\))
\( C_{xin}, C_{Sin} \) concentrations of inlet biomass and inlet substrate in reactor (kg/m\(^3\))
\( C_{HS} \) concentration of unionized substrate in the reactor (kg/m\(^3\))
\( D, D_A \) dispersion and effective diffusion coefficients (m\(^2\)/hr)
\( D_f \) dispersed flow in the reactor (m\(^3\)/hr)
\( F_o \) entered volumetric flow rate to the reactor (m\(^3\)/hr)
\( f \) fraction of volume of reactor occupied by biological granules (dimensionless)

\( f_{CH_4} \) fraction of methane gas in the biogas produced in UASB reactor (dimensionless)
\( k_t \) mass transfer coefficient (m/hr)
\( K_A, K_I, K_S \) substrate equilibrium, inhibition and Monod half velocity constants (kg/m\(^3\))
\( K_d \) microorganism decay constant (hr\(^{-1}\))
\( K, k \) reaction rate constant and substrate volumetric conversion rate (hr\(^{-1}\))
\( pH, Pe \) refers to hydrogen ion concentration, Peclet number (dimensionless)
\( q_{gb}, R \) gas amount in reactor bed zone (m\(^3\)/hr), radius of biological granule (m)
\( R_{CH_4} \) methane gas production rate in reactor bed zone (kg/m\(^3\)/hr)
\( R_s \) biomass reaction rate in the reactor (kg/m\(^3\)/hr)
\( V_s, W_{up} \) granule settling velocity (m/hr), wastewater up-flow velocity (m/hr)
INTRODUCTION

Mathematical kinetic-hydraulic modeling of up-flow anaerobic sludge blanket (UASB) reactor plays an impressively relevant role within the environmental aspects for biological wastewater treatment; the kinetic parameters can reflect biomass reaction rate attribution on biodegradation of substrate concentration as chemical oxygen demand (COD) which is significantly influenced by both microorganism concentration growth (Rodriguez & Moreno 2009; Parsamehr 2012) and sludge particle amount in reactor (Korsak et al. 2008). On the other hand, the hydraulic parameters imply the behavior of wastewater flow in reactor zones concerning flow dispersion, wastewater up-flow velocity ($W_{up}$), hydraulics retention time (HRT), granule settling velocity and particle diameter size (Rodríguez-Gómez et al. 2013). The parameters' variation allows researchers to reach an optimum design method for UASB reactors by enhancing different alternatives to treat various substrate concentrations using previous reactor models (Blumensaat & Keller 2005; Parsamehr et al. 2008; Rodriguez & Moreno 2009; Parsamehr 2012; Rodríguez-Gómez et al. 2013).

Modifications can also be suggested in further extension work depending on these parameters to illustrate more flexibility and reliability of the mathematical modeling for the UASB reactors as reported by Elmitwalli (2013). According to Parsamehr (2012), the reactor is hydraulically divided into bed and blanket zones with different biomass concentrations based on Van der Meer & Heerjes (1985) and Pontes & Pinto (2006). In contrast, Korsak et al. (2008) considered the reactor as one zone with different dispersion values and ignored the biomass transport between bed and blanket zones. However, Parsamehr (2012) presumed the bacterial growth only by utilization of substrate according to Andrews (1968), neglecting both substrate degradation by diffusion into sludge granules and flow dispersion indicated by Korsak et al. (2008) and Rodríguez-Gómez et al. (2013). In this regard, both Parsamehr and Parsamehr models are not accurately simulating the real reaction due to ignorance of the biological granule role in bacterial growth by Parsamehr (2012) and the difference in biomass concentration in bed and blanket zones of reactor by Korsak et al. (2008) as well.

The aim of this work is to overcome such deficiencies in these discussed models where biodegradable substrate as acetic acid can be used to investigate the bacterial growth in both reactor bed and blanket zones during treatment of various substrate concentrations in reactor. Accordingly, a modified UASB reactor model is proposed on a basis of a linear combination of the biomass reaction rates introduced by Parsamehr (2012) and Korsak et al. (2008) using an extra degree of freedom. A novel alteration is displayed between the two recent models and many fundamentals are provided such as the direct and indirect growth of microorganisms incorporated with biogas produced by methanogens at dynamic state of reactor, influence of kinetic parameters on reactor performance, and exploration of biomass concentration at steady state of reactor with extra degrees of freedom. In addition, model validation is carried out by adjusting the most suitable degree of freedom in non-linear numerical technique to obtain a consistent model that agrees with both literature survey and experimental outcomes.

MATERIALS AND METHODS

Modified kinetic model description

Two kinetic models were individually presumed (Korsak et al. 2008; Parsamehr 2012) based on substrate diffusion into granules or bacterial growth kinetics. The proposed model tries to merge between these two factors as shown in Figure 1(a) where a linear integrated kinetic model is presented. More details are described in Figure 1(b) in order to identify biomass reaction with both substrate-granules interaction and bacterial growth kinetics under predominant biomass concentration in reactor bed and blanket zones. The biological parameters introduced in Figure 1(b) strictly illustrate that complex biodegradable substrate organics ($C_S$) hydrolyze into less molecular mass compounds which are dissociated into unionized substrate organics ($C_{HS}$). During the feast period, part of these organics is directly used by bacteria in the growth process and another part of the substrate diffuses into the biological granules ($X_g$)
which indirectly helps the bacterial growth. These granules are formed by accumulation of solids in the reactor bed zone where the granules’ settling velocities exceed the upflow velocity. Wastewater nutrients are consumed by bacteria in the feast period to increase the biomass concentration \(C_X\) in the reactor. During the famine period of bacteria, the biomass concentration decays in the form of inert microorganisms \(X_d\) due to nutrients depletion (Zhou et al. 2013; El-Seddik et al. 2014). The combined reaction rate of the modified model can be expressed as:

\[
R_{S1,2} = a(\mu_{1,2} - K_d) \frac{C_{X1,2}}{Y} + (1 - a)K_{1,2}C_{S1,2}
\]

(1)

where \(a \in [0, 1]\) represents the relative weight of kinetic reaction rate, and the subscripts 1, 2 are related to the reactor bed and blanket zones, respectively. The previous equation presents a generalized kinetic model using the added parameter \(a\) where Korsak and Parsamehr kinetic models can be accomplished at \(a = 0\) and 1, respectively. Moreover, infinite intermediate cases can be obtained when \(a\) becomes in the open range \((0, 1)\) which implies various weights of the former reaction rates. The available differential equations of the UASB reactor model that describe the rate of change of biomass and substrate concentrations in bed and blanket zones with respect to time are included in Table 1. Biogas production rate can also be simulated for reactor (Christ et al. 2000; Pontes & Pinto 2006). Numerical analyses are carried out by Runge–Kutta 4th order method using Matlab software to apply the UASB reactor modified model. Acetic acid substrate is examined with fixed kinetic parameters based on Andrews (1968), de Beer et al. (1992) and Turdkogan-Aydinol et al. (2011) as comprised in Tables 1 and 2 where \(\mu_{\text{max}}\) is the maximum specific growth rate of bacteria at \(pH = 7\) and \(\mu_{\text{max}}\) is the maximum specific growth rate of bacteria at any \(pH\).

**Modified kinetic-hydraulic model of reactor**

Beyond kinetics, a hydraulic modification is established for the modified kinetic UASB model to consider the flow dispersion and influent recirculation in bed and blanket zones of the reactor as a result of biogas production during substrate degradation (Peña et al. 2006). During the first stage of flow movement in reactor bed zone, a recirculation of the influent substrate concentration \(C_{S\text{in}}\) occurs without treatment that may owe to lack of bacteria in substrate degradation at high flow dispersion. However, the influent substrate concentration is utilized for bacterial growth in the next stages as illustrated in Figure 1(c) where the flow dispersion gradually declines causing a distinct reduction in substrate concentration \(C_S\) in reactor
Table 1 | Kinetic equations found in literature for anaerobic digestion of biodegradable organic substrates in UASB reactors

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Equation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chemical reaction rate constant</td>
<td>$K = \frac{3k_0(D_x(\sec \theta - \sinh \phi))}{R(D_x(\sec \theta - \sinh \phi) + Rk_0 \sinh \phi)}$</td>
<td>Korsak et al. (2008)</td>
</tr>
<tr>
<td>2</td>
<td>Thiele modulus, conversion rate</td>
<td>$\phi = \sqrt{\frac{K}{D_x}} R_x$, $k = c X_S$</td>
<td>Levenspiel (1999); Korsak et al. (2008)</td>
</tr>
<tr>
<td>3</td>
<td>Substrate mass balance in the reactor</td>
<td>$\frac{dCS}{dt} = D \frac{\partial^2 CS}{\partial z^2} - W_{up} \frac{\partial CS}{\partial z} - KC_S$</td>
<td>Korsak et al. (2008)</td>
</tr>
<tr>
<td>4</td>
<td>Peclet number</td>
<td>$Pe = \frac{W_{up} h}{D}$, $Pe = 10.3 - 8.4 \frac{W_{up}}{h} - 0.3 q_{gb}$</td>
<td>Singhal et al. (1998); Peña et al. (2006)</td>
</tr>
<tr>
<td>5</td>
<td>Biomass mass balance in reactor bed zone</td>
<td>$V_1 \frac{dCX_1}{dt} = F_{in} C_{xin} - \eta_{gb} q_{gb} C_{X1} + A C_{X2} V_3 + R_{S1} V_{Y1}$</td>
<td>Parsamehr (2012)</td>
</tr>
<tr>
<td>6</td>
<td>Biomass mass balance in reactor blanket zone</td>
<td>$V_2 \frac{dCX_2}{dt} = \eta_{gb} q_{gb} C_{X1} - A C_{X2} V_3 - (1 - \eta) F_{in} C_{X2} + R_{S2} V_2$</td>
<td>Parsamehr (2012)</td>
</tr>
<tr>
<td>7</td>
<td>Substrate mass balance in reactor bed zone</td>
<td>$V_1 \frac{dCS}{dt} = F_{in} C_{xin} + F_{21} C_{S2} - F_{21} C_{S1} - R_{S1} V_1$</td>
<td>Parsamehr (2012)</td>
</tr>
<tr>
<td>8</td>
<td>Substrate mass balance in reactor blanket zone</td>
<td>$V_2 \frac{dCS}{dt} = F_{21} C_{S1} + SF_{in} C_{xin} - F_{21} C_{S2} - F_{in} C_{S2} - R_{S2} V_2$</td>
<td>Parsamehr (2012)</td>
</tr>
<tr>
<td>9</td>
<td>Biomass reaction rates in reactor bed zone</td>
<td>$R_{S1} = (\mu_1 - K_d) \frac{C_X}{V}$</td>
<td>Parsamehr (2012)</td>
</tr>
<tr>
<td>10</td>
<td>Biomass reaction rates in reactor blanket zone</td>
<td>$R_{S2} = (\mu_2 - K_d) \frac{C_X}{V}$</td>
<td>Parsamehr (2012)</td>
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<td>11</td>
<td>Influent flow, by-pass flow fraction</td>
<td>$F_{in} = SF_{in} + F_o$, $SF = 0.13 + 0.17 h_1$</td>
<td>Van der Meer &amp; Heertjes (1985)</td>
</tr>
<tr>
<td>12</td>
<td>Flow from bed to blanket zones, backmixing flow</td>
<td>$F_{12} = F_{21} + F_o$, $F_{21} = q_{gb} \left( \frac{10}{10 + h_2} \right)$</td>
<td>Van der Meer &amp; Heertjes (1985)</td>
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<tr>
<td>13</td>
<td>Methane gas rate in bed zone</td>
<td>$q_{gb} = R_{CH4} V_3 \frac{V_1}{Y_{CH4}} = f_{CH4} \frac{(1 - Y) \mu_1 C_{X1}}{Y}$</td>
<td>Pontes &amp; Pinto (2006)</td>
</tr>
<tr>
<td>14</td>
<td>Specific growth rate of bacteria</td>
<td>$\mu = \frac{\mu_{max}}{1 + \frac{K_S}{C_{HS}} + \frac{K_{H_2}}{C_{HS} + K_H}}$, $C_{HS} = \frac{10^{-pH} C_S}{K_A + 10^{-pH}}$</td>
<td>Andrews (1968)</td>
</tr>
<tr>
<td>15</td>
<td>Maximum specific growth rate of bacteria</td>
<td>$\mu_{max} = \mu_{max} e^{-0.5 \frac{pH - 7}{0.62}}$, $\mu_{max} = 0.013Y - 0.129$</td>
<td>de Beer et al. (1992); Turkdogan-Aydinol et al. (2011)</td>
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</table>

Bed zone. Similarly, the reactor blanket zone is affected by flow dispersion. Thus, in order to implement the effect of flow dispersion in reactor modified model, the substrate mass balance equation in reactor introduced by Korsak et al. (2008) can be expressed without biomass reaction based on Fick’s law of dispersion as:

$$\frac{dCS}{dt} = D \frac{\partial^2 CS}{\partial z^2} - W_{up} \frac{\partial CS}{\partial z} \approx D \frac{(C_{S0} - C_S)}{h^2} - W_{up} \frac{(C_{S0} - C_S)}{h}. \quad (2)$$
blanket zones \((D_{fl,2})\) can be presented as:

\[
V_{1,2} \frac{dC_{S1,2}}{dt} = \frac{W_{sb}V_{1,2}}{h_{1,2}} \left( 1 + \frac{1}{Pe} \right) (C_{Sin,1} - C_{S1,2}) \\
= D_{fl,1} (C_{Sin,1} - C_{S1,2}). \tag{3}
\]

By applying the kinetic-hydraulic modification in Equations (5)–(8) shown in Table 1, the modified UASB reactor model in bed and blanket zones can be expressed as follows:

\[
V_1 \frac{dC_{X1}}{dt} = F_0 C_{Xin} - \eta_{dr}x_{qb}C_{X1} + AC_{X2}V_s \\
+ (1 - \alpha)(\mu_1 - K_d)C_{X1}V_1 + (1 - \alpha)K_1C_{S1}YV_1 \tag{4a}
\]

\[
V_2 \frac{dC_{X2}}{dt} = \eta_{dr}x_{qb}C_{X1} - AC_{X2}V_s - (1 - \eta)F_{in}C_{X2} \\
+ (1 - \alpha)(\mu_2 - K_d)C_{X2}V_2 + (1 - \alpha)K_2C_{S2}YV_2 \tag{4b}
\]

\[
V_1 \frac{dC_{S1}}{dt} = F_0 C_{Sin} + F_{21}C_{S2} + D_{fl}(C_{Sin} - C_{S1}) - F_{12}C_{S1} \\
- (1 - \alpha)(\mu_1 - K_d) \frac{C_{X1}}{Y} V_1 + (1 - \alpha)K_1C_{S1}V_1 \tag{4c}
\]

\[
V_2 \frac{dC_{S2}}{dt} = F_{12}C_{S1} + SFF_{in}C_{Sin} + D_{fl}(C_{S1} - C_{S2}) \\
- F_{21}C_{S2} - F_{in}C_{S2} - (1 - \alpha)(\mu_2 - K_d) \frac{C_{X2}}{Y} V_2 \\
- (1 - \alpha)K_2C_{S2}V_2. \tag{4d}
\]

**RESULTS AND DISCUSSION**

**COD and biogas simulations using modified kinetic model**

The simulated influent COD is considered as a totally biodegradable substrate of acetic acid concentration of 3 kg/m³ which is significantly affected by the weighed value of contribution of the reaction rate \(\alpha\). Several modified models can be shown in Figure 2 by varying \(\alpha\) between 0.0 and 1.0 in Equation (4a)–(4d) at fraction of volume of UASB reactor occupied by granules \(f = 0.2\) and \(pH = 7\). The substrate degradation in reactor bed and blanket zones rapidly increases at \(\alpha\) varies from 0.0 to 1.0 as indicated in Figure 2(a) and 2(b). Parsamehr model is illustrated for \(\alpha = 1.0\) while modified models are shown for \(\alpha\) not equals 1.0. The modified models indicate much lower COD removal efficiencies than that of Parsamehr model as the reactor efficiency reaches about 75% for \(\alpha = 0.0\) as shown in Figure 2(a) and 2(b). Also, the variation of reaction rate contribution value considerably affects the biogas produced in reactor where Figure 2(c) and 2(d) show the rate of methane gas produced by methanogenic bacteria in reactor bed and blanket zones for various modified models using Equation (13), included in Table 1. The concentration of methane gas in the reactor bed and blanket zones is also illustrated in Figure 2(e) and 2(f), respectively, for different modified models of the reactor at \(f = 0.2\) and \(pH = 7\). A smooth increased transition appears in methane gas concentration in reactor bed and blanket zones as \(\alpha\) decreases that reveals the influence of bacteria indirect growth on biogas production in UASB reactor. The simulated results indicated in Figure 2(c) and 2(d) also demonstrate that Parsamehr model involves 0.55–0.05 m³CH₄/kgCOD for reactor bed and blanket zones at 90% COD removal. Nevertheless, the reactor modified kinetic model for average value of \(\alpha\) results in 0.53–0.07 m³CH₄/kgCOD for bed and blanket zones at 85% COD removal using \(f = 0.2\) and \(pH = 7\) as shown in Figure 2(c) and 2(d). In short, the UASB reactor modified model of \(\alpha = 0.5\) implies an average biogas rate of 0.3 m³CH₄/kgCOD that agrees with van Lier (2009) and Coskun et al. (2012) in contrast with Parsamehr model that implies an average biogas rate of 0.2 m³CH₄/kgCOD for the reactor ignoring the influence of \(f\) on biogas production.

**Influence of kinetic parameters on modified UASB performance**

The substrate degradation as acetic acid in reactor bed zone is indicated in Figure 3(a) for different dispersion values by varying Peclet number \(Pe\) from 0.5 to 50 assuming \(\alpha = 0.5\) in the modified model (Equation (4c)) at \(f = 0.2\) and \(pH = 7\). Although the reactor performance appears to be reduced for \(Pe\) less than 2, the decline in performance is relatively minor as the dispersed flow \(D_{fl}(1,2)\) isn’t superior enough. That is why only high dispersion values attributed to low fractional Peclet numbers could considerably influence the reactor. The developed model also reveals that biodegradable substrate concentration decreases with time, achieving about 80% COD removal efficiency after 4 hours’ reactor operation if suitable \(pH\) value is introduced with HRT of 8 hours (Elmitwalli 2013). Therefore, the influence of \(pH\) value on reactor performance should be
recognized in Figure 3(b)–3(d), where a decrement in the effluent substrate concentration can be detected in Figure 3(b) at 6 < pH < 7 for different temperatures using Equations (14) and (15), indicated in Table 1. However, the reactor performance deteriorates suddenly at pH < 6 and gradually at pH > 7. Consecutively, Figure 3(c) shows the independence of the ratio of specific growth rate of bacteria to maximum specific growth rate of bacteria (μ/μmax) on pH value for different unionized substrate concentrations (CHS). Moreover, Figure 3(c) illustrates that Monod half velocity constant (Ks) and inhibition coefficient (Ki) could reach 0.002–0.039 kg/m³, respectively, as unionized substrate concentration for acetic acid substrate concentration of 3 kg/m³ at μ/μmax = 0.5. On the other hand, Figure 3(d) illustrates the significant effect of both pH value and temperature (T) on the specific growth rate of bacteria (μ) where the assessed kinetic parameters (Ks, Ki) for acetic acid concentration of 3 kg/m³ are used in simulations at fixed substrate equilibrium constant (pKs) = 4.5 and yield (Y) = 0.04. Accordingly, it is evident from results that the peak specific growth rate of bacteria (μp) occurs at pH = 7 and T = 35 °C. However, μ is distinctly reduced when pH not equals 7 at a fixed temperature while μp decreases from 0.22 d⁻¹ at T = 35 °C to 0.04 d⁻¹ at T = 15 °C.
Steady state response of reactor

The steady state behavior of the UASB reactor proposed model can be obtained by setting the time derivative to zero for the four main dynamical mass balance equations (Equation (4a)–(4d)). The solution of these non-linear equations is simultaneously carried out using Newton Raphson numerical technique to indicate the biomass concentration in reactor bed zone ($C_{X1}$) during the treatment of biodegradable substrate as acetic acid of 3 kg/m$^3$ at reactor steady state for modified model of $\alpha = 0.5$ and $Pe = 2$. Figure 4(a) illustrates the effect of granules amount on $C_{X1}$ for different modified models of the reactor considering $pH$ of 7 and $Pe$ of 2 at the steady state. It is found that $C_{X1}$ reaches about 76 kg/m$^3$ as indicated by point A in Figure 4(b) at modified model of $\alpha = 0.5$ and $f = 0.2$, whereas biomass density in reactor reaches about 380 kg/m$^3$ at $pH$ of 7 as illustrated in Figure 4(c). The results also reveal that biomass density decreases as $f$ increases from 0.1 to 0.5 acclimatizing $C_{X1}$ between 70 and 90 kg/m$^3$ at $pH = 7$ and $\alpha = 0.5$ while an increase in $pH$ value boosts biomass density at a fixed $f$. Similarly, the mass balance equations of modified model of UASB reactor are implemented to indicate $C_{X1}$ during the treatment of biodegradable substrate as acetic acid of 3 kg/m$^3$ at reactor dynamic state considering various initial biomass concentrations. Figure 4(d) shows that $C_{X1}$ approaches the steady state results during the reactor start-up using Equation (4a) for the UASB modified model of $\alpha = 0.5$ and $Pe = 2$ at $f = 0.2$ and $pH = 7$, regardless of various initial biomass concentrations. Figure 4(d) also shows that $C_{X1}$ reaches its highest value after about 70 days (Radjaram & Saravanane 2011). However, owing to psychrophilic temperature, low initial biomass concentrations in reactor entails more start-up time which is expected to decrease at high temperatures (Poh & Chong 2014).

Sensitivity analysis of modified model

Various modified models of UASB reactor are discussed for the influence of variation of $f$ and $W_{up}$ at reactor steady state using various values of $\alpha$ at $Pe = 2$ and $pH = 7$. The influence of $f$ on reactor bed and blanket zones’ performance displayed in Figure 5(a)–5(d) indicates that reactor sensitivity to the granules amount increases as $\alpha$ decreases. The biomass and substrate concentrations in reactor bed and blanket zones remain almost constant as $f$ increases at high values of $\alpha$. However, a significant increase in biomass concentration accompanied with a decrease in substrate concentration occurs as $f$ increases at low values of $\alpha$ that
shows that the indirect growth of bacteria should be considered in reactor bed and blanket zones. Therefore, the modified models illustrate that biomass concentration depends on the granules amount in reactor in contrast to the conventional model. Regarding up-flow velocity, the reactor modified model seems to be as sensitive as the conventional model in simulating biomass concentration in reactor bed and blanket zones that increases by decreasing \( W_{up} \) as shown in Figure 5(e) and 5(f). The reactor bed and blanket zones’ performance also increases as the growth rate of bacteria increases, considering the decay constant. The effect of particle size on biomass reaction rate in reactor bed zone can only be illustrated through reactor modified models where the reaction rate decreases as granule diameter increases, causing a reduction in treatment efficiency (Huang et al. 2006).

### Experimental results

#### UASB performance in Sanhour plant, Egypt

UASB Sanhour plant is used to serve 140,000 capita through two phases where organic matter in wastewater is removed in UASB reactors divided into compartments as shown in Figure 6(a). The input values of biochemical oxygen demand (BOD), COD and total suspended solids (TSS) in UASB reactors were found to be 300 mg/L, 600 mg/L and 450 mg/L, respectively (Table 3), while the output values of UASB reactors were measured as 60 mg/L, 150 mg/L and 50 mg/L, respectively (Nada et al. 2008). Therefore, the UASB reactor could remove about 80% of BOD, 75% of COD, and 90% of TSS (Elmitwalli & Otterpohl 2007; Nada et al. 2008).

### Validation of reactor modified model

Two models of reactor are verified compared to the UASB Sanhour wastewater treatment plant results in Fayoum, Egypt using the biodegradable fraction of substrate concentration of 0.3 kg/m³ as BOD. A modified model of \( \alpha = 0.2 \) and Parsamehr model (\( \alpha = 1.0 \)) are assembled in Figure 6(b) and 6(c) to simulate the substrate degradation in reactor bed and blanket zones at \( Pe = 2, f = 0.2 \) and \( pH = 7 \). The biomass concentration in reactor bed and blanket zones are estimated during steady state using the kinetic parameters at 11°C (Table 2) and \( pH \) of 7 for substrate concentration of 0.3 kg/m³. Simulations demonstrate that the modified model of \( \alpha = 0.2 \) approaches more approximate results to the measured effluent BOD of 0.06 kg/m³ rather than Parsamehr model as presented in Figure 6(b) and 6(c).
modified model simulated results also converge to the measured BOD results of Sanhour plant with 3.5% error in opposite to the conventional model of $\alpha = 1.0$ that implies 15.5% error (Table 3) where biomass concentration reaches about 50.4 kg/m$^3$ and 4.77 kg/m$^3$ in reactor bed and blanket zones respectively during the steady state at 11°C. Thus, regarding biodegradable substrates, the modified kinetic-hydraulic model of $\alpha = 0.2$ and $Pe = 2$ represents accurate simulations for UASB reactors using $pH = 7$ and $f = 0.2$. These findings also reveal a high agreement with Rodrigues et al. (2003) for treating low-strength wastewater in anaerobic stirred reactors. In brief, the modified model enhances the reactor impact to fit the experimental results described before by Elmitwalli & Otterpohl (2007) and Nada et al. (2008), predicts the actual UASB performance under crucial circumstances, and acts as a robust tool towards innovative management of environmental issues.

**CONCLUSIONS**

The main contribution of this paper can be summarized as follows:

- A modified kinetic-hydraulic UASB reactor model could be applicable for the biological treatment of biodegradable organic substrates as acetic acid where an extra degree of freedom for biogas production could be illustrated as 0.35–0.8 m$^3$CH$_4$/kgCOD$_r$ and 0.05–0.15 m$^3$CH$_4$/kgCOD$_r$ in reactor bed and blanket
Figure 6 | (a) UASB reactors in Sanhour wastewater treatment plant in Fayoum governorate, Egypt, and model simulations of the UASB Sanhour wastewater treatment plant results for different models in reactor (b) bed and (c) blanket zones.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Values of kinetic parameters assessed for acetic acid substrate in the UASB reactor model</th>
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<tbody>
<tr>
<td>$T$ (°C)</td>
<td>$\mu_{\text{max}}$ ($d^{-1}$)</td>
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<tr>
<td>---------</td>
<td>------------------</td>
</tr>
<tr>
<td>15</td>
<td>0.038</td>
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<td>11</td>
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<table>
<thead>
<tr>
<th>Table 3</th>
<th>Characteristics of domestic wastewater in UASB reactors at Sanhour plant in Fayoum, Egypt</th>
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</thead>
<tbody>
<tr>
<td>Time (hr)</td>
<td>measured BOD (kg/m³)</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------</td>
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<tr>
<td></td>
<td>$C_{11}$</td>
</tr>
<tr>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>7</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>0.06</td>
</tr>
</tbody>
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$\Sigma/n_\text{ref}$ refers to number of points.
zones, respectively, for total substrate concentration of 3 kg/m³ using \( f = 0.2 \) and \( pH = 7 \).

- In contrast with conventional models, flexibility was provided to the modified model where biomass concentration in the UASB reactor bed zone could reach 70–90 kg/m³ for \( f \) fluctuates from 0.1 to 0.5 at \( \alpha = 0.5 \), \( Pe = 2 \) and \( pH = 7 \) during the treatment of biodegradable substrate as acetic acid of 3 kg/m³ at steady state of reactor.

- Monod half velocity constant and inhibition coefficient reached 0.002–0.039 kg/m³, respectively, as unionized substrate concentration for total acetic acid concentration of 3 kg/m³ where \( pH \) of 7 was recommended to maximize bacterial specific growth rate.

- Compared with the conventional model, the modified model of \( \alpha = 0.2 \), \( Pe = 2 \), \( f = 0.2 \) and \( pH = 7 \) implied a convergence to overall reactor efficiency of 80% during wastewater treatment of biodegradable substrate concentration of 0.3 kg/m³ where biomass concentration could reach about 50.4–4.7 kg/m³ at 11°C in reactor bed and blanket zones, respectively.

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REFERENCES


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