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1. Introduction

With the development of the economy of the world, eutrophication has spread fast and led to serious aquatic environmental pollution, especially in the developing countries. The excessively discharged nitrogen can cause many negative impacts, such as eutrophication. Therefore, nitrogen removal shall be processed in a sustainable way, especially for wastewater treatment with a low C/N ratio. With the lower capital investment, less operational maintenance, no additional organic carbon source, 90% reduction of sludge and the limited emission of N₂O, the anaerobic ammonia oxidation (anammox) process is a new nitrogen removal technology that has gained widespread attention.^{1,2} However, despite the increasing interest in the anammox application, there were still many difficulties, such as the low bacterial growth rate and the sensitivity to the environmental factors.³

Investigation of the process stability of different anammox configurations and assessment of the simulation validity of various anammox-based kinetic models

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Over the last 30 years, the successful implementation of the anammox process has attracted research interest from all over the world. Various reactor configurations were investigated for the anammox process. However, the construction of the anammox process is a delicate topic in regards to the high sensitivity of the biological reaction. To better understand the effects of configurations on the anammox performance, process-kinetic models and activity kinetic models were critically overviewed, respectively. A significant difference in the denitrification capabilities was observed even with similar dominated functional species of anammox with different configurations. Although the kinetic analysis gained insight into the feasibility of both batch and continuous processes, most models were often applied to match the kinetic data in an unsuitable manner. The validity assessment illustrated that the Grau second-order model and Stover–Kincannon model were the most appropriate and shareable reactor-kinetic models for different anammox configurations. This review plays an important role in the anammox process performance assessment and augmentation of the process control.

Anammox processes can be conducted in many different configurations. Each process has its own optimized operations and characteristics based on the design of the reactor. However, it is generally known that common reactors have certain shortcomings, and that appropriate operation conditions should be fully investigated to prevent the process from failure without optimized operation.4 Different reactors have different capabilities of nitrogen removal. Among the applied reactors, the Sequencing Batch Reactor (SBR), Up Flow Anaerobic Sludge Blanket (UASB) and Membrane Bio-Reactor (MBR) were the most popular configurations with different configuration structures that benefit the biomass enrichment in the form of the biofilm or for avoiding sludge wash out.5-7 The aim of optimizing the operational conditions is to enhance the efficiency of nitrogen removal.8 The effects of environmental factors at various operational options on the anammox microbial community were also reported.9 Moreover, the microbial residence time plays a critical role in the taxonomic composition and functional description of the microbial communities.10

A large number of previous studies focused on experimental and mathematical methods.¹¹⁻¹³ The process-kinetic models are powerful tools for investigating the performances of different configurations during the anammox process. Appropriate kinetic mathematical models are enabled to assess, control, and mitigate the process inhibition and process optimization.

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These models can be employed to achieve many key objectives involving the optimization of the chemical processes, assessment of the reaction hazards, and the design of emergency relief systems.14,15 Process-kinetic models enhance the comprehension of the constructed system, and are conducive to the formulation and validation of a hypothesis. The prediction of the system's behaviour at a variety of conditions was developed to reduce the operation risks. However, certain selection criteria and conditions must be obeyed when the proper evaluation and application of the process models were performed for understanding the process or predicting the performance. In order to identify a suitable model, a correct model type shall be selected, and the parameters of the model shall be estimated with the available data. To a great extent, the validity of the studies relies on the model, which is defined by the proper preference of a mathematical model first, and then the validity of the kinetics evaluation. Generally, an evaluation on the process performance is still characterized by the application of the simple kinetics models and methods for evaluating their reactions.

Kinetic models are proved to be a conventional way to estimate and prospect the performances and operations of different processes. It is very important to choose a suitable model relating to the kinetics evaluation of the anammox process assessment. Quantitative process-kinetics can gain insight into the underlying operational strategy with feasibility investigations in both batch and continuous processes. However, it is a pity that most frequently used models cannot fit the kinetic data well. It is necessary for us to know which model is better, and which is perfect in the simulated conditions. Moreover, the optimized operation conditions of the anammox process are also important for the lab scale and full-scale process design.

A majority of previous papers of different configurations (EGSB, UASB, SBR, MBR, and CSTR) were related to discussions of the treatment performance or engineering application. However, only a limited number of articles are available for solving the specific problems of the kinetics evaluation. So far, studies in investigating the anammox process-kinetics with different configurations are relatively limited, and the assessment of anammox performance in different reactors is rare. Thus, the performance of the anammox system in different reactors is reviewed in this paper with regards to validation of the commonly used process kinetic models.

2. Process-kinetics approaches

Different reactors used in the anammox process were summarized, and the performance comparison and kinetic simulation were also evaluated. Currently, we are mainly focusing on the application of four kinds of substrate removal models, including the first-order substrate removal model, the Grau second-order substrate removal model, the modified Stover-Kincannon model and the Monod equation, to investigate the anammox process kinetics.

2.1 First-order substrate removal model

With regard to the application of the first-order substrate removal model to the bioreactor, the change rate of the substrate concentration in the completely mixed system may be expressed as follows:¹²

$$-\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{QS_{\mathrm{i}}}{V} - \frac{QS_{\mathrm{e}}}{V} - k_1 S_{\mathrm{e}} \tag{1}$$

Because the change rate (-dS/dt) can be neglected under a pseudo-steady-state situation, the equation is derived as:

$$\frac{S_{\rm i} - S_{\rm e}}{\rm HRT} = k_1 S_{\rm e} \tag{2}$$

where S_i and S_e are the total nitrogen concentrations (g L⁻¹) in the influent and effluent, HRT is the hydraulic retention time (day), k_1 is the constant of the first-order substrate removal rate constant (1/d), Q is the inflow rate (L/d) and V is the volume of the reactor (L).

2.2 Grau second-order substrate removal model

The general equation of a second-order model is described as shown below.¹⁶ By integration and linearization, the above equation can be expressed as eqn (3):

$$-\frac{\mathrm{d}S}{\mathrm{d}t} = k_2 \left(\frac{S_\mathrm{e}}{S_\mathrm{i}}\right)^2 \tag{3}$$

By integration and linearization, the above equation is expressed as eqn (4):

$$\frac{S_{i}HRT}{S_{i}-S_{e}} = HRT + \frac{S_{i}}{k_{2}X}$$
(4)

If $S_i/(k_2X)$ is considered as a constant (*a*) and $(S_i - S_e)/S_i$ is replaced by the substrate removal efficiency (*E*), *b* is a constant for the Grau second-order model, the above equation can be represented as a simple one:

$$\frac{\text{HRT}}{E} = a + b\text{HRT}.$$

2.3 Modified Stover-Kincannon model

As for the Stover–Kincannon model,¹⁶ initially, the equation was applied to predict the development of the attached-growth biomass in a rotating biological contactor. Later, the model was further modified, and widely used to describe and predict the performances of the bioreactor.^{17,18} The original model is expressed, as shown below:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{U_{\max}\left(\frac{QS_{\mathrm{i}}}{A}\right)}{K_{\mathrm{B}} + \left(\frac{QS_{\mathrm{i}}}{A}\right)} \tag{5}$$

where dS/dt is the substrate removal rate (kg m⁻³ d⁻¹), U_{max} is the constant of the maximum utilization rate (kg m⁻³ d⁻¹), *A* is the surface area of the disc (*L*), and K_B is the constant of the saturation value (kg m⁻³ d⁻¹). If the volume of the reactor (*V*) takes the place of the surface area (*A*), the Stover–Kincannon model can be modified as below:¹⁸

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{U_{\max}\left(\frac{QS_{\mathrm{i}}}{V}\right)}{K_{\mathrm{B}} + \left(\frac{QS_{\mathrm{i}}}{V}\right)} \tag{6}$$

where the Stover–Kincannon model takes dS/dt as a function of the loading rate of substrate at a steady state: $\frac{dS}{dt} = \frac{Q}{V} \times (S_i - S_e)$, so it can be further expressed as shown below in eqn (7):

$$\frac{V}{Q(S_{\rm i}-S_{\rm e})} = \frac{\frac{K_{\rm b}V}{U_{\rm max}}}{QS_{\rm i}} + \frac{1}{U_{\rm max}}$$
(7)

2.4 Monod model

The Monod model was extensively employed.¹⁹ The modified versions of the Monod equation were developed concerning the model anammox process in terms of the oxygen concentration, ammonia concentration and missing alkalinity:²⁰

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{KS_{\mathrm{e}}}{K_{\mathrm{s}} + S_{\mathrm{e}}} \tag{8}$$

where *K* is the maximum substrate utilization rate (kg m⁻³ d⁻¹), and *K*_s is the half saturation concentration (g L⁻¹).

2.5 Other models used for the anammox-based process

Generally, the anammox bacteria cooperated with other functional bacteria to degrade the wastewater in the applied fields, such as SHARON and anammox process based on the continuity model.²¹ The ASM2, ASM2d and ASM3 models were also used to simulate the anammox process, which is enriched from municipal activated sludge.²² The more complex microbial communities with AOB, NOB DHB and anammox were simulated with complex models, as reported.²³

3. Anammox processes conducted in different reactors

In recent years, the interest in anammox has been increased significantly with more and more articles being published as time has passed, as showed in Fig. 1a. Since 2005, an average of 78 more papers has been published every year. In 2014, 300 papers were published. Fig. 1b shows the number of anammox processes conducted in different reactors, as previously reported. The sequencing batch reactor (SBR) was recognized as the most dominantly employed bioreactor, which was the topic in one third of published papers, followed by the upflow anaerobic sludge blanket (UASB), membrane bio-reactor (MBR), expanded granular sludge bed (EGSB), continuous stirred-tank reactor (CSTR), sequencing biofilm batch reactor (SBBR) and upflow anaerobic fixed bed (UAFB), subsequently. While the number of applied UASBs was two-thirds of that of applied SBRs, both SBRs and UASBs were the most popular reactors conducted for the anammox process. Many advantages of the reactor are summarized in Table 1. The high NLR (nitrogen

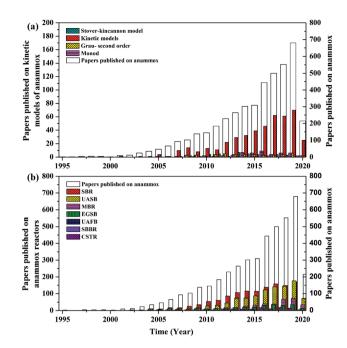


Fig. 1 Published papers in each year: (a) kinetic models used in the anammox process and (b) enrichment reactors. (Web of Scopus, access data: 2020.04.06).

loading rate) and NRR (nitrogen removal ratio), enrichment granular sludge, fast start up and high settleability can be obtained when the UASB or EGSB is applied. However, the MBR (with a long sludge retention time (SRT)) brought a fast startup of the process and a high accumulation rate for anammox enrichment, which was commonly evaluated with special purposes (Table 1). The general comparison of the anammox process conducted in different processes is shown in Table 2. The contents regarding the general process descriptions, applications, advantages and disadvantages, and design criteria are given for each technology based on previous research studies as the referenced applications. The advantages and disadvantages of each reactor constructed for anammox are listed in Table 2. Biofilm, granule and flocculent were the three main kinds of anammox conducted in different reactors, among which the biofilm and granule were the most popular ones. A previous investigation showed that UASB and SBR were the most popular bioreactors that can make granules or keep high anammox biomass. The long retention time of the active sludge is the key factor to influence the successful development of a high-rate anaerobic wastewater treatment. The long retention time of sludge can be realized due to the specific reactor configuration design and fixed biomass in the form of static biofilms, particle-supported biofilms or granule sludge. It was observed that the UASB with upflow can easily change the sludge into granules. The high loading rate of UASB with high removal efficiency was often reported.7 In contrast, the engineering applications of anammox included more than 100 fullscale partial nitridation/anammox installations worldwide by

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Table 1 Anammox processes conducted in different configurations (most popular reactors)^a

| | MBBR/SBR | And | High stability; fast enrichment; biofilm culturing | Costly to operate; biofilm fall off |
|---|------------|--|---|--|
| | UAFB | entra entr | High stability of process; fast start up/ enrichment; high sludge concentration; high NRR with free cell or/ granular sludge | Costly to operate; membrane cleaning; lighter, fluffier sludge flocs |
| | Nov-BFR | | High stability; fast enrichment; biofilm culturing; high degree of automation | Costly to operate |
| | (G/F) MBR | ender the second | High stability of process; fast start up/enrichment; high sludge concentration; high NRR with free cell or/granular sludge; high effluent quality; high degree of automation | Costly to operate; membrane cleaning and replacement; process sensitive to sustained peak hour flow; sophisticated operation |
| | SGBR/SASBR | The second secon | High stability of process enrichment granular sludge; fast start up; high substrate con.; adjust process timing <i>via</i> PLC, convent operation | Costly to operate; sludge washout; negative effect on downstream processes; high peak flow may disrupt performance |
| - | CSTR | Bin the second sec | Intensive mixing; ideal model for simulation | Low SRT; consume energy |
| 6 | EGSB | the contraction of the contracti | High NLR and NRR; enrichment granular sludge; fast start up; high settleability | Costly to operate; sludge washout; sludge floatation consume energy |
| | UASB | Monton of the second | High NLR and NRR; enrichment granular sludge; high settleability | Dead zone areas and substrate inhibition; influent hierarchy; sludge washout; sludge floatation with layer distribution |
| | | | Advantage | Disadvantage |

^a SGBR: static granular bed reactor; SASBR: static anaerobic sludge bed reactor; Nov-BFR: Noven biofilm reactor; MBBR: moving bed biofilm reactor.

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 Table 2
 Performance of anammox process conducted in different reactors^a

| | | | | | | | | | Sludge | |
|------------------|---|----------------------|--------------------|----------------|-------------------------|--|--|---|--|------------|
| Reactor type | Inoculum sludge | Operation day (d) | $T(^{\circ}C)$ | Hq | Ammonium removal (%) | $\frac{\rm NLR}{\rm d^{-1}}(\rm kg~N~m^{-3}$ | $\mathrm{NH_4^{+}-N}$ influent (mg $\mathrm{L^{-1}})$ | $NO_2^{-}N$ influent (mg L^{-1}) | $(VS L^{-1})$ or anammox purity (96) | Reference |
| UASB | Anaerobic | 400 | 35 ± 1 | 7.0 | 86.5-92.3 | 6.4 | 1027 | 1409 | I | 46 |
| UASB | granules Aerobic granules | 300 | 30 | 7.0 | 06 | 0.5 | 200 | 220 | | 26 |
| UASB | Nitrifying + | >1400 | Normal | 6.3-7.3 | 06> | 9.5 | 400 - 550 | 575 - 175 | 50-60 | 47 |
| | anammox | | | | Ľ | | | | | |
| | Nitritying | 220 | 30-33 25 | 7.5-8.0 | 97 00 30 (TNT) | 0.16 | 115 158 | 130 575 | | 48 |
| UASB | eranules | C 5 7 | C C | /.8-8.0 | (NII) 67.66 | 1.03 | 864 | c/c | 41.2-92.4 | 49 |
| UASB | AN-GS A-AS | 320 | -35 | 7.3-7.9 | 95 | 1.25 | | | I | 50 |
| UASB | Anaerobic | 214/450 | 35 ± 1 | 6.8-7 | 6.99-97 | 74.3-76.7 | -200 | 240 | $42-57~{ m g~VS~L^{-1}}$ | 7 |
| | granular sludge anammov sludøe | | | | | | | | | |
| 1 L UASB | Synthetic | 70 | 35 ± 1 | 6.8-7.0 | 93.2 ± 7.1 | | 30-70 | 30-70 | | 51 |
| CDD | medium As biomass | 000 600 | о Л | 0 0 | | | | | | 63 |
| SED | Angmmov | 320 | C4 2.2 | 0.0 7 0-8 0 | 00-100 | 0.42 | 1 80 | 750 | | 1 L 2 L |
| | Antannuo Antimetod chudan | 320 | 50 - 50 | | 001-66 | 0.40 | 1000 | 1002 | | |
| SBK | Activated sludge | 505 400 | 30 ± 0.3 25 ± 1 | 7.8-0.1 | 99.9 50 (TNI) | 1.0 | 1208 | 100.14 | 0.68 | 0 1 |
| ADK CDD | Anamilox | 400 | 1 H CC | 0./-/.U 7 E | 00 (IIN) 70 (TNI) | 0.26 0.26 | 700 JEO | | ц Ц Ц | 40 10 |
| | Anamiliox | 400 | 1 H CC | 00 11 | /8 (IIV) 00 | 0.30 | 200-230 | 150 | CC> | C7 |
| DBK | AIIAIIIIIOX | 212 | 30 ± 1 | 0.8-6.1 | 98 | 0.5 | net | net | I | 66 |
| 2 L SBR | granues Nitritation- | 180 | 33 ± 1 | | 85-94 | 0.18 g N per g | 500 | | 1.8 g VSS per L | 56 |
| | anammox | | | | | VSS per d | | | 18-19% Ca. | |
| | synthetic | | | | | 4 | | | Jettenia (16.8%) | |
| | wastewater | | | | | | | | and | |
| | | | | | | | | | Nitrosomonas (20.1%) | |
| 18 L SBR | Raw | 94 | 37 | 7.8-8.0 | | $10{-}33~{ m g~m^{-3}~d^{-1}}$ | 183 - 200 | | | 57 |
| Pa + AN | optoelectronic industrial wastewater | | | | | ì | | | | |
| 3 L SBR | $0.6 \mathrm{kg}\mathrm{N}\mathrm{m}^{-3}\mathrm{d}^{-1}$ | 50 d start up | 30 | 8.1 ± 1 | 91 ± 10 97 | 0.5–0.6 g Nper L | Ι | $NO_{2}-N$ | $274 \pm 45\%$ 2.3 g | 58 |
| | piggery waste production/no dilution | | | | | per d | | removed/ NH ₄ –N removed | TSS per L and 79% VSS/TSS | |
| | | | | | | | | molar ratio was 1.28 ± 14% | | |
| 3 L SBR CANON | Trace N_2H_4 (4 mg L ⁻¹) was added into the influent | 80 | 31 ± 1 | I | 70 ± 7 (TN) | 0.33 ± 0.06 kg N per L per d | 150 mg N per L | I | Ca. Scalindua, 3.14×10^9 to 5.86×10^{10} copies per g (dry sludge) | 59 |
| | | | | | | | | | | |

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Table 2 (Contd.)

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| Reactor type | Inoculum sludge | Operation day (d) | $T(^{\circ}C)$ | Н | Ammonium removal (%) | NLR (kg N m^{-3} d ⁻¹) | NH ₄ ⁺ -N influent (mg L ⁻¹) | NO ₂ ^N influent (mg L ⁻¹) | Sludge concentration (VS L^{-1}) or anammox purity (%) | Reference |
|--|---|---|---------------------------------------|---|---------------------------------------|---|--|---|---|--------------|
| MBBR | Synthetic wastewater 2 L of virgin carrier media | 86-121 | 33.4-35 | 7.5 ± 0.1 | 0.57-0.64 ± 0.17 | 0.03-0.22 | 348.36-507 | 0.48-0.77 | Ca. Brocadia fulgida shift to Ca. Kuenenia stuttgartiensis AOB1.83-1.4 NOR | 09 |
| 10 L MBR | Synthetic wastewater | | 30 | 6.8-7.5 | 85% (TN) | 1 g N per L per d | 12.9 mM | 3.4 mM (1.21) | Growth rate of 0.21 d ⁻¹ | 2 |
| 15 L/8 L MBR | Synthetic wastewater | 250 | 37 | 7.1-7.5 | | | 1680 | 1680 | 0.23 day as free cells | 61 |
| 1.6 L MBR | Synthetic medium | 63 | 30 ± 1 | 7.0 ± 0.2 | 82.14 | 293/1680 | 840 | 840 | Ca. Brocadia 60% | 62 |
| 1.8 L GSBF | Effluent of the A- stage of the WWTP | 20 °C/1-52 15 °C/60-127 10 °C/134-285 | 20 and 10 | 7-7.5 | I | $50 \pm 7 \text{ mg N}$ per g VSS per d | 0.4 g N per L per d | 50 ± 7 mg N per g VSS per d | Ca. Brocadia 0.35 g TSS/12 g TSS | 63 |
| 6 L SBBR | Synthetic ammonium-rich wastewater | 30 | 35 ± 1 | 74 | | I | 470 | . | | 64 |
| SBBRs | Synthetic medium | 06 | 35 ± 1 | 7.0-7.8 | 88 | 1.62 kg N m ⁻³ d ⁻¹ | | I | Ca. Anammoxoglobus (DQ317601.1) | 65 |
| 2.6 L FBR | Synthetic wastewater | 65 | 35 ± 0.2 | 8 ± 0.2 | | 0.05-0.06 kg N $\text{m}^{-3} \text{ d}^{-1} 0.25$ $\text{ko N m}^{-3} \text{ d}^{-1}$ | $50~{ m mg~L^{-1}}$ | $50~{ m mg~L^{-1}}$ | ca. Kuenenia Stuttgartiensis | 66 |
| EMBRs 5 L AnR | — Synthetic medium | 50 102 | 33 ± 1 32 | 8.0 ± 0.3 7.8 ± 0.3 | 06 | $0.30 \text{ g N L}^{-1} \text{ d}^{-1}$ | - 1230 \pm 61 mg L^{-1} | | | 67 68 |
| ^a NLR: nitro nitrification | ^{<i>a</i>} NLR: nitrogen loading rate; anammox purity: the percentage of anammox in the biomass; MBBR: movin nitrification and anammox reactor; GSBF: granular fluidized bed reactor; SGSR: stirred gas solid reactor. | ammox purity: the or; GSBF: granular | percentage of an fluidized bed rea | ammox in the bio actor; SGSR: stirre | mass; MBBR: mo od gas solid reacto | ^a NLR: nitrogen loading rate; anammox purity: the percentage of anammox in the biomass; MBBR: moving bed biofilm reactor; EMBRs: external MBR; FBR: fixed bed reactor; PAN-An R: partial nitrification and anammox reactor; GSBF: granular fluidized bed reactor; SGSR: stirred gas solid reactor. | or; EMBRs: exterr | ial MBR; FBR: fixe | d bed reactor; PAN-A | n R: partial |

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2014. Most of them were conducted in the one-stage configuration, and the most commonly applied reactors were SBRs, followed by granular systems and MBBRs.²⁴

4. Characteristic and stability analysis of the anammox process in different reactor setups

Different reactors used for the anammox process are summarized in Table 2. The performance such as the startup time, nitrogen-loading rate, removal efficiency, substrate concentration, and the purification of sludge is described and compared in detail. The most commonly used SBR reactor has an NLR that varied from 0.3 kg m⁻³ d⁻¹ to 1.6 kg m⁻³ d⁻¹ with the highest removal efficiency over 99%.6 The comparison of the most commonly used UASB and SBR processes with the maximum NRR and startup time is shown in Fig. 2. Generally, the UASB process can obtain a high NRR over $2 \text{ kg m}^{-3} \text{ d}^{-1}$. However, that of the SBR reactor was lower than 2 kg $m^{-3} d^{-1}$ with a shorter time for startup. By comparing the anammox sludge with an organic C content lower than 35%25 and a content higher than 99%,6 it was found that the anammox sludge with higher purity can obtain a higher nitrogen removal efficiency. Similarly, the UASB reactors with different purities and operation conditions had relatively large differences in the NRRs, which might vary from 0.5 kg m⁻³ d⁻¹ (ref. 26) to 76 kg m⁻³ d⁻¹. To data, the highest NRR obtained was 76 kg m^{-3} d⁻¹ when the UASB reactor was fed with substrate of low concentration under short HRT.7 Other reactors for the anammox process were reported to have different NRRs varying from 0.3 kg m⁻³ d⁻¹ to 1.62 kg m⁻³ d^{-1} (Table 2).

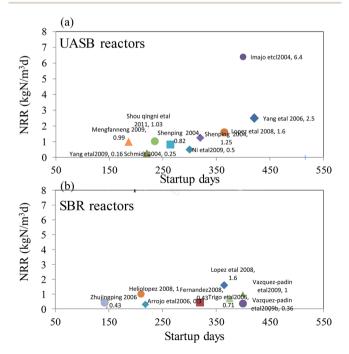


Fig. 2 The start up time and maximum NRR comparison of the anammox process of the most used reactors (a) UASB and (b) SBR.

Over the past twenty years, many studies carried out have focused on the optimization of the anammox process parameters. The relative issues involving the substrate inhibition, temperature effect, organic matter and salinity have been extensively investigated.27 The drawback of the anammox process with quite low bacteria growth rate can be overcome by MBR, which is more effective than most other reactors for enrichment.⁵ A reactor configuration with a high capacity of biomass retention is essential for the anammox process. Recently, a novel process conducted in an MBR with pure freecell suspension of highly active anammox was successful, with a higher growth rate than the specific maximum growth rate ever reported for the biomass, 0.21–0.23 d^{-1.5} This strategy has a number of potential capacities in the cultivation of seeding anammox in terms of practical engineering projects.² MBR or MBBR and Nov-BFR with carriers can accumulate a certain amount of anammox to keep the process stable. Additionally, inherent with each technology are the advantages and disadvantages of the process, and/or operation and maintenance. Discharging standards are often the primary consideration in selecting a treatment technology.

Anammox processes conducted in different reactors can accumulate different kinds of anammox bacteria following the substrata and operation conditions. Because of its potentials in nitrogen removal during the biological process, the high treatment performance and stability of the anammox process have been constantly studied for engineering application. Most of the lab-scale enrichment anammox bacteria were 'Ca. Brocadia' and 'Ca. Kuenenia', which are almost mono-species in the anammox process, illustrating a competition relationship of the anammox species owing to their different substrate affinities. It should be worth noting that under specific physiological conditions, Ca. Kuenenia outgrows 'Ca Brocadia', resulting in overgrowth when the substrate concentration is low.28,29 Meanwhile, the ecological roles of the functional microbe and their potentials should be extensively explored in order to attain new perspectives for further design, operation, and maintenance of the process.

Generally, a large number of gas bubbles will be generated in gas tunnels and gas pockets in some high-loading bioreactors inoculated with anammox bacteria of high activity. It is speculated that the gas bubbles entrapped in the gas pockets might be a pivotal factor to cause sludge floatation, especially in the upflow reactor, such as a UASB or an EGSB. After the hollows are filled with gas bubbles, the anammox granules will unavoidably float and be washed out of the reactor, leading to a failure of the anammox process. The granule floatation can be undoubtedly responsible for instability, or even failure of the anammox reactor.^{30,31} The existence of this washout obstacle compels the implementation of a large number of studies in pursuit of a feasible way to overcome this obstacle.

5. Process-kinetic analysis of different anammox processes

Bibliometric analysis showed that the investigation on the reactor-kinetic models in the published paper was only one-

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Table 3 Comparison of the kinetics used for the anammox reactor^a

| K, | R^{2} R ² 0.71-0.94 | R ² 0.71- 0.94 | R^2 0.71-0.94 0.99 | R^2 R^2 0.51-0.94 - 0.599 0.599 0.599 | R^2 R^2 0.599 0.599 0.599 0.599 0.993 | R^2 R^2 0.599 0.599 0.599 0.599 0.993 | R^2 (0.599 0.599 0.993 0.993 | $\begin{array}{c} & R^2 \\ 0.94 \\ - \\ 0.599 \\ 0.599 \\ 0.993 \end{array}$ | R^2 0.599 0.599 0.599 0.593 0.933 | R^2 (0.599 0.599 0.993 0.993 | R^2 0.599 0.599 0.599 0.993 |
|---|---|--|--|---|---|---|---|---|---|---|--|
| $K_{ m s} \qquad M_{ m max} \ ({ m g~L}^{-1}) (1/{ m d})$ | 981 0.002446 0.007408 0.0059 0.3511 | | | 9 | 9 | 5 6 | 5 0 | 5 6 | 5 0 | 5 0 | 5 0 |
| $R_{ m m} = K_{ m B} = R^2 = ({ m g~L})^2$ | | | | 9 | 9 | 5 00 | 5 0 | 5 0 | 5 6 | 5 0 | 5 0 |
| k_2 (1/d) R^2 $R_{ m m}$ | 2 2.064 0.9954 22.29 27.25 0.981 | | | | | | | | | | 10 |
| $a R^2 = (1/d) b$ | 0.6102 1.09 0.02 | 0.6102 1.09 0.02 0.172 1.4 0.96 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 5 0.706 0.11 1.11 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 5 0.706 0.11 1.11 0.756 0.06 1.14 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 5 0.706 0.11 1.11 0.756 0.06 1.14 0.756 1.06 1.14 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 0 0.756 0.011 1.14 0.756 0.06 1.14 0.756 0.06 1.14 0.767 0.011 1.10 | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 0.706 0.11 1.11 0.756 0.06 1.14 0.756 0.06 1.14 0.756 0.06 1.14 0.756 0.06 1.14 0.756 0.06 1.14 0.756 0.06 1.14 0.756 0.06 1.14 | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | 0.6102 1.09 0.02 0.172 1.4 0.96 0.707 0.11 1.11 0.706 0.11 1.11 0.756 0.011 1.11 0.756 0.11 1.11 0.756 0.06 1.14 0.756 1.04 1.06 1.4 0.96 1.14 0.756 0.05 1.04 0.03 1.04 0.06 0.05 1.04 0.05 0.05 1.04 0.04 0.05 1.04 0.05 0.05 1.04 0.05 | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ |
| $\begin{array}{c} \mathrm{HRT} & k_1 \\ \mathrm{d}^{-1}) & (\mathrm{d}) & (\mathrm{1/d}) & l \end{array}$ | 1.0- 66.9 0.066 | $\begin{array}{rrr} 1.0- & 66.9 \\ 0.066 & \\ 0.08-0.6 & 0.44 \end{array}$ | 1.0- 66.9 0.066 0.44 0.08-0.6 0.44 5 0.6-3.0 5.31 | 1.0- 66.9 0.066 6.44 0.08-0.6 0.44 5 0.6-3.0 5.31 0.6-2.9 5.305 | 1.0- 66.9 0.066 6.44 0.08-0.6 0.44 5 0.6-3.0 5.31 0.6-2.9 5.305 0.25-1.0 7.44 | 1.0- 66.9 0.066 0.44 0.08-0.6 0.44 0.06-3.0 5.31 0.6-2.9 5.305 0.25-1.0 7.44 0.08-0.6 0.08-0.6 | 1.0- 66.9 0.066 0.44 0.08-0.6 0.44 0.06-3.0 5.315 0.6-2.9 5.305 0.25-1.0 7.44 0.08-0.6 7.44 1-0.25 h | 1.0- 66.9 0.066 0.44 0.08-0.6 0.44 0.6-3.0 5.315 0.6-2.9 5.305 0.25-1.0 7.44 0.08-0.6 7.44 1-0.25 h 1-0.25 h | $\begin{array}{cccc} 1.0- & 66.9 \\ 0.066 & 0.44 \\ 0.08-0.6 & 0.44 \\ 0.6-2.9 & 5.305 \\ 0.6-2.9 & 5.305 \\ 0.25-1.0 & 7.44 \\ 0.08-0.6 \\ 1-0.25 & h \\ 1-0.25 & h \\ 3-9.62 & h \end{array}$ | $\begin{array}{cccc} 1.0- & 66.9 \\ 0.066 & 0.44 \\ 0.08-0.6 & 0.44 \\ 0.6-2.9 & 5.305 \\ 0.6-2.9 & 5.305 \\ 0.6-2.9 & 5.305 \\ 0.08-0.6 & 7.44 \\ 1-0.25 & 1 \\ 1-0.25 & 1 \\ 3-9.62 & 1 \\ 3-9.65 & 1 \\ \end{array}$ | 1.0- 0.066 0.08-0.6 0.6-2.9 0.25-1.0 0.08-0.6 1-0.25 h 1-0.25 h 3-9.62 h 3-9.65 h |
| NLR (g L^{-1} | | | XOL | Xou | Xou | Xou | X | X | v v v v v v v v v v v v v v v v v v v | nox s-40+ | nox -40+- |
| ate Inoculum | etic PN-anammox vater granular | r | 1. | 19 | r hetic | hetic | hetic | hetic | t hetic | r hetic | r r r r |
| T V(L) (°C) Substrate | $24/20 30 \pm $ Synthetic 1 wastewater | $\begin{array}{c} 30 \pm 330 \pm 35 \end{array}$ | $\begin{array}{c} 30 \pm 1 \\ 35 \\ 35 \end{array}$ | $\begin{array}{c} 30 \pm 1 \\ 35 \\ 35 \\ 35 \\ 35 \end{array}$ | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | $egin{array}{cccccccccccccccccccccccccccccccccccc$ | $egin{array}{cccccccccccccccccccccccccccccccccccc$ | $\begin{array}{cccccccccccccccccccccccccccccccccccc$ |
| \sim | 5^{r} | 24 | 5 | 5 | 0.0 | 0.0 | × 0.0 | ă <u> </u> | ⁷ 1 0 0 0 | 1 1 00 0 ⁵ | |

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| | l able 5 | (Lonia.) | ~ | | | | |
|---|-----------|----------|----------|--------------|-------------------------------|---|-------------|
| r $V(L)$ T NIR (C) SubstrateInoculum $(g, L^{-1} d^{-1})$ 1 $35 \pm$ Synthetic $0.16 \times 10^{0.24}$ 14.6 1 $35 \pm$ Synthetic $0.16 \times 10^{0.24}$ 14.6 1 $35 \pm$ Synthetic $0.16 \times 10^{0.24}$ 14.6 1 $35 \pm$ SyntheticCopper(1) $1.6 \times 10^{0.24}$ 14.6 1 $35 \pm$ SyntheticCopper(1) $1.6 \times 10^{0.24}$ 14.6 1 $35 \pm$ SyntheticCopper(1) $1.6 \times 10^{0.24}$ 14.6 1 $35 \pm$ SyntheticRe-startup $1.6 \times 10^{0.24}$ 14.6 1.5 $35 \pm$ SyntheticRe-startup $1.6 \times 10^{0.24}$ $1.6 \times 10^{0.24}$ 1.5 $35 \pm$ SyntheticRe-startup $1.6 \times 10^{0.24}$ $1.6 \times 10^{0.24}$ 1.5 $35 \pm$ SyntheticRe-startup $20-266$ 1.5 $35 \pm$ SyntheticRe-startup $20-266$ 1.5 $35 \pm$ SyntheticRestartup $20-266$ 1.6 $35 \pm$ SyntheticRestartup $20-266$ 1.7 $35 \pm$ SyntheticRestartup $20-266$ 2 $37 \times$ Synthetic <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>First-order</td> | | | | | | | First-order |
| rTNIRr $V(L)$ (^{C}C) SubstrateInoculum $(^{C}L^{-1} d^{-1})$ 1 $35 \pm$ Synthetic $0.16 \times 10^{0.24}$ 14.6 1 $35 \pm$ SyntheticCopper(ii) 14.6 1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1.6 $35 \pm$ SyntheticRe-startup1.7 $35 \pm$ SyntheticRe-startup1.8 $35 \pm$ SyntheticRe-startup1.9 $35 \pm$ SyntheticRe-startup1.15 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1.6 $37 +$ SyntheticRe-startup2.7 $35 \pm$ SyntheticRe-startup2.8 $37 +$ SyntheticRe-startup2.1 $35 \pm$ SyntheticRe-startup2.2 $41 +$ wastewater $70-267$ 2.3 $36 +$ Reject water $116 +$ $70-267$ 2.4 $41 +$ wastewater $20-28-1$ 2.5 $41 +$ wastewater $12-262 +$ $70-267 +$ $70-267 +$ $70-267 +$ $70-267 +$ $70-267 +$ $70-267 +$ $70-267 +$ $70-267 +$ 70 | | | | | | | |
| 135 ± Synthetic0.16 × 10^{0.24}14.6135 ± Synthetic0.16 × 10^{0.24}14.6135 ± SyntheticCopper(n)14.6135 ± SyntheticCopper(n)15135 ± SyntheticCopper(n)16.51.535 ± SyntheticCopper(n)16.51.535 ± SyntheticRe-startup1.535 ± SyntheticRe-startup1.635 ± SyntheticRe-startup1.735 ± SyntheticRe-startup1.835 ± SyntheticRe-startup1.935 ± SyntheticRe-startup1.135 ± SyntheticRe-startup1.535 ± SyntheticRe-startup1.637Synthetic2.7SyntheticSingle feed2.8Reject waterLab-scale2.1wastewaterLab-scale2.2MtpStanular2.3SyntheticMastewater2.3SyntheticMastewater2.3SyntheticMatter2.3SyntheticMastewater2.4Mtp2.5Mtp2.5Southetic2.6Mtp </td <td>Reactor</td> <td>V (L)</td> <td></td> <td>Substrate</td> <td>Inoculum</td> <td>$\frac{\text{NLR}}{\text{(g L}^{-1} \text{ d}^{-1})}$</td> <td></td> | Reactor | V (L) | | Substrate | Inoculum | $\frac{\text{NLR}}{\text{(g L}^{-1} \text{ d}^{-1})}$ | |
| 1 wastewater kg Sm ³ 1 35 ± Synthetic Copper(ii) 1 35 ± Synthetic Re-startup 15 35 ± Synthetic Re-startup 15 35 ± Synthetic Re-startup 1 wastewater Re-startup 15 35 ± Synthetic Re-startup 16 1 wastewater Re-startup 17 wastewater Re-startup 18 35 ± Synthetic Re-startup 19 35 ± Synthetic Re-startup 10 35 ± Synthetic Re-startup 11 wastewater Re-startup 12 35 ± Synthetic Re-startup 13 5 ± Synthetic Re-startup 1 35 ± Synthetic Re-startup < | UASB | | 35 + | | $0.16 \times 10^{0.24}$ | 14.6 | |
| 1 35 ± Synthetic Copper(n) 1 wastewater recovery 1 wastewater OTC recovery 1 wastewater recovery 15 35 ± Synthetic Re-startup 1 wastewater Re-startup 15 35 ± Synthetic Re-startup 1 wastewater Re-startup 15 35 ± Synthetic Re-startup 1 wastewater Re-startup 1 wastewater Re-startup 1 wastewater Re-startup 1 1 wastewater Re-startup 1 1 wastewater Re-startup 1 wastewater Re-startup 70-265 1 wastewater Re-startup 70-265 1 35 ± Synthetic Re-startup 70-265 1 35 ± Synthetic Re-startup 20-366 2 | | I | | | kg Sm ³ d1would | | |
| 1 wastewater recovery 1 35 ± Synthetic OTC recovery 1 wastewater Re-startup 1.5 35 ± Synthetic Re-startup 1.6 35 ± Synthetic Re-startup 1.7 35 ± Synthetic Re-startup 1.8 35 ± Synthetic Re-startup 1.1 wastewater Single feed 70-266 1.8 35 ± Synthetic Re-startup 70-266 1.1 wastewater Single feed 0.15-2.8 2.1 35 ± Synthetic Multi feed 0.15-2.8 2.1 35 ± Synthetic Activated 0.15-2.8 2.1 35 ± Synthetic | UASB | - | $35 \pm$ | | Copper(II) | | 0.4 - 2. |
| 1 35 ± Synthetic OTC recovery 1 wastewater Re-startup 1.5 35 ± Synthetic Re-startup 1.6 35 ± Synthetic Re-startup 1.7 35 ± Synthetic Re-startup 1.8 35 ± Synthetic Re-startup 1.9 35 ± Synthetic Re-startup 1.1 wastewater Single feed 70-266 1.1 wastewater Single feed 70-266 2.1 35 ± Synthetic Multi feed 0.15-2.8 2.8 Multi feed 0.15-2.8 2.1 35 ± Synthetic Activated 0.15-2.8 2.1 37 Synthetic | | | Ļ | wastewater | recovery | | ų |
| 1wastewater1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1.6 $35 \pm$ SyntheticRingle feed1 $35 \pm$ SyntheticSingle feed1 $35 \pm$ SyntheticSingle feed1 $35 \pm$ SyntheticMulti feed2 37 SyntheticMulti feed2.5 37 SyntheticAnamnox2.5 36 Reject waterLab-scale2.5 36 Reject waterLab-scale2 wtp fill-draw2 wtp digester of2 30 SyntheticWastewater2 30 SyntheticMastewater2 30 SyntheticMastewater2 30 SyntheticMastewater2 30 Synthetic 30 | UASB | 1 | $35 \pm$ | | OTC recovery | | 0.4 - 2. |
| 1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1.6 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed70-2661 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed0.15-2.82 37 SyntheticAnamnox0.28-12 37 SyntheticAnamnox0.28-12 36 Reject waterLab-scale2 36 Reject waterLab-scale2 30 SyntheticMesophilic2 30 SyntheticMastewater2 30 SyntheticMastewater2 30 Synthetic 30 | | | - | - | | | ų |
| 1 u wastewater1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed70-2661 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed70-2672 37 SyntheticAnamnox0.15-2.82 37 SyntheticAnamnox0.28-12 wtp fill-draw1.4 wastewater2 30 SyntheticMesophilic2 30 SyntheticMastewater0.93- | UASB | 1.5 | 35 ± | | Re-startup | | |
| 1.5 35 ± 5 SyntheticRe-startup1.5 35 ± 5 SyntheticRe-startup1.6 35 ± 5 SyntheticRe-startup1.7 35 ± 5 SyntheticSingle feed $70-266$ 1 35 ± 5 SyntheticMulti feed $70-267$ 1 35 ± 5 SyntheticMulti feed $70-267$ 1 35 ± 5 SyntheticMulti feed $70-267$ 2 37 SyntheticAnamnox $0.15-2.8$ 2 37 SyntheticAnamnox $0.28-1$ 2 37 SyntheticAnamnox $0.28-1$ 2.5 36 Reject waterLab-scale2 30 SyntheticMesophilic2 30 SyntheticMastewater2 30 SyntheticMastewater2 30 Synthetic $30-93-1$ | | 1 | - ; | | | | |
| 1wastewater1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticSingle feed70-2661 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed70-2672 37 SyntheticMulti feed0.15-2.82 37 SyntheticAnamnox0.28-12 37 SyntheticAnamnox0.28-12.5 36 Reject waterLab-scale2 30 SyntheticMesophilic2 30 SyntheticWastewater0.93-2 30 SyntheticWastewater0.93- | UASB | 1.5 | 35 ± | | Re-startup | | |
| 1.5 35 ± 5 SyntheticRe-startup1.5 35 ± 5 SyntheticRe-startup1.5 35 ± 5 SyntheticRe-startup1.5 35 ± 5 SyntheticRe-startup1.6 35 ± 5 SyntheticRe-startup1 35 ± 5 SyntheticSingle feed70-2661 35 ± 5 SyntheticMulti feed70-2671 35 ± 5 SyntheticMulti feed70-2671 35 ± 5 SyntheticMulti feed70-2672 $37 + 5$ SyntheticMulti feed0.15-2.82 $37 + 5$ SyntheticAnamnox0.28-12 $37 + 5$ SyntheticAnamnox0.28-12.5 $36 + 7$ Reject waterLab-scale2 $30 + 5$ SyntheticMesophilic2 $30 + 5$ SyntheticMastewater2 $30 + 5$ SyntheticMastewater2 $30 + 5$ Synthetic 10.93^{-1} | | 1 | - 6 | | f | | |
| 1wastewater1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed $70-266$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 2 $37 \pm$ SyntheticMulti feed $0.15-2.8$ 50 $37 \pm$ SyntheticAnammox $0.28-1$ 50 $37 \pm$ SyntheticAnammox $0.28-1$ 51 $28 \pm$ Reject waterIab-scale52wtpfill-draw2.5 $36 \pm$ Reject waterMesophilic2 $30 \pm$ SyntheticWastewater2 $30 \pm$ SyntheticMestowater2 $30 \pm$ SyntheticMestowater2 $30 \pm$ SyntheticMestowater2 $30 \pm$ Synthetic $10.93-$ | UASB | 1.5 | 35 ± | | Re-startup | | |
| 1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed $70-266$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 2 $37 \pm$ SyntheticMulti feed $0.15-2.8$ 50 $37 \pm$ SyntheticAnamnox $0.28-1$ 50 $37 \pm$ SyntheticAnamnox $0.28-1$ 51 $28 \pm$ Reject waterIlab-scale52wtpfill-draw2.5 $36 \pm$ Reject waterMesophilic2 $30 \pm$ SyntheticWastewater2 $30 \pm$ SyntheticMestewater2 $30 \pm$ SyntheticWastewater2 $30 \pm$ Synthetic $30 \pm$ | | | | - | | | |
| 1wastewater1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed70-2661 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed0.15-2.85 $37 \pm$ SyntheticAnamnox0.28-15 $37 \pm$ SyntheticAnamnox0.28-15 $37 \pm$ SyntheticAnamnox0.28-15 $37 \pm$ Reject waterIlab-scale12.5 $36 \pm$ Reject waterLab-scale2.5 $36 \pm$ SyntheticMesophilic2 $30 \pm$ SyntheticWastewater0.93-2 $30 \pm$ SyntheticWastewater0.93- | UASB | 1.5 | 35 ± | | Re-startup | | |
| 1.5 $35 \pm$ SyntheticRe-startup1 $35 \pm$ SyntheticSingle feed $70-266$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 2 $37 \pm$ SyntheticMulti feed $0.15-2.8$ 50 $37 \pm$ SyntheticAnammox $0.28-1$ 6dwastewatergranular $0.15-2.8$ 51 $37 \pm$ SyntheticAnammox $0.28-1$ 6dwastewatergranular $0.32-1$ 6d2wtpfill-draw2.536 Reject waterMesophilic2.530 SyntheticWastewater $0.93-$ | | | | - | | | |
| 1wastewater1 $35 \pm$ SyntheticSingle feed70-2661 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed70-2671 $35 \pm$ SyntheticMulti feed0.15-2.850 37 SyntheticAnamnox0.28-16dwastewatergranular0.28-150 37 SyntheticAnamnox0.28-16dwastewatergranular2.8 \pm Reject waterfill-draw2.536Reject waterMesophilic2.530SyntheticWastewater0.93-230SyntheticWastewater0.93- | UASB | 1.5 | $35 \pm$ | | Re-startup | | |
| 1 $35 \pm$ SyntheticSingle feed $70-266$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1 $35 \pm$ SyntheticMulti feed $70-267$ 1wastewaterActivated $0.15-2.8$ 50 37 SyntheticAnammox6dwastewatergranularactor 5 $28 \pm$ Reject waterLab-scale2.5 36 Reject waterMesophilic2 30 SyntheticWastewater2 30 Synthetic 0.93^{-1} | | | - | wastewater | | | |
| 1wastewater1 $35 \pm$ SyntheticMulti feed70-2671wastewaterActivated0.15-2.850 37 SyntheticAnamnox0.28-16dwastewatergranular0.28-16dwastewatergranular0.28-150 37 SyntheticAnamnox0.28-151 $28 \pm$ Reject waterLab-scale1.15-2.8actor 5 $28 \pm$ Reject waterLab-scale2.5 36 Reject waterMesophilic2.5 36 Reject waterMesophilic2 30 SyntheticWastewater0.93- | UASB | - | $35 \pm$ | | Single feed | 70-266 | 1.52 - |
| 1 $35 \pm$ SyntheticMulti feed $70-267$ 1wastewaterActivated $0.15-2.8$ 2 37 SyntheticAnammox $0.28-1$ 50 37 SyntheticLab-scale 52 $28 \pm$ Reject waterLab-scale 2.5 36 Reject waterMesophilic 2.5 36 Reject waterMesophilic 2.5 30 SyntheticWastewater $0.93-$ | | | - | | | | 2.06 } |
| 1wastewater 1 wastewater 30 37 50 37 50 37 50 37 50 37 50 37 51 $28 \pm$ 52 $28 \pm$ 22 $28 \pm$ 215 36 25 36 25 36 25 36 30 | UASB | 1 | $35 \pm$ | | Multi feed | 70–267 | 1.52 - |
| $\begin{array}{c cccc} Activated & 0.15-2.8\\ sludge & 0.15-2.8\\ sludge & 0.28-1\\ ed & wastewater & Anammox & 0.28-1\\ ed & wastewater & granular\\ actor 5 & 28 \pm Reject water & Lab-scale\\ 2 & wtp & fill-draw & reactor\\ 2.5 & 36 & Reject water & Mesophilic\\ wtp & digester of & a municipal\\ 2 & 30 & Synthetic & Wastewater & 0.93-\\ \end{array}$ | | | - | wastewater | | | 2.06 |
| 50 37 Synthetic Anammox 0.28-1 ed wastewater Anammox 0.28-1 actor 5 2± Reject water Lab-scale 2 wtp fill-draw 2.5 36 Reject water Mesophilic 2.5 36 Reject water Mesophilic 2 wtp digester of a municipal 2 30 Synthetic Wastewater 0.93- | UASB | | | | Activated | 0.15 - 2.8 | 0.2 - 3. |
| 50 37 Synthetic Anammox 0.28-1 ed wastewater granular actor 5 28 ± Reject water Lab-scale 2 wtp fill-draw 2.5 36 Reject water Mesophilic 2.5 36 Reject water Mesophilic 2 30 Synthetic Wastewater 0.93- | | | | | sludge | | |
| led wastewater granular eactor 5 28 ± Reject water Lab-scale 2 wtp fill-draw 2.5 36 Reject water Mesophilic 2.5 30 Synthetic Wastewater 0.93- | UASB | 50 | 37 | Synthetic | Anammox | 0.28 - 1 | Ÿ |
| eactor 5 28 ± Reject water Lab-scale 2 wtp fill-draw reactor 2.5 36 Reject water Mesophilic wtp digester of a municipal 2 30 Synthetic Wastewater 0.93- | recycled | | | wastewater | granular | | |
| 2 wtp fill-draw reactor 2.5 36 Reject water Mesophilic wtp digester of a municipal 2 30 Synthetic Wastewater 0.93- | PN reacto | | $28 \pm$ | | Lab-scale | | |
| reactor 2.5 36 Reject water Mesophilic wtp digester of a municipal 2 30 Synthetic Wastewater 0.93- | | | 2 | wtp | fill-draw | | |
| 2.5 36 Reject water Mesophilic wtp digester of a municipal 2 30 Synthetic Wastewater 0.93- | | | | | reactor | | |
| wtp digester of a municipal 2 30 Synthetic Wastewater 0.93– | UAF | 2.5 | 36 | Reject water | Mesophilic | | |
| a municipal 2 30 Synthetic Wastewater 0.93– | | | | wtp | digester of | | |
| 2 30 Synthetic Wastewater 0.93- | | | | | a municipal | | |
| | UAF | 7 | 30 | Synthetic | Wastewater | | 2-14. |

42 16

0.773

|

|

0.225

0.092

0.999

 $12.1 \quad 11.4$

0.999

0.804 0.09 1.03

11.6

0.999

27.5

27.8

0.96

30

13.9

0.9340.932

17.5

15

37.5

27.5

49 73 73

12

74

0.9572

5.39

5.77

(NH₄)₂SO₄ 12-21 h

7.34 g L^{-1}

0.39-6.96 g L^{-1}

wastewater Municipal treatment

> wastewater $30 \pm \text{Synthetic}$

H

3.8

ILAR

plant

wastewater

treatment

plant

0.979

12

12.4

0.986

0.4395 0.175 1.397 0.964

0.97

31.2 42.1

^{*a*} ILAB: internal-loop airlift bio-particle reactor; ANMR: non-woven membrane reactor; MAR: marine anammox reactor; VAF: upflow anaerobic filter; R^2 : correlation coefficient; k_1 and k_2 is the substrate removal rate constant (1/d) of each equation.

Review

Monod

Modified Stover-Kincannon

Grau second-order

Ref.

 R^2

 $K_{\rm d}$ (1/d)

 $egin{array}{ccc} K_{
m s} & M_{
m max} \ ({
m g~L}^{-1}) & (1/{
m d}) \end{array}$

 R^2

 $K_{\rm B}$

 $R_{\rm m}$

 R^2

qa (1/d)

 R^2

 k_1 (1/d)

 k_2 (1/d)

95.29 84.03 0.9758

Y (mg VSS per mg N)

7

72 72 41 41 41

0.985

49.5 56.8

454.5 528 0.995

212.8 228.4 0.746

151.5 157.9 0.73

41 41 42

476.2 553 0.996

144.9 153.7 0.99

384.6 447.7 0.99

tenth of the total. Meanwhile, the Stover-Kincannon model was the most commonly used one, which was followed by the Monod model and the Grau-second model (Fig. 1b). It was confirmed by many studies that the anammox bacteria were very sensitive to operational conditions, such as dissolved oxygen, temperature, pH and composition of organic matters. Unfavorable conditions will largely reduce the activity of the anammox bacteria, and eventually cause a failure in bioreactor performance. Therefore, it is of practical significance to effectively augment the activity of the anammox bacteria in order to achieve a high-rate process under the mainstream conditions, which might cause a large decrease in the specific activity of anammox. Most of the literature reached a consensus in that the process control for anammox is a prerequisite to practically ensure the successful performance under unstable influent conditions.32

The common bioreactors have certain shortcomings since different reactors have different optimal operating conditions. For instance, the UASB reactor often encounters unsatisfactory substrate removal efficiency, severe sludge washout, and large dead zone areas. An EGSB is costly in term of the huge consumption of energy and operation cost. In addition, a biofilm reactor has a long sludge age and sporadic sludge flotation. The main objectives of process modeling are to control and evaluate the performance of the process, as well as to optimize the system design and scale up the pilot plant investigations.³³ For example, the concentrations and activities of anammox measured in different reactors could be used in conjunction with models to control the process parameters, involving the influent loading rate and hydraulic residence time in order to

maximize nitrogen removal. To date, process control is widely considered in the literature as an essential factor to guarantee good performance in various bioreactors.

Modeling and parameter identification are subjects with wide ranges, offering a realm of approaches and methods. In many practical industrial projects, most knowledge is available in the form of heuristic rules achieved from rich experience in a variety of processes. Until now, the successful application of anammox in practical projects is still facing huge challenges. The kinetics involves operational and environmental factors, affecting the utilization rates of the substrates. By means of the kinetics evaluation, the optimization on the plant design and prediction of the performance of treatment plants can be conducted,14,33 and the process models relating to the anammox process can be further discussed (Table 3).^{11,14,34-38} Furthermore, the anammox enrichment culture can be significantly promoted because the kinetics can provide a convincing basic recipe for dealing with the operational and environmental factors affecting the performance of substrate removal.¹¹ It is well known that many mathematical models, such as first-order substrate removal models, Grau second-order substrate removal models, Stovere-Kincannon models, and Monod models are widely adopted in the field of wastewater treatment (Table 3). For example, the first-order and second-order substrate removal models are effective for estimating the kinetic constants in anammox processes.14,39,40 In addition, the Monod model was initially applied to represent the growth of microorganisms, and widely employed to express the degradation kinetics. Moreover, the Stovere-Kincannon model is one of the most expensively developed mathematical models for

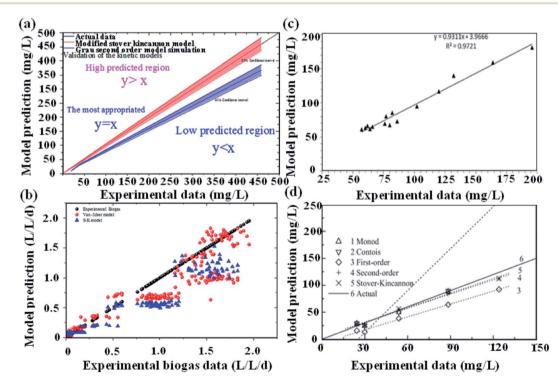


Fig. 3 Reactor-kinetic validation assessment. (a), N₂ gas production (b),¹³ substrate consumption (c),⁴⁵ and the model comparison (d).^{15,45}

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Table 4 Comparison of kinetic models applied to anammox reactors

| $ \begin{array}{c ccccccccccccccccccccccccccccccccccc$ | | | | | | Constants of | | c | |
|---|-------------------|---------------|----------------------------|--------------------------|-------------|--------------|------------|--------|-----------|
| | Models | Reactor | Inoculum | NLR (g $L^{-1} d^{-1}$) | HRT (d) | models | | R^2 | Reference |
| $ \begin{array}{c ccccccccccccccccccccccccccccccccccc$ | First-order model | Upflow filter | Cultured activated sludge | 0.93-7.34 | 0.08-0.6 | 0.44 | | 0.172 | 69 |
| $ \begin{array}{ ccccccccccccccccccccccccccccccccccc$ | | ANMR | Flocculent anammox sludge | 0.107 - 0.746 | 0.6 - 3.0 | 5.31 | | 0.707 | 35 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | | UASB | Activated sludge | 0.15 - 2.8 | 0.2 - 3.2 | 11.6 | | 0.804 | 16 |
| $ \begin{array}{{ccccccccccccccccccccccccccccccccccc$ | | MAR | Cultured anammox sludge | 0.08 - 1.94 | 0.25 - 1.0 | 7.44 | | 0.756 | 11 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | | UASB | Anammox granules | 167-278 | 0.2 - 3.2 | 11.64 | | 0.8043 | 49 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | | | | 191-411 | | | | | |
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$ | | UASB | Activated sludge | 0.93 - 7.34 | 1.5 - 12 | 0.458 | | 0.43 | 13 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | | UASB | Anaerobic digestion sludge | 0.93 - 7.34 | 1.5 - 12 | 0.561 | | 0.04 | 13 |
| cond-order Up/low filter Cultured activated sludge $0.97.34$ $0.6 + 0.6$ 1.4 0.961 | | UASB | 1 | 0.93 - 7.34 | 1.5 - 12 | 0.798 | | 0.18 | 13 |
| $ \begin{array}{ c c c c c c c c c c c c c c c c c c c$ | | | | | | а | q | | |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | Grau second-order | Upflow filter | Cultured activated sludge | 0.93 - 7.34 | 0.08 - 0.6 | 1.4 | 0.964 | 0.985 | 69 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | model | ANMR | Flocculent anammox sludge | 0.107 - 0.746 | 0.6 - 3.0 | 0.105 | 1.11 | 0.995 | 35 |
| MAR Cultured anamox sluge 0.08-134 0.23-1.0 0.0554 113.6 0.991 AUR Floculent anamnox sluge 115-37 0.1-1.99 0.0554 113.97 0.9654 AMR Floculent anamnox sluge 115-313 0.2-3.2 0.0356 1.397 0.965 UASB Anamnox granules 115-713 0.2-3.2 0.0361 1.0287 0.965 UASB Anamox granules 107-411 1.5-12 0.037 1.13 0.93 UASB Anaerobic digestion sluge 0.93-7.34 1.5-12 0.037 1.13 0.93 MR Pollow filter Cultured anamox sluge 0.107-0746 0.65-3.0 7.89 8.86 0.97 MAR Cultured anamox sluge 0.107-0746 0.67-3.0 7.89 8.86 0.99 MAR Cultured anamox sluge 0.17-0746 0.25-3.0 0.14 1.2.1 0.99 MAR Floculent anamox sluge 0.17-0746 0.25-3.1 0.14 1.2.1 0.99 MA | | UASB | Activated sludge | 0.15 - 2.8 | 0.2 - 3.2 | 0.0936 | 1.03 | 0.999 | 16 |
| AUF Synthetic medium $10-1.199$ $10-1.199$ 1397 064 AMMR Flocuetter anarmox studge $157-313$ $0.6-29$ 0.1054 11101 0.9954 UASB Anarmox granules $177-278$ $0.5-32$ 0.10361 1101 0.9954 TAB Anarmox granules $177-278$ $0.2-32.2$ 0.00361 11101 0.9954 Table Activated studge $0.937-344$ $1.5-12$ 0.0031 1.144 0.9954 Table Cultured anarmox studge $0.337-344$ $1.5-12$ 0.0031 1.144 0.9954 Table Cultured anarmox studge $0.107-0746$ $0.6-30$ 0.137 0.997 MMR Flocuetert anarmox studge $0.157-218$ $0.23-32$ 1.144 0.297 MMR Flocuetert anarmox studge $0.157-238$ $0.23-32$ 1.144 0.999 MMR Flocuetert anarmox studge $0.157-238$ $0.23-32$ 1.241 2.24 0.999 MMR | | MAR | Cultured anammox sludge | 0.08 - 1.94 | 0.25 - 1.0 | 0.0554 | 1.136 | 0.991 | 11 |
| ANR Floculent anamnox sludge 115-27 0.6-29 0.1054 1.1101 0.3954 UASB Anamnox granules $15^{-3}-313$ 0.6-29 0.1054 1.1101 0.3954 UASB Anamnox granules $15^{-3}-313$ 0.2-3.2 0.09361 1.0287 0.3955 Lokab Artivated sludge 0.39-7.34 1.5-12 0.091 1.113 0.39 The Upflow filter Cultured activated sludge 0.39-7.34 1.5-12 0.091 1.114 0.39 The Upflow filter Cultured activated sludge 0.3-7.34 1.5-12 0.091 1.114 0.39 Mark Floceulent anamoox sludge 0.170-7.0746 0.6-5.30 7.39 0.393 0.393 MAR Activated sludge 0.177-0746 0.2-3.22 1.14 1.2 0.393 MAR Activated sludge 0.177-0746 0.2-3.22 1.2.4 1.2 0.393 MAR Activated sludge 0.37-39 1.2.4 1.2.4 0.393 MAR Fl | | AUF | Synthetic medium | | 10.1 - 1.99 | | 1.397 | 0.964 | 12 |
| UASB Anamox granules $153-713$ $0.2-32$ 0.0361 1.0287 0.9955 T- UASB Aracrobic digestion sludge $0.93-7.34$ $1.5-12$ 0.037 1.133 0.33 T- Upflow filter Cultured activated sludge $0.93-7.34$ $1.5-12$ 0.031 1.14 0.93 T- Upflow filter Cultured activated sludge $0.93-7.34$ $1.5-12$ 0.091 1.120 0.93 del ANMR Ploculent anamox sludge $0.93-7.34$ $1.5-12$ 0.091 1.14 0.995 dots Filter Cultured activated sludge $0.97-7.34$ $0.107-0.746$ $0.6-3.32$ 1.14 1.21 0.999 dots ANMR Floculent anamox sludge $0.107-0.746$ $0.6-3.32$ 1.14 1.21 0.999 ANMR Floculent anamox sludge $0.107-0.746$ $0.6-3.32$ 1.14 1.21 0.999 ANMR Floculent anamox sludge $1.15-28$ $0.2-3.32$ 1.14 1.24 < | | ANMR | Flocculent anammox sludge | 115-297 | 0.6 - 2.9 | 0.1054 | 1.1101 | 0.9954 | 14 |
| UASB Anarmox granules 167-278 0.2-3.2 0.09361 1.0287 0.9965 $Arrivated studge 0.39-7.34 1.5-12 0.037 1.13 0.93 Arrivated studge 0.39-7.34 1.5-12 0.061 1.14 0.98 Arrivated studge 0.39-7.34 1.5-12 0.061 1.14 0.99 Arrivated studge 0.39-7.34 1.5-12 0.061 1.14 0.99 Arrivated studge 0.39-7.34 1.5-12 0.061 1.14 0.99 Arrivated studge 0.37-7.34 1.5-12 0.061 1.14 1.2 0.99 Arrivated studge 0.17-0.746 0.5-30 7.89 8.98 0.999 Arrivated studge 0.15-2.8 0.2-3.1 11.14 12.1 0.99 Arrivated studge 0.15-2.48 0.2-3.2 11.14 12.1 0.99 Arrivated studge 15-297 0.2-3.2 12.1 11.4 0.99 Arrivated studge 15-297 0.2-3.2 $ | | | | 153 - 313 | | | | | |
| Activated sludge 033-7.34 1.5-12 0.087 1.13 0.93 r- UASB Anaerobic digestion sludge 033-7.34 1.5-12 0.087 1.13 0.93 r- Upflow filter Cultured activated sludge 0.33-7.34 1.5-12 0.081 1.24 0.93 odel ANMR Floculent anamox sludge 0.33-7.34 0.5-30 7.89 8.98 0.999 MAR Cultured anamox sludge 0.15-28 0.6-30 7.37 8.98 0.999 MAR Flocculent anamox sludge 0.15-28 0.2-31 7.37 0.993 MAR Flocculent anamox sludge 0.15-29 0.89 0.393 0.99 MAR Flocculent anamox sludge 0.15-29 0.2-31 1.14 0.393 MAR Flocculent anamox sludge 0.15-218 0.2-32 1.14 0.393 MAR Flocculent anamox sludge 0.15-218 0.2-32 1.24 1.24 0.993 MAR Anaerobic digestion sludge 0.93-7.34 | | UASB | Anammox granules | 167-278 191-411 | 0.2 - 3.2 | 0.09361 | 1.0287 | 0.9985 | 15 |
| UASB Thereobic digestion sludge $0.37.7.34$ $1.5-12$ 0.001 $1.1.4$ 0.37 r- Upflow filter Cultured activated sludge $0.37.7.34$ $1.5-12$ 0.001 $1.1.4$ 0.97 del ANMR Flocculent anarmox sludge $0.107-0.746$ $0.6-3.06$ 1.24 1.20 0.999 dot ANMR Flocculent anarmox sludge $0.107-0.746$ $0.6-3.06$ 7.89 0.999 MAR Cultured activated sludge $0.107-0.746$ $0.6-3.06$ 7.89 0.999 MAR Flocculent anarmox sludge $0.107-0.746$ $0.6-2.9$ 8.98 0.999 AUMR Flocculent anarmox sludge $0.11-1.99$ $0.2-3.2$ 11.4 $1.2.1$ 0.999 AUM Flocculent anarmox sludge $0.11-1.997$ $0.2-3.2$ 11.4 $1.2.1$ 0.999 AUM Flocculent anarmox sludge $0.11-1.99$ $0.2-3.2$ 11.4 $1.2.1$ 0.999 AUMS Anarrobic digestion sludge $0.3-3.7.34$ <t< td=""><td></td><td></td><td>Activated cludoe</td><td>0 93-7 34</td><td>1 5-12</td><td>0.087</td><td>1 13</td><td>0.93</td><td>13</td></t<> | | | Activated cludoe | 0 93-7 34 | 1 5-12 | 0.087 | 1 13 | 0.93 | 13 |
| Orabit Anactoric ugestion studge $0.33-7.34$ $1.5-12$ 0.001 1.114 0.36 α el NMR Cultured activated studge $0.37-7.34$ $1.5-12$ 0.001 1.114 0.37 α el NMR Flocculent anamnox studge $0.07-0.746$ $0.66-0.6$ 7.24 1.2 0.979 α AR Cultured anamnox studge $0.17-0.746$ $0.6-0.6$ 7.38 8.98 0.999 α AR Cultured anamnox studge $0.15-2.8$ $0.2-3.2$ 11.4 $1.2.1$ 0.979 α AR Cultured anamnox studge $0.15-2.8$ $0.2-3.2$ 11.4 $1.2.1$ 0.999 α ANR Flocculent anamnox studge $0.15-2.8$ $0.2-3.2$ 12.1 12.1 0.999 α ANR Flocculent anamnox studge $0.15-2.8$ $0.2-3.2$ 12.1 12.1 0.999 α ANR Flocculent anamnox studge $0.93-7.34$ $1.5-12$ 0.992 0.993 α ANR Flocculent anamnox studge $0.93-7.34$ </td <td></td> <td></td> <td>Anomahin dissection durdse</td> <td></td> <td>7T 0.T</td> <td>0.061</td> <td>114</td> <td>000</td> <td>5 5</td> | | | Anomahin dissection durdse | | 7T 0.T | 0.061 | 114 | 000 | 5 5 |
| T Upflow filter Cultured activated sludge $0.33-7.34$ $1.5-12$ 0.091 1.20 0.97 odel NMR Flocculent anamnox sludge $0.03-0.5$ 7.89 8.98 0.999 UMR Flocculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 7.89 8.98 0.999 UMR Cultured anamnox sludge $0.08-1.94$ $0.25-3.0$ 7.89 8.98 0.999 MR Cultured anamnox sludge $0.08-1.94$ $0.25-3.0$ 7.89 8.98 0.999 MR Cultured anamnox sludge $0.08-1.94$ $0.2-3.2$ 11.14 12.1 0.999 MR Flocculent anamnox sludge $0.15-2.78$ $0.2-3.2$ 12.1 12.7 0.999 MMR Anamnox granules $167-2.78$ $0.2-3.2$ 12.1 12.4 0.999 MMR Anamnox granules $167-2.78$ $0.2-3.2$ 12.11 11.4 0.999 MMR Flocculent anamnox sludge $0.93-7.34$ $1.5-12$ | | UASB | Anaeronic digestion siudge | 0.93-/.34 | 71-C.I | TC0.0 | 1.14 | 96.0 | 13 |
| T- Upflow filter Cultured activated sludge $0.93-7.34$ $0.08-0.6$ 12.4 $12.$ 0.979 odel AMMR Flocculent anammox sludge $0.10^{-}0.746$ $0.6-3.0$ 7.89 8.98 0.999 UASB Activated sludge $0.10^{-}0.746$ $0.5-3.0$ 7.89 8.98 0.999 MAR Cultured anamnox sludge $0.15-2.8$ $0.25-1.0$ 6.41 7.37 0.999 MAR Cultured anamnox sludge $0.15-2.8$ $0.25-1.0$ 6.41 7.37 0.999 MAR Flocculent anamnox sludge $115-12$ $0.6-2.9$ 8.98 0.999 ANMR Flocculent anamnox sludge $15-2.8$ $0.2-3.2$ 12.1 11.4 0.999 ANMR Flocculent anamnox sludge $10.1-1.99$ 12 11.4 0.999 ANMR Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ $1.11.10$ 0.994 VASB Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ $1.1.11.1$ | | | | 0.93 - 7.34 | 1.5 - 12 | 0.091 | 1.20 | 0.97 | 13 |
| T- Upflow filter Cultured activated sludge $0.93-7.34$ $0.08-0.6$ 12.4 12 0.99 videl NMR Flocculent anarmox sludge $0.10^{-0}.746$ $0.5-3.0$ 7.89 8.98 0.999 MAR Cultured anarmox sludge $0.15-2.8$ $0.25-3.0$ 7.89 8.98 0.999 MAR Cultured anarmox sludge $0.15-2.8$ $0.25-3.0$ 7.14 12.1 0.999 MAR Cultured anarmox sludge $0.15-2.8$ $0.25-3.0$ 5.41 7.37 0.999 ANMR Flocculent anarmox sludge $115-297$ $0.2-3.2$ 11.4 12.1 0.999 ANMR Flocculent anarmox sludge $115-297$ $0.2-3.2$ 12.1 11.4 0.999 ANMR Flocculent anarmox sludge $197-41.1$ $15-12$ 11.4 0.999 UASB Anarcobic digestion sludge $0.93-7.34$ $1.5-12$ $1.0.19$ 0.94 VAR Flocculent anarmox sludge $0.93-7.34$ $1.5-12$ | | | | | | $R_{ m m}$ | $K_{ m B}$ | | |
| | Modified stover- | Upflow filter | Cultured activated sludge | 0.93 - 7.34 | 0.08 - 0.6 | 12.4 | 12 | 0.979 | 69 |
| UASB Activated sludge $0.15-2.8$ $0.2-3.2$ 11.4 12.1 0.993 MAR Cultured anamnox sludge $0.08-1.94$ $0.25-1.0$ 6.41 7.37 0.993 AUF Anamnox sludge $0.08-1.94$ $0.25-1.0$ 6.41 7.37 0.993 AUF Anamnox sludge $157-297$ $0.2-3.2$ 12.1 12.4 0.993 ANMR Flocculent anamnox sludge $157-238$ $0.2-3.2$ 12.1 11.4 0.999 ANMR Flocculent anamnox sludge $157-238$ $0.2-3.2$ 12.1 11.4 0.999 UASB Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ 0.892 1.0119 0.94 MR Flocculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 0.1692 0.912 0.93 MR Flocculent anamnox sludge $0.17-0.746$ $0.6-3.0$ 0.1692 0.192 0.98 MAR Flocculent anamnox sludge $0.15-2.87$ $0.06-3.0$ 0.102 | Kincannon model | ANMR | Flocculent anammox sludge | 0.107 - 0.746 | 0.6 - 3.0 | 7.89 | 8.98 | 0.999 | 35 |
| | | UASB | Activated sludge | 0.15 - 2.8 | 0.2 - 3.2 | 11.4 | 12.1 | 0.999 | 16 |
| AUFAnamnox sludge10.1-1.991212.40.979ANMRFlocculent anamnox sludge $115-297$ $0.6-2.9$ 8.98 7.89 0.996 ANMRFlocculent anamnox sludge $157-278$ $0.2-3.2$ 12.1 11.4 0.999 UASBAnamnox granules $167-278$ $0.2-3.2$ 12.1 11.4 0.999 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 0.892 1.019 0.94 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 1.0119 0.94 UASBAnamnox granules $0.93-7.34$ $1.5-12$ 1.0119 0.98 UASBAnamnox sludge $0.93-7.34$ $1.5-12$ 1.0119 0.98 MMRFlocculent anamnox sludge $0.93-7.34$ $1.5-12$ 1.01109 0.98 MMRFlocculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 0.1692 0.192 0.986 MARFlocculent anamnox sludge $0.16-2.87$ $0.6-3.0$ 0.1692 0.773 0.432 0.925 0.996 UASBArtivated sludge $0.15-2.87$ $0.2-3.2$ 0.2256 0.0922 0.773 0.932 MARCultured anamnox sludge $0.86-1.94$ $0.2-3.2$ 0.2256 0.0924 0.773 UASBArtivated sludge $0.95-7.34$ $1.5-12$ 0.2246 0.0924 0.773 UASBArtivated sludge $0.93-7.34$ $1.5-12$ $-1.5-12$ 0.2246 0.0924 0.7725 UASB< | | MAR | Cultured anammox sludge | 0.08 - 1.94 | 0.25 - 1.0 | 6.41 | 7.37 | 0.993 | 11 |
| MMRFlocculent anamox sludge115-297 $0.6-2.9$ 8.98 7.89 0.9986 UASBAnamnox granules $167-278$ $0.2-3.2$ 12.1 11.4 0.9986 UASBAnamnox granules $167-278$ $0.2-3.2$ 12.1 11.4 0.9986 UASBAnaerobic digestion sludge $167-278$ $0.2-3.2$ 12.1 11.4 0.9986 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 0.892 1.019 0.94 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 3.333 4.037 0.98 ANMRFlocculent anamnox sludge $0.93-7.34$ $1.5-12$ 3.333 4.037 0.98 ANMRFlocculent anamnox sludge $0.93-7.34$ $1.5-12$ 3.333 4.037 0.98 ANMRFlocculent anamnox sludge $0.107-0.746$ $0.6-0.33$ 0.6032 0.192 0.739 MARCultured anamnox sludge $0.15-2.87$ $0.6-0.33$ 0.632 0.107 0.793 UASBActivated sludge $0.15-2.87$ $0.2-3.22$ 0.225 0.0922 0.773 MARCultured anamnox sludge $0.75-2.87$ $0.2-3.22$ 0.2025 0.0922 0.773 UASBActivated sludge $0.98-1.94$ $0.2-3.22$ 0.225 0.0922 0.773 UASBActivated sludge $0.93-7.34$ $1.5-12$ 2.246 0.0922 0.773 UASBActivated sludge $0.93-7.34$ $1.5-12$ 2.46 0.0922 | | AUF | Anammox sludoe | | 10.1-1.99 | 12. | 12.4 | 0.979 | 12 |
| MARE Anamnox granules $157-278$ $0.2-2.7$ 0.290 0.290 UASB Anamnox granules $167-278$ $0.2-3.2$ 12.1 11.4 0.999 UASB Activated sludge $191-411$ $157-278$ $0.2-3.2$ 12.1 11.4 0.999 VASB Activated sludge $0.93-7.34$ $1.5-12$ 0.892 1.019 0.94 VASB Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ 1.0110 0.98 ANMR Flocculent anamnox sludge $0.93-7.34$ $1.5-12$ 3.33 4.037 0.98 ANMR Flocculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 0.169 0.192 0.599 EGSB Anamnox granules $0.15-2.87$ $0.66-0.33$ 0.632 0.092 0.773 MAR Cultured anammox sludge $0.15-2.87$ $0.2-3.22$ 0.107 0.996 MAR Cultured anammox sludge $0.15-2.87$ $0.225-3$ 0.092 0.773 MAR <td></td> <td>ANIMP</td> <td>Elocations anomnov chidae</td> <td>115-307</td> <td>0 6-2 0</td> <td>0 00</td> <td>00 2</td> <td>0 0006</td> <td>1 7</td> | | ANIMP | Elocations anomnov chidae | 115-307 | 0 6-2 0 | 0 00 | 00 2 | 0 0006 | 1 7 |
| UASIS Anaminox grammes $10^{1-2.18}$ $0.2^{-5.12}$ 12.1 11.4 0.999 VASIS Activated sludge $0.91-411$ $15-12$ 0.892 1.019 0.94 VASIS Ancerobic digestion sludge $0.93-7.34$ $1.5-12$ 0.892 1.019 0.98 VASIS Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ 1.0110 0.98 ANMR Flocculent anammox sludge $0.93-7.34$ $1.5-12$ 3.33 4.037 0.98 ANMR Flocculent anammox sludge $0.107-0.746$ $0.6-3.0$ 0.169 0.192 0.599 EGSIS Anammox granules $0.76-22.87$ $0.06-0.33$ 0.632 0.773 0.995 UASIS Activated sludge $0.772-2.887$ $0.2-3.2$ 0.2022 0.773 0.995 UASIS Anamox granules $0.16-2.2.87$ $0.2-3.2$ 0.2025 0.0924 0.773 UASIS Anamox granules $167-278$ $0.2-3.2$ 0.2246 0.0924 | | | r locculont anamino studgo | | 0.0 0.0 | 10.0 | · · · · | 00000 | ₽ L |
| Activated sludge $0.37-7.34$ $1.5-12$ 0.892 1.019 0.94 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 0.892 1.019 0.98 UASBAnaerobic digestion sludge $0.93-7.34$ $1.5-12$ 1.3 1.110 0.98 ANMRFloculent anamnox sludge $0.93-7.34$ $1.5-12$ 3.33 4.037 0.98 ANMRFloculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 0.169 0.192 0.399 EGSBAnamnox granules $0.76-22.87$ $0.6-0.33$ 0.632 0.092 0.773 MARCultured anamnox sludge $0.15-2.8$ $0.25-1.0$ 0.952 0.092 0.773 MARCultured anamnox sludge $0.15-2.8$ $0.2-3.2$ 0.225 0.092 0.773 UASBAnamnox granules $167-278$ $0.2-3.2$ 0.2255 0.0924 0.773 UASBAnamnox granules $167-278$ $0.2-3.2$ 0.2326 0.0924 0.7725 UASBActivated sludge $0.93-7.34$ $1.5-12$ $ -$ UASBActivated sludge $0.93-7.34$ $1.5-12$ $ -$ UASBActivated sludge $0.93-7.34$ $1.5-12$ $ -$ Distributed sludge $0.93-7.34$ $1.5-12$ $ -$ | | OADD | Analimox granules | 10/-2/8 101-111 | 0.2-3.4 | 1.21 | 11.4 | 666.0 | CT |
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| UASB Anaerobic digestion sludge $0.93-7.34$ $1.5-12$ 1 1.110 0.98 NMR Floculent anamnox sludge $0.93-7.34$ $1.5-12$ 3.33 4.037 0.98 ANMR Floculent anamnox sludge $0.107-0.746$ $0.6-3.0$ 0.169 0.192 0.599 EGSB Anamnox granules $0.76-22.87$ $0.06-0.33$ 0.632 0.192 0.599 MAR Cultured anamnox sludge $0.15-2.87$ $0.06-0.33$ 0.632 0.208 0.986 MAR Cultured anamnox sludge $0.15-2.8$ $0.2-3.2$ 0.225 0.092 0.773 MAR Cultured anamnox sludge $0.93-7.34$ $1.5-12$ 0.225 0.0924 0.773 VASB Anamox granules $167-278$ $0.2-3.2$ 0.2246 0.0924 0.773 UASB Activated sludge $0.93-7.34$ $1.5-12$ $ -$ | | | Activated sludge | 0.93 - 7.34 | 1.5 - 12 | 0.892 | 1.019 | 0.94 | 13 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | | UASB | Anaerobic digestion sludge | 0.93 - 7.34 | 1.5 - 12 | 1 | 1.110 | 0.98 | 13 |
| ANMRFlocculent anamnox sludge $0.107-0.746$ $0.6-3.0$ R_m K_s EGSBAnamnox granules $0.76-22.87$ $0.6-0.33$ 0.169 0.192 0.599 EGSBAnamnox granules $0.76-22.87$ $0.06-0.33$ 0.632 0.208 0.986 UASBActivated sludge $0.15-2.8$ $0.2-3.2$ 0.225 0.092 0.773 MARCultured anamnox sludge $0.8-1.94$ $0.2-3.2$ 0.225 0.092 0.773 UASBAnamnox granules $167-278$ $0.2-3.2$ 0.2246 0.0924 0.773 UASBActivated sludge $0.93-7.34$ $1.5-12$ 0.2246 0.0924 0.7725 UASBActivated sludge $0.93-7.34$ $1.5-12$ $ -$ | | | | 0.93 - 7.34 | 1.5 - 12 | 3.33 | 4.037 | 0.98 | 13 |
| ANMR Flocculent anamnox sludge 0.107-0.746 0.6-3.0 0.169 0.192 0.599 EGSB Anamnox granules 0.76-22.87 0.06-0.33 0.632 0.208 0.986 UASB Activated sludge 0.15-2.8 0.06-0.33 0.632 0.208 0.986 UASB Activated sludge 0.15-2.8 0.2-3.2 0.225 0.092 0.773 MAR Cultured anamnox sludge 0.15-2.8 0.2-3.2 0.225 0.092 0.773 MAR Cultured anamnox sludge 0.08-1.94 0.2-3.2 0.225 0.092 0.773 UASB Anamnox granules 167-278 0.2-3.2 0.2246 0.0924 0.725 UASB Activated sludge 0.93-7.34 1.5-12 - - - - Maerobic digestion sludge 0.93-7.34 1.5-12 - | | | | | | $R_{ m m}$ | $K_{ m s}$ | | |
| Anammox granules 0.76–22.87 0.06–0.33 0.632 0.208 0.986 Activated sludge 0.15–2.8 0.2–3.2 0.225 0.092 0.773 Activated anammox sludge 0.08–1.94 0.2–3.2 0.225 0.092 0.773 Anamnox granules 167–278 0.2–3.2 0.2246 0.0924 0.725 Activated sludge 0.93–7.34 1.5–12 0.2246 0.0924 0.775 Anaerobic digestion sludge 0.93–7.34 1.5–12 - - - | Monod model | ANMR | Flocculent anammox sludge | 0.107 - 0.746 | 0.6 - 3.0 | 0.169 | 0.192 | 0.599 | 35 |
| Activated sludge 0.15-2.8 0.2-3.2 0.225 0.092 0.773 Cultured anammox sludge 0.08-1.94 0.25-1.0 0.952 0.107 0.933 Anamnox granules 167-278 0.2-3.2 0.246 0.0924 0.775 Activated sludge 0.93-7.34 1.5-12 0.2246 0.0924 0.7725 Anaerobic digestion sludge 0.93-7.34 1.5-12 - - - | | EGSB | Anammox granules | 0.76 - 22.87 | 0.06 - 0.33 | 0.632 | 0.208 | 0.986 | 75 |
| Cultured anamox sludge 0.08-1.94 0.25-1.0 0.952 0.107 0.993 Anamox granules 167-278 0.2-3.2 0.246 0.0924 0.7725 Activated sludge 0.93-7.34 1.5-12 - - - - Anaerobic digestion sludge 0.93-7.34 1.5-12 - - - - | | UASB | Activated sludge | 0.15 - 2.8 | 0.2 - 3.2 | 0.225 | 0.092 | 0.773 | 16 |
| Anamnox granules 167–278 0.2–3.2 0.2246 0.0924 0.7725 Activated sludge 0.93–7.34 1.5–12 - | | MAR | Cultured anammox sludge | 0.08 - 1.94 | 0.25 - 1.0 | 0.952 | 0.107 | 0.993 | 11 |
| Activated sludge 0.93–7.34 1.5–12 — — — — — — — — — — — — — — — — — — — | | UASB | Anammox granules | 167 - 278 | 0.2 - 3.2 | 0.2246 | 0.0924 | 0.7725 | 15 |
| Activated sludge 0.93–7.34 1.5–12 — — — — — — — — — — — — — — — — — — — | | | ¢ | 191 - 411 | | | | | |
| ion sludge | | UASB | Activated sludge | 0.93 - 7.34 | 1.5 - 12 | | | | 13 |
| | | | Anaerobic digestion sludge | | | | | | |

 Table 5
 Most popular kinetic models used for the activity simulation^a

| Simulation equations | Reference |
|---|-----------|
| $q = \frac{Sq_{\max}}{K_{\rm s} + S + \frac{S^2}{K_{\rm I}}}$ | 76 |
| $\begin{pmatrix} & S \end{pmatrix} \begin{pmatrix} & S \end{pmatrix}$ | 77 |

$$q = q_{\max}\left(\exp\left(-\frac{S}{K_{I}}\right) - \exp\left(-\frac{S}{K_{S}}\right)\right)$$

$$q = q_{\max}\left(1 - \exp\left(-\frac{S}{K_{S}}\right)\right)$$
78

$$r = \frac{Sr_{\max}}{K_{e} + S + \frac{S^{2}}{S}}$$
79

$$r = \frac{Sr_{\max}(1 - S/S_{\mathrm{m}})^{n}}{K_{\mathrm{s}} + S}$$
80

$$r = \frac{Sr_{\max}(1 - S/S_{m})^{n}}{S + K_{s}(S/S_{m})^{m}}$$
81

$$= \frac{Sr_{\max}}{K_{\rm s} + S} \exp\left(-\frac{S}{k_{\rm ip}}\right)$$
⁸²

^{*a*} Where *q* is the specific substrate conversion rate constant (d^{-1}) ; q_{max} is the maximum specific substrate conversion rate constant (d^{-1}) ; K_s is the half saturation constant (mg N L⁻¹); K_I is the inhibition constant (mg N per L); K_{IH} is the inhibition constant of Haldane (mg N per L); k_{ip} is the inhibition constant of Aiba; r_{max} is the maximum specific activity (mg L⁻¹); S_m is the maximum removal efficiency (mg L⁻¹ d⁻¹).

determining the kinetic constants in immobilized bioreactors. Also, it was reported that the Stovere–Kincannon model has been investigated in continuously operated mesophilic and thermophilic upflow anaerobic filters for the treatment of soybean wastewater, paper pulp liquors, and simulated starch wastewater, and the determination of kinetic constants in a packed bed reactor for decolonization.¹¹

A detailed comparison of different substrate removal kinetic models for anammox reactors is listed in Table 4. Compared with the various processes conducted in the UASB, MAR, ANMR and up-filters, the result of the first-order simulation showed that the UASB had the highest K_1 of 11.64 (d⁻¹) with R^2 being 0.80, and the up-filter had the lowest K_1 of 0.43 (d⁻¹) with R^2 being 0.439.^{12,15} All of the first-order simulations proved that R^2 was low, indicating the poor fitting of the data. While these data simulated by second-order simulation proved a higher R^2 , which was 0.99 or 0.98, respectively. Meanwhile, the modified Stover-Kincannon also gave a high R² of 0.98 in a UAF system.¹² In the UASB system, among the most commonly used modified Stover-Kincannon model, R_{max} varied from 15 to 476, as reported due to the different operational conditions.41,42 The difference in the U_{max} values was probably due to the different adopted reactor configurations, different treated wastewater characteristics and developed microorganisms in various studies. The Stover-Kincannon model was suitable for the kinetic analysis of a complicated anaerobic process. This is partially due to the simplification of this model without diffusion of the modeling substrate, hydraulic dynamics and other

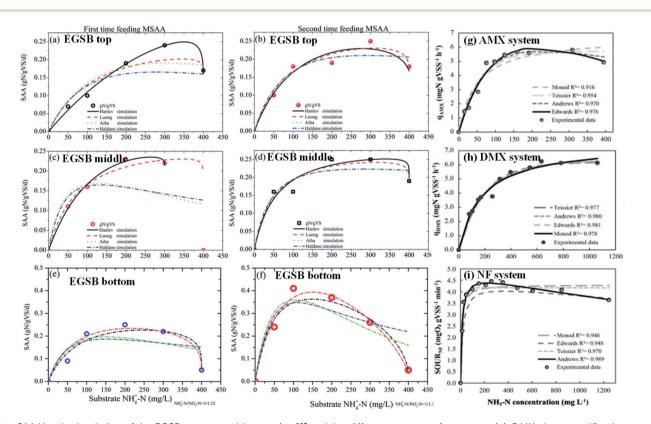


Fig. 4 SAA kinetic simulation of the EGSB-anammox biomass $(a-f)^{13}$ and the different systems of anammox (g), DMX-deammonification system (h), and NF-nitrifying system (i).⁴³

Review

parameters, which might be key factors for the reactor performance, but were difficult to measure. The methods of validity assessment between the experiment and prospect can be conducted by the linear regression equation, y = x (Fig. 3). The modified Stover-Kincannon model and the Grau second-order model are both practical because in the case that $U_{\rm max}$ is equal to $k_{\rm B}$, the Grau second-order model can be transformed to the modified Stover-Kincannon model. Thus, the total nitrogen concentration in the effluent predicted by the Grau secondorder and modified Stover-Kincannon models may display high correlation with actual measured data. Conversely, the Monod model and the first-order model were proven to be not feasible in many cases. The Grau second-order model and the modified Stover-Kincannon model were both acceptable to predict the total nitrogen concentration in the effluent since their plot lines nearly coincided with the actual line (Fig. 3). The process kinetic models also illustrated that the substrate concentration and granule size should be carefully controlled as the main process parameters. Different types of kinetic models should be used to obtain the appropriate model. For the activity test simulations, most popular kinetic models used for the activity simulation are shown in Table 5. The specific anammox activity (SAA) kinetic simulation of the EGSB-anammox biomass (a-f)¹³ and the differences between the anammox (g), DMXdeammonification system (h), and the NF-nitrifying system (i)⁴³ were compared and verified (Fig. 4). Other simple kinetic ASM1 models for granular biomass floatation were also investigated.44 Among the kinetic models, the basic Monod equation for the DMX process, the extended Edwards and Luong equation for the AMX process, and the Andrews equation for the NF process were used and validated to be the most appropriate equations for the process.

A simplified kinetic model lacks the capacity of expressing the detailed mechanism, but it can be used to properly describe the main characteristics of a reaction. A good model not only provides a better understanding of the complex biological and chemical fundamentals, but is also fundamental for the process design, start-up, dynamics predictions, and process control and optimization. Obviously, the simplified models with limited variables, which are confirmed suitable for practical engineering applications, were proved to be powerful tools for anammox at low growth rates. Although different kinetic models were investigated to describe the anammox process carried out in different reactors, the modified Stover-Kincannon and Grau second-order models seemed to be the most suitable for describing nitrogen removal.4,12,37 However, these models still had problems since the limitations of these kinetic models cannot describe cellular metabolism and regulation. Moreover, these models did not give any insight to the variables that could influence cell growth. In addition, these models shall be further modified when the special phase of the process was simulated to get the actual kinetics. More analysis methods and technologies for a more in-depth study shall be extensively carried out with the purpose of improving the understanding of the reaction mechanisms and microbial community dynamics.

6. Conclusions

In the review, the process-kinetics of different anammox configurations with process performance was investigated. Among the configurations, SBR, UASB and MBR were the most commonly used and favored for bacterial accumulation. The simulation models of the kinetics were proved as valuable information for process construction and rector operation. The kinetic model validation proved that the modified Stover-Kincannon model and Graus second-order model could be appropriate for different reactor anammox processes. Rather than the correlation coefficient, the validation revealed that the modified Stover-Kincannon model was more appropriate for nitrogen removal kinetics in most configurations. Based on the simulation of correlated indexes, the activity kinetic models illustrated that the modified Han-levenspiel, Luong and Andrews models were the most appropriate kinetic models for the activity simulation in the anammox process. The appreciate configurations could improve the denitrification efficiency, and contribute to the biomass enrichment in the projects of engineering application.

Conflicts of interest

There are no conflicts of interest to declare.

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