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Kinetic equation of aerobic granular sludge cultivation in a Sequencing Batch Reactor (SBR) treating municipal wastewater in Vietnam

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KEYWORDS

Granular sludge
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ABSTRACT

During the formation of aerobic granular sludge in wastewater treatment systems, numerous factors influence the granulation time, granule size, and structural stability of the sludge. The kinetics of granule formation are associated with the increase in granule size over the cultivation period. Kinetic-related factors include the influent organic loading rate, aeration intensity, and the nitrogen-to-COD (N/COD) ratio. In this study, the kinetic equation and the kinetic profile of aerobic granular sludge cultivation using Sequencing Batch Reactor (SBR) technology for domestic wastewater treatment under laboratory conditions in Vietnam are presented. The research was conducted using a laboratory-scale SBR model with a reactor diameter of 0.110 m, a height of 1 m, and a working volume of 2.5 L. Each operational cycle lasted 4 hours and consisted of four phases: a feeding phase of 1–2 minutes, an aeration phase of 180 minutes, a settling phase of 20–30 minutes, and a discharge phase of 10–15 minutes. The influent wastewater with an organic loading rate ranging from 2.7 to 3.0 kg COD/m^3·day. The total experimental duration was 140 days. The results indicated that the kinetic model could successfully predict the formation and development of aerobic granular sludge with a reliability coefficient of 0.985 ($R^2 \approx 0.98$).

1. Introduction

Urban wastewater treatment is one of the critical issues for maintaining sustainable environmental development. However, to date, only approximately 10–20 % of urban wastewater in Vietnam has been collected and treated [2].

Various wastewater treatment technologies have been applied in Vietnam; nevertheless, no full-scale treatment plant has yet implemented aerobic granular sludge technology. The application of aerobic granular sludge for wastewater treatment in Vietnam remains at the laboratory research stage.

Globally, aerobic granular sludge has been applied in Sequencing Batch Reactors (SBR) since the 1970s [1] and has subsequently been extensively investigated using various substrates, including glucose, acetate, ethanol, molasses, sucrose, starch, phenol, phthalic acid, chloroanilines, tert-butyl alcohol, and other synthetic wastewater components [3]. Numerous studies have demonstrated that aerobic granular sludge can be widely applied to different substrates and wastewater types. International research has also shown that aerobic granular sludge can adapt to wastewater with varying organic loading rates.

Compared with conventional activated sludge, aerobic granular sludge exhibits a well-defined granular structure, high biomass retention capacity, and the ability to treat toxic compounds present in wastewater [4]. In addition to effective carbon removal, aerobic granular sludge is capable of removing nitrogen and phosphorus [5; 9]. Therefore, it has been applied to the treatment of domestic wastewater, food processing wastewater, livestock wastewater, industrial wastewater, tannery wastewater, slaughterhouse wastewater, and brewery wastewater [5; 8].

The successful cultivation of aerobic granular sludge under Vietnamese laboratory conditions, using municipal wastewater collected from the influent of a wastewater treatment plant in Hanoi, represents a novel and practically significant research outcome. The authors successfully developed a kinetic model describing the aerobic granular sludge cultivation process. The results enable prediction of the formation and development of aerobic granular sludge with a reliability coefficient of 0.985 ($R^2 \approx 0.98$).

2. Materials and Methods

The research subject of this study was aerobic granular sludge. The experiments were conducted under laboratory conditions in Vietnam using two cylindrical Sequencing Batch Reactor (SBR) models made of transparent acrylic. Each reactor had a diameter of 0.11 m and a total height of 1 m, with a working water height of 0.8 m and an effective working volume of 2.5 L.

The SBR system operated at six cycles per day, with each cycle lasting 4 hours. Each operational cycle consisted of four phases: a feeding phase of 1–2 minutes, an aeration phase of 180 minutes, a settling phase of 20–30 minutes, and a discharge phase of 10–15 minutes.

The influent used for aerobic granular sludge cultivation was municipal wastewater with an organic loading rate (OLR) ranging

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from 2.7 to 3.0 kg COD/m^3·day, which is consistent with the typical characteristics of urban wastewater in Vietnam.

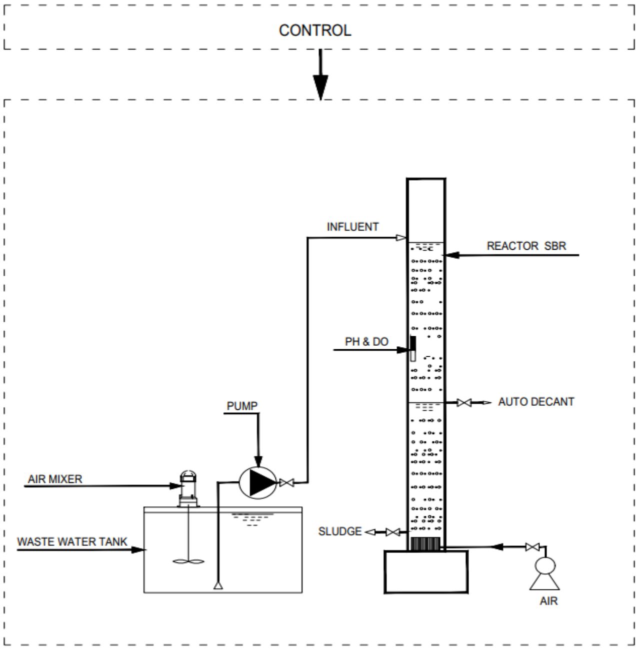

Figure 1. Schematic diagram of the experimental Sequencing Batch Reactor (SBR) model.

3. Results and Discussion

After 140 days of aerobic granular sludge cultivation under laboratory conditions using wastewater with a relatively low organic loading rate (OLR) of 2.7–3.0 kg COD/m^3·day, well-developed aerobic granules were successfully formed. The predominant granule size ranged from 3 to 5 mm, accompanied by significant growth of filamentous bacteria.

The granules exhibited a spherical morphology with smooth surfaces and a yellow-brown color. They demonstrated good settling ability, with a settling efficiency exceeding 80 %.

Based on the granulation results, the authors established a kinetic equation describing the granule formation process. After 140 days of experimental cultivation, a kinetic model for the formation of aerobic granular sludge was successfully developed as follows:

$$D = 4{,}306(1 - e^{-0{,}03665t})$$

Where:

D – diameter of aerobic sludge granules at a given time (mm);

t – time at which the granule size is determined (days).

The above kinetic equation describes the formation process of aerobic granular sludge in a Sequencing Batch Reactor (SBR) operated with a settling time of 20–25 minutes, an aeration flow rate of 1.5–5.0 L/min, and a superficial air velocity of 12.5–28.5 m^3/m^2·h. The influent wastewater had an N/COD ratio of approximately 0.2, corresponding to an organic loading rate (OLR) of 2.7–3.0 kg COD/m^3·day and a pH range of 6.1–8.0.

Operational parameters and wastewater characteristics significantly influenced the granulation rate, lag phase duration, and equilibrium granule diameter (De) determined in this study, which are consistent with previously published international research. At an OLR of 2.7–3.0 kg COD/m^3·day, the equilibrium granule diameter (De) was determined to be 4.3 mm, which is larger than the values reported in comparable studies [6].

Yang et al. (2003) reported that when the OLR increased from 1.5 to 3 and 9 kg COD/m^3·day, the equilibrium granule diameter (De) increased from 1.5 to 1.7 and 2.0 mm, respectively [7; 10].

A higher organic content stimulates biofilm structure formation, enhances microbial density, and promotes the growth of heterotrophic aerobic biomass responsible for carbohydrate oxidation in wastewater. A relatively high N/COD ratio (approximately 0.2) corresponded to a lag phase of 5–7 days and a granule growth rate of $\mu = 0.03665\ day^{-1}$, which was relatively slow in this study. This phenomenon can be explained by the slower formation and growth rate of nitrifying bacteria compared to heterotrophic aerobic bacteria. Therefore, a higher N/COD ratio tends to prolong the lag phase and reduce the final granule size in the reactor.

Aeration intensity and airflow rate also influence the specific growth rate (μ) of aerobic granular sludge and the equilibrium granule diameter (De) within the reactor system. Yang et al. (2003) reported shear forces corresponding to superficial air velocities in the range of 1.2–3.6 cm/s, which were higher than those applied in the present study [11].

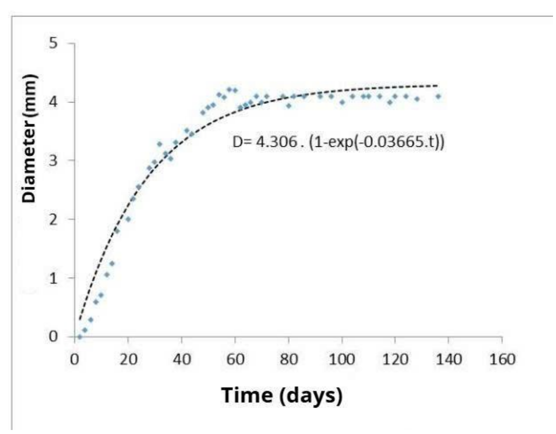

Figure 2. Kinetics of aerobic granular sludge formation and development at an organic loading rate (OLR) of 2.7–3.0 kg COD/m^3·day.

Previous studies have indicated that higher aeration intensity and shear force tend to reduce both granule diameter and the granulation rate. Therefore, a lower aeration intensity range (corresponding to a superficial air velocity < 1.2 cm/s) is generally recommended, provided that sufficient aerobic–anoxic phase conditions are maintained in the SBR system.

However, due to the limited variation in operational regimes and wastewater characteristics investigated in this study, the influence of operating parameters and influent characteristics on the granulation rate, lag phase duration, and equilibrium granule diameter (De) requires further comprehensive investigation. Future studies should expand the experimental conditions to include a broader range of operational settings and real wastewater types.

The chart illustrates the growth process of aerobic granular sludge diameter over a cultivation period of 160 days. It can be observed that during the first 60 days, the granule diameter increased most rapidly, indicating an intensive formation and development phase of the granular structure. Beyond this period, the granule size continued to increase; however, the growth rate gradually decreased, suggesting a transition toward a more stable and mature stage of granule development over time.

The kinetic model results demonstrated that the formation and development of aerobic granular sludge could be predicted with a reliability coefficient of 0.985 ($R^2 \approx 0.98$), corresponding to approximately 98 % predictive accuracy. The table below presents the calculated diameters of aerobic granular sludge during the first 60 days of cultivation, based on the kinetic equation of the granulation process.

Table 1. Predicted aerobic granular sludge diameter based on the kinetic equation in 60 days.

Time (t) - days	Granule Diameter (D) - mm	Time (t) - days	Granule Diameter (D) - mm	Time (t) - days	Granule Diameter (D) - mm
0	0	21	2.31	41	3.35
1	0.15	22	2.38	42	3.38
2	0.30	23	2.45	43	3.42
3	0.45	24	2.52	44	3.45
4	0.59	25	2.58	45	3.48
5	0.72	26	2.65	46	3.51
6	0.85	27	2.71	47	3.54
7	0.97	28	2.76	48	3.56
8	1.09	29	2.82	49	3.59
9	1.21	30	2.87	50	3.62
10	1.32	31	2.92	51	3.64
11	1.43	32	2.97	52	3.67
12	1.53	33	3.02	53	3.69
13	1.63	34	3.07	54	3.71
14	1.73	35	3.11	55	3.73
15	1.82	36	3.16	56	3.75
16	1.91	37	3.20	57	3.77
17	2.00	38	3.24	58	3.79
18	2.08	39	3.27	59	3.81
19	2.16	40	3.31	60	3.83
20	2.24				

4. Conclusion

The successful cultivation of aerobic granular sludge in a laboratory-scale Sequencing Batch Reactor (SBR) treating municipal wastewater in Vietnam provides a promising new approach for wastewater treatment technology in the country.

The successful development of a kinetic model describing the granulation process at an organic loading rate (OLR) of 2.7–3.0 kg COD/m^3·day enables accurate prediction of the formation and development of aerobic granular sludge, with a reliability coefficient of 0.985 ($R^2 \approx 0.98$).

These findings create favorable conditions for further research and potential application of aerobic granular sludge technology in municipal wastewater treatment in Vietnam.

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