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# Effect of primary sludge to waste activated sludge mixing ratio on anaerobic digester performance

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**A B S T R A C T**

In this research, the effect of mixing ratio between primary sludge (PS) and waste activated sludge (WAS) on anaerobic digester performance was investigated. PS to WAS ratios of 65% PS/35% WAS v/v, 50% PS/50% WAS v/v, 35% PS/65% WAS v/v were assessed for a sludge retention time of 23 d at mesophilic temperature of 36.5°C. The sludge with the mixing ratio of 65/35 v/v produced the highest amount of methane for 500 mL digester volume considered in the study. This particular mixing ratio is similar to the large scale operational condition in Beenyup Wastewater Treatment Plant, Western Australia. The kinetics of the digestion process was faster for this mixing ratio. In addition, methane to carbon dioxide ratio for this mixing ratio of 65/35 v/v was found to be the highest (2.5–3.1). Sludge biodegradability in terms of reduction of total chemical oxygen demand was 46.6%, 53.7% and 72.3% and volatile solid removal was 32.6%, 25.8% and 34% for mixing ratios of (65/35, 50/50, 35/65)v/v, respectively. The sludge sample with greater proportion of WAS showed better dewaterability. In general, mixed sludge with higher proportion of PS has better effects on overall digester performance.

*Keywords:* Dewaterability; Kinetic parameters; Sludge mixing ratio; Wastewater treatment

## 1. Introduction

Anaerobic digestion is a biological degradation of organic biomass in oxygen-deficient or oxygen-free environment by a complex microbial consortium. During the process, the digestible organic biomass mainly produces methane, carbon dioxide, energy and other organic by-products. The nitrogen which is not used for microbial growth will be released as ammonia [1–3]. It is an efficient sludge treatment technology used in a number of municipal wastewater treatment plants to stabilize organic matter. Mass reduction, methane production and improved dewatering properties of the treated sludge are the main features of this process [4]. Biogas production through anaerobic digestion has recently captured global attention because of its substantial benefits including eco-friendly energy generation, greenhouse gas emission reduction, high organic removal from effluent and production of fertilizers. It is rated as one of the most energy-efficient and environmentally beneficial technologies for bioenergy production [5–7]. Mass reduction, methane production and improved dewatering properties of the treated sludge are the main features of this process [8]. It is a very effective sludge treatment technology applied in municipal and industrial wastewater treatment plants to stabilize organic matter [9].

The process involves four major microbiological degradation steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. One of the disadvantages of anaerobic digestion technique is the slow hydrolysis of microorganisms that accounts for 70% of waste sludge which is the primary degradation step in the anaerobic digestion process [9]. The microorganisms in the waste sludge contain extracellular polymeric substances (EPS) that are resistant

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to biodegradation which in turn limits the rate of the whole anaerobic digestion process [10]. Sludge disintegration, solubilization and enzymatic hydrolysis are mostly represented in general kinetic term of hydrolysis for most practical application as hydrolysis is the slowest rate determining step in the process [11]. Acidogenesis stage is considered to be the fastest step in the methanogenesis process. There should be a balance between the different steps of the process for enhanced methane production. The overall rate is determined by the slowest rate-limiting step for multistep reactions of this kind. The rate-limiting step in anaerobic digestion process with suspended organic matter is the hydrolysis of step [12–14].

The advantages of anaerobic digestion process over aerobic digestion is the production of minimum waste sludge [15]. Different types of sludge are subjected to the anaerobic digestion process in wastewater treatment plants. Primary sludge (PS) which is also called raw PS comes from the bottom of the primary clarifier. It is easily digestible as it consists of highly degradable carbohydrates and fats, compared with activated sludge which consists of complex carbohydrates, proteins and long-chain hydrocarbons. Hence, biogas production from PS is easily digestible unless it contains less digestible complex organics like cellulose and lignin [15]. Activated sludge, waste sludge or waste activated sludge (WAS) is the output of the secondary treatment process. It is the result of over production of microorganisms and is more difficult to digest than PS [15].

Process kinetics plays a central role in the development and operation of anaerobic treatment systems. Based on the biochemistry and microbiology of the anaerobic process, kinetics provides a rational basis for process analysis, control and design. In addition to the quantitative description of the rates of waste utilization, process kinetics also deals with operational and environmental factors affecting these rates. A sound knowledge of kinetics allows the optimization of performance, a more stable operation as well as better control of the process [16].

Anaerobic digestion efficiency is increased with increasing total solids (TSs) concentration. Therefore, the TS contents should be optimized by considering both the disintegration efficiency and the anaerobic digestibility efficiency [17].

In this study, the effect of PS to WAS mixing ratio on anaerobic digester performance based on methane production capacity, solid reduction capacity, process kinetics, microbial content and sludge dewaterability was investigated experimentally. Determining the optimum mixing ratio enhances methane production, effluent sludge quality, dewaterability and pathogen removal and overall plant economy. Hence, thorough investigation on the effect of operational parameters like TS content and PS to WAS mixing ratio is essential for all different sludge types [18].

## 2. Materials and methods

### *2.1. Sampling and characterization*

PS was collected from PS gallery, primary sedimentation tank No. 4, and WAS was collected from Module 4 of the secondary treatment section of BWWTP, Western Australia. PS and WAS samples were mixed with ratios of 65/35, 50/50 and 35/65 v/v and 500 mL of sludge sample with these ratios were introduced to the jacketed digesters. Later, samples were withdrawn from each anaerobic digester for characterization purpose. The characteristics of sludge fed to the three digesters are presented in Table 1.

### *2.2. Experimental setup for methane potential and sludge biodegradability tests*

In the experimental setup, the biochemical methane potential tests were conducted in 1 L continuously stirred batch anaerobic digesters. These simultaneously operating three single-stage digesters were kept at a mesophilic temperature of 36.5°C and were first fed with 50 mL digested sludge as seed for inoculation purpose. The digesters were acclimated with digested sludge for 5 d and were separately fed with equal 450 mL of mixed sludge samples with the characteristics as given in Table 1. The pH in each digester was adjusted to 7.0 using sodium hydroxide and/or hydrochloric acid. The methane generated was allowed to pass through buffer tanks to remove any condensate before the gas volume was measured in inverted cylinders by water displacement technique at a temperature of 22°C. The biogas composition and other parameters were continuously monitored until biogas generation ceased after 23 d of digestion.

### *2.3. Analytical methods*

All the characterization and monitoring tests required for the experimental work in this study including determination of TS, volatile solid (VS), soluble chemical oxygen demand (SCOD), total chemical oxygen demand (TCOD), pH, dewaterability (capillary suction time, CST) were conducted. The total and VS content were determined according to [19]. pH was measured with WP-90 and WP-81 conductivity/total dissolved solids (TDS)–pH/temperature meter equipped with a glass electrode according to [19]. pH was measured before and during the anaerobic digestion process on regular basis. Total and SCOD was determined by using oxidation method with Hach COD reagent and colorimetric analysis on Orion UV/Vis spectrometer. Bicarbonate alkalinity was measured as alkalinity according to [19]. The biogas composition was measured using biogas analyzer (Thermo Fisher Scientific GA 2000 plus). The concentration of ammonia and hydrogen sulphide was monitored by this gas meter in addition to the other components of the biogas. Temperature measurement was conducted using WP-90 and WP-81 conductivity/TDS–pH/temperature meter during all analytical techniques to ensure consistency of the results. The dewaterability of different sludge samples was measured using CST (Type 304 CST equipment).

Table 1
Characteristics of feed sludge with different mixing ratios

| Parameter | Digester 1 (65/35) | Digester 2 (50/50) | Digester 3 (35/65) |
|---|---|---|---|
| TS (%) | 2.1 | 1.4 | 1.5 |
| VS (% TS) | 89.1 | 86.2 | 87 |
| TCOD (g/L) | 53.3 | 44.4 | 40.1 |
| pH | 7.1 | 7.1 | 7.2 |

*2.4. Determination of hydrolysis rate constant, lag time and daily methane production based on Gompertz equation*

It is known that the hydrolysis step is the rate-limiting process which ultimately determines the rate of methanogenesis and the overall performance of the digestion process. There are several model equations used for the determination of the hydrolysis rate constant. In this work, the lag-phase before the start of methane production, the methane production potential and the maximum methane production rate were determined using the Gompertz equation as shown in Eq. (1):

$$M = P \times \exp\left\{-\exp\left|\frac{Rm \times e}{p}(\lambda - t) + 1\right|\right\} \quad (1)$$

where $M$ is the cumulative methane production (mL), $P$ is the methane production potential (mL), $Rm$ the maximum methane production rate (mL/d), $\lambda$ is the duration of the lag phase (d) and $t$ is the duration of anaerobic digestion time in which cumulative methane production $M$ is calculated (d).

*2.4.1. Determination of hydrolysis rate constant*

The rate of hydrolysis is the key step in anaerobic digestion process that determines the methane production rate, sludge retention time and overall performance of the digester. Determination of the hydrolysis rate constant helps to quantitatively understand the kinetics of the process [20]. Hydrolysis rate constant $K$ for the anaerobic digestion experiment on the effect of mixing ratio was described as first-order rate kinetics. Thus, the production of methane was assumed to follow Eq. (2):

$$M = P.(1 - \exp(-Kt)) \quad (2)$$

where $M$ represents the cumulative methane production (mL) at time $t$ (d), $P$ is the methane production potential (mL) and was assumed to be equal to the final cumulative methane volume.

## 3. Results and discussion

*3.1. Effect of various sludge mixing ratios on methane production*

The digester with primary to waste activated mixing ratio of 65/35 v/v showed the highest average daily methane production rate of 69.3 mL/d followed by daily rates of 47.2 and 37 mL/d for mixing ratios of 50/50 and 35/65 v/v, respectively, as shown in Fig. 1. Higher PS content favoured higher methane production. The cumulative methane production and the kinetics of biogas production were much higher for PS to WAS mixing ratio of 65/35 v/v as shown in Fig. 2. Total volume of methane produced was the highest at 36.5 mL/g TCOD for the sludge sample with greater proportion of PS followed by 26.2 and 25.9 mL/g TCOD for the 50/50 and 35/65 v/v mixtures as shown in Fig. 3. It has been stated that biogas production from PS is higher unless the sludge contains less digestible complex organics like cellulose and lignin [15]. This is mainly due to the availability of easily biodegradable organics compared with the complex organic molecules in WAS.

*3.2. Effect of mixing ratio on sludge biodegradability (COD and VS removal)*

TCOD reduction of 46.6%, 53.7% and 72.3% and VS removal of 32.6%, 25.8% and 34% were achieved for mixing

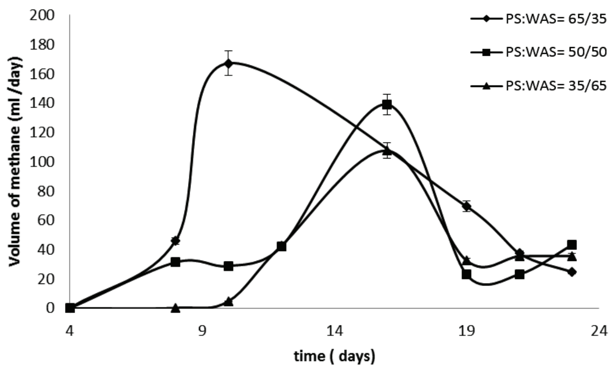


Fig. 1. Daily methane production for the three different sludge compositions.

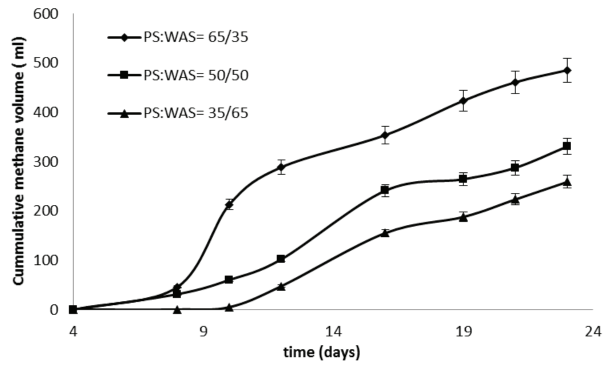


Fig. 2. Cumulative methane production for different sludge mixing ratios.

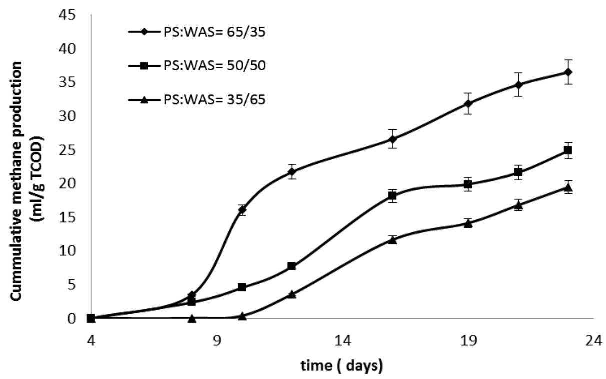


Fig. 3. Specific methane production for different sludge mixing ratios.

ratios of 65/35, 50/50 and 35/65, respectively, as shown in Fig. 4. The highest reduction in TCOD was achieved for the sample with more WAS (35/65) due to the presence of greater amount of microbial biomass and biodegradable organic produced during the activated sludge treatment process. In terms of VS removal, higher VS percentage reduction was also obtained for this mixing ratio and the volatile fatty acids (VFA) and other volatile organics in the microbial biomass are readily available for degradation. However, the sample with mixing ratio of 65/35 v/v had the highest methane production of 36.5 mL/g TCOD. The hydrolysis and biodegradation rate for this process was also faster than the other two combinations. Greater methane gas quality (higher methane to carbon dioxide ratio) was achieved for the sludge with mixing ratio of 65/35 v/v due to the presence of more digestible carbohydrates and fats, which can be converted to methane through hydrolysis as shown in Fig. 5 [21,22].

### 3.3. Effect of mixing ratio on sludge dewaterability

One of the major objectives of anaerobic performance enhancement is improvement of the dewaterability of digested sludge, the output of the digestion process. The study on the dewaterability of different PS to WAS mixing ratios showed that the sample with greater percentage of WAS resulted in better filterability as measured in CST. The lesser the concentration of WAS the bigger was the CST value in seconds with reduced dewaterability as shown in Fig. 6. This is due to EPS that are mainly available in activated sludge than the PS due to the biological degradation during the activated sludge process, such polymeric substances assist floc formation and result in subsequent improvement of dewaterability but very significant amount of EPS may result in deterioration of dewaterability due to increased amount of bound water that is difficult to separate [23].

### 3.4. Microbial content and sludge mixing ratio

The microbial biomass content of digested sludge from the three digesters was estimated using the bacterial count method. The digested mixed sludge sample with more WAS contained more *Escherichia coli* and coliform as shown in Fig. 7. The destruction of pathogens and microorganisms was also one of the targets. Hence, the pathogen removal for the

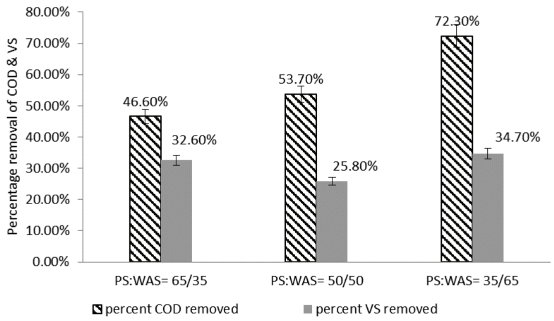


Fig. 4. Percentage reductions in COD and VS content for different sludge mixing ratios.

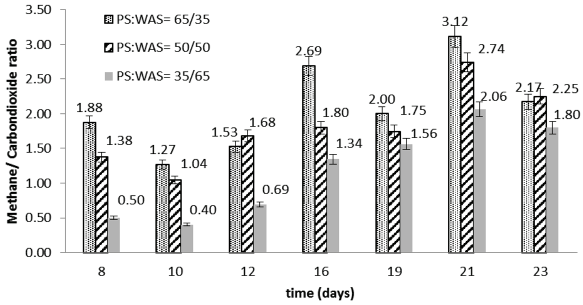


Fig. 5. Average methane/carbon dioxide ratio in biogas generated during anaerobic digestion for different sludge mixing ratios.

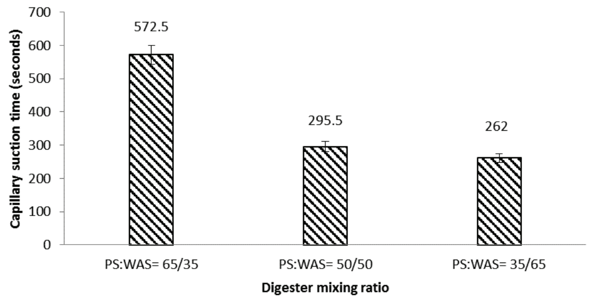


Fig. 6. Dewaterability of digested sludge for different sludge mixing ratios.

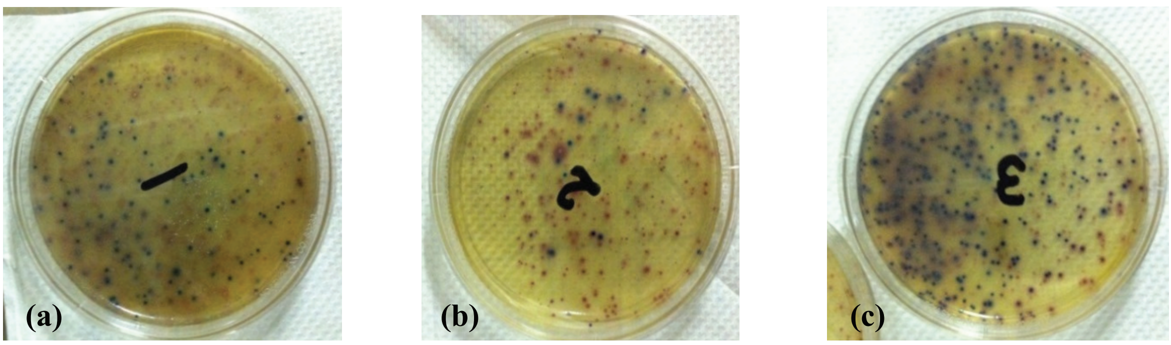


Fig. 7. Test for microbial content in the mixed sludge samples with different mixing ratios: (a) PS:WAS = 65/35, (b) PS:WAS = 50/50 and (c) PS:WAS = 35/65.

mixed sludge with 50/50 v/v mixing ratio was greater than the others as shown in Table 2.

*3.5. Application of Gompertz model for prediction of biochemical methane production*

The experimental data from anaerobic digestion study that was carried out to investigate effect of sludge mixing ratio were used for model fitting and prediction of methane production. Gompertz equation was applied to predict the methane potential, lag time, daily and cumulative methane production by the non-linear regression method.

The parameters $P$, $\lambda$ and $Rm$ from the Gompertz equation were estimated by applying a least squares fit of Eq. (1) to the experimental data set as shown in Fig. 8. The methane production potential and other parameters determined using this model were compared with those obtained from experimental investigation for the effect of mixing ratio as presented in Figs. 3 and 4.

It can be observed from Tables 3 and 4 that the predictions made based on Gompertz model fit well to the experimental data with very high correlation coefficient of 0.99. The methane production potential and daily rate for the mixed sludge sample with higher proportion of PS was higher with shorter lag time as shown in Fig. 8. This confirms well that methanogenic activity achieved for the anaerobic digester with greater proportion of PS is higher.

*3.5.1. Determination of hydrolysis rate constant*

The estimation of the first-order hydrolysis constant was made by linearizing Eq. (2) and the linearized plot is shown in Fig. 9. The hydrolysis rate constant at different mixing ratios were obtained by model fitting using Eq. (2) are shown in Table 5. As the pH in the experiment was always in the range of 6.8–7.2, the consumption of volatile fatty acid was significant that there was no accumulation of VFA.

## 4. Conclusion

The study on the effects of PS to WAS mixing ratio shows that higher methane production was achieved for the mixture with greater percentage of PS. Optimization of the WAS to PS ratio helps to improve the performance of anaerobic digesters and understand the effects of changing the ratio of PS to WAS on the characteristics of mixed digester feed sludge and its degradation behaviour. Greater methane gas quality (higher methane to carbon dioxide ratio) was achieved for the sludge with mixing ratio of 65/35 v/v due to the presence of more digestible carbohydrates and fats. The solid removal was significant for the sludge with larger percentage of WAS and the dewaterability was also found to be better with this sludge type.

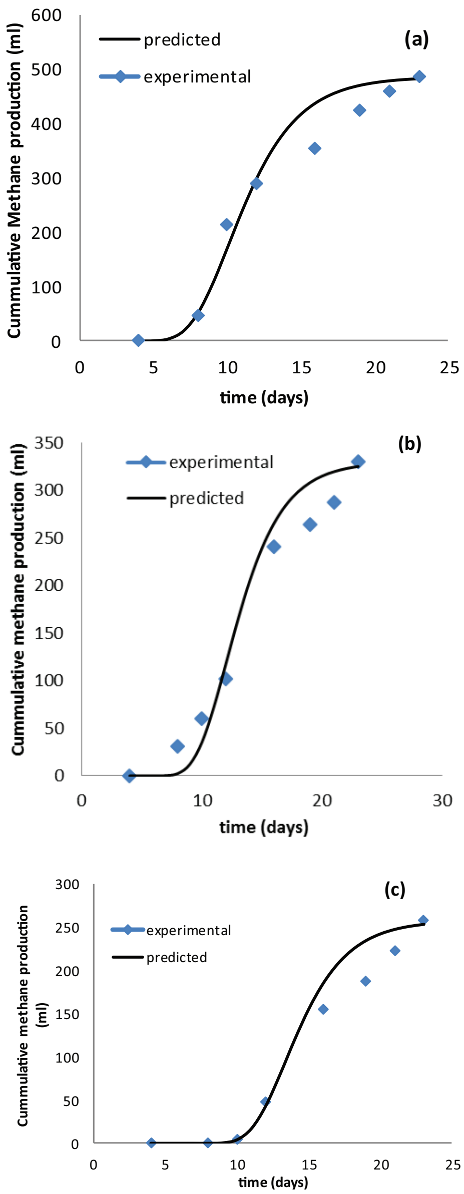


Fig. 8. Prediction of methane production by Gompertz model for the three mixing ratios: (a) PS:WAS = 65/35, (b) PS:WAS = 50/50 and (c) PS:WAS = 35/65.

Table 2
Microbial count for the digested sludge with different mixing ratio

| Reactor type | *E. coli* | Coliform | Total |
|---|---|---|---|
| PS:WAS = 65/35 | 10,100 | 11,000 | 21,100 |
| PS:WAS = 50/50 | 17,00 | 14,700 | 16,400 |
| PS:WAS = 35/65 | 22,500 | 4,100 | 26,600 |

Table 3
Methane potential, daily rate and lag time for anaerobic digestion experiment for different mixing ratios

| Sludge mixing ratio | Methane potential ($P$) | Maximum daily rate ($Rm$) | Lag time ($\lambda$) | $R^2$ |
|---|---|---|---|---|
| PS:WAS = 65/35 | 481.5 | 68.5 | 8.5 | 0.985 |
| PS:WAS = 50/50 | 325.32 | 47.2 | 10.5 | 0.989 |
| PS:WAS = 35/65 | 253.5 | 40 | 12 | 0.989 |

Table 4
Predicted and experimental methane production

| Cumulative methane (mL) | PS:WAS = 65/35 | PS:WAS = 50/50 | PS:WAS = 35/65 |
|---|---|---|---|
| Predicted | 481.6 | 325.32 | 256 |
| Experimental | 485.42 | 330.67 | 258.81 |
| Standard deviation | 1.91 | 2.675 | 1.405 |

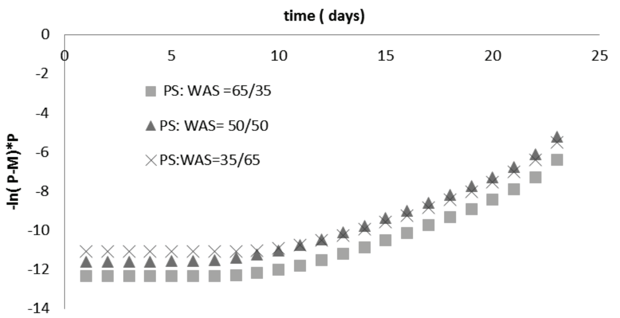


Fig. 9. First-order rate constant determination for the different mixing ratios.

Table 5
Determination of hydrolysis rate constant for different sludge mixing ratios

| Sludge mixing ratio | Kinetic constant (–*d*) | Correlation coefficient |
|---|---|---|
| PS:WAS = 65/35 | 0.256 | 0.86 |
| PS:WAS = 50/50 | 0.279 | 0.89 |
| PS:WAS = 35/65 | 0.233 | 0.82 |

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