Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1146920

57 (2016) 24724–24732
November

Optimizing the energy efficiency of sludge disintegration via the combined homogenate and ultrasonic method

Xianjin Li, Tong Zhu*, Meiyan You, Tianyu Chai, Yang Shen, Yuanhua Xie

School of Mechanical Engineering and Automation, Northeastern University, 3–11, Wenhua Road, Heping District, Shenyang 110004, China, Tel. +86 024 83679925; email: 15940153182@163.com (X. Li), Tel. +86 024 83679926; emails: tongzhu@mail.neu.edu.cn (T. Zhu), 296578095@qq.com (M. You), Tel. +86 024 83679925; emails: chai_tianyu@qq.com (T. Chai), 543451383@qq.com (Y. Shen), Tel. +86 024 83679926; email: islandxyh@126.com (Y. Xie)

Received 6 July 2015; Accepted 21 January 2016

ABSTRACT

To enhance the effect of sludge disintegration, we proposed the following two-stage process and a new index: (1) dispersion of sludge to facilitate homogeneity and to reduce the size of flocs; (2) destruction of zoogloea and bacterial cells; energy disintegration ratio ($EDR = DD_{COD}/E_S$) was used to evaluate this process energy efficiency. Thus, a combined homogenate + ultrasonic (H + U) method was implemented to disintegrate sludge. The analysis of the disintegration degree (DD_{COD}), EDR, and particle size distribution revealed the high efficiency of the H + U pretreatment method for sludge disintegration. And it also turned out that EDR was an important rational index for sludge disintegration. Transmission electron microscope images showed intuitive evidence for sludge disintegration of the two-stage process. According to the central composite design and response surface methodology results, the second-order response surface model can adequately predict sludge disintegration. The optimal condition was sludge disintegration of 12 min (H of 2 min and U of 10 min). DD_{COD}, EDR, and median particle size were 28.9, 7.01%, and 7.8 μm, respectively. These results also proved the effectiveness of the proposed two-stage process. Moreover, the selection of effective disintegration methods that correspond to sludge characteristics could increase the efficiency of sludge disintegration and reduce the amount of energy consumed in the process.

Keywords: Homogenate method; Ultrasonic method; Sludge disintegration; Energy disintegration ratio; Response surface methodology

1. Introduction

Rapid urbanization and population growth have resulted in the increased production of excess sludge in wastewater treatment plants [1]. Excess sludge can lead to serious environmental problems [2]. Sludge disintegration is a pretreatment method of sludge degradation to reduce organic matter in sludge and increase the efficiency of resource recovery from sludge [3]. Various technologies of sludge disintegration have been proposed; these technologies include thermal hydrolysis, mechanical treatment, chemical treatment, and combined treatment method [4]. However, these methods have common disadvantages of extensive energy consumption and high pollution.

*Corresponding author.

To address the need to select effective disintegration methods that correspond to sludge characteristics, we proposed the following two-stage sludge disintegration process: (1) dispersion of sludge to facilitate homogeneity and to reduce the size of flocs; and (2) destruction of zoogloea and bacterial cells. This process could increase efficiency and reduce the energy consumption of sludge disintegration.

Excess sludge typically contains a large amount of organics and heavy metals. A large amount of organics mainly exists in the form of zoogloea and flocs [5–7]. Sludge flocs are perceived as a polymeric network formed by cross-linked extracellular polymeric substance (EPS) and microbial cells or zoogloea [8,9]. The particle sizes of sludge flocs range from 25 to 250 μm [10]. The cohesion and adhesion of EPS in sludge are weak [11], and the bacterial cell walls have an elastic macromolecule structure, which define the shape of the bacterium and enable it to resist hostile environments [12].

The homogenate method, which is an efficient pretreatment technology, is reportedly capable of improving the rate and extent of sludge disintegration through the combination of highly focused turbulent eddies and strong shearing forces [1,13,14]. Moreover, the sludge disintegration efficiency of this method is weak, and the EPS are degraded easily by macroscopic fluid shear stress, which is characteristic of the homogenate method. However, disintegration is difficult with this method when the bacteria are small (1–10 μm) [13] because the bacterial cell walls are firm. These conditions result in excessive heat energy dissipation.

Ultrasonic method is widely applied to disintegrate sludge. The combination of its multiple effects—high shear force, thermal hydrolysis, free radical species, and ultrasound—can disintegrate bio-macromolecules and bacteria in sludge [4,15–17]. Nevertheless, because of the inhomogeneity of sludge, microscopic ultrasonic effects cannot be fully maximized. This condition leads to high-energy consumption. In addition, microscopic ultrasonic effects are weaker than the macroscopic fluid shear stress from traditional mechanical methods with regard to the flocs disintegration in the sludge [4,14].

In the present study, the macroscopic fluid shear stress from the homogenate method is assumed to generate homogeneous sludge and small flocs efficiently; the same assumption is made for the microscopic ultrasonic effects for disintegrating small flocs, zoogloea, and bacteria in homogeneous sludge. Hence, the homogenate method (H), ultrasonic method (U), and homogenate + ultrasonic (H + U) methods for sludge disintegration are compared in this work, and the combined H + U pretreatment method is optimized with the response surface methodology (RSM).

2. Material and methods

2.1. Material

Seed sludge was obtained from a sewage plant. The active sludge was artificially cultivated in a laboratory. The characteristics of the sewage sludge used for the subsequent experiments were as follows: soluble chemical oxygen demand (SCOD) of 127.5 mg l^{-1}, a total chemical oxygen demand (TCOD) of 12,820 mg l^{-1}, a total solid (TS) of 14,735 mg l^{-1}, and median particle diameter of 114 μm.

2.2. Experimental and analysis method

Sludge disintegration was conducted using a homogenizer (HGB550, Waring, USA; volume of 2,000 ml, speeds of 19,000 rpm and 24,000 rpm, and power of 746 W) and an ultrasonic cell disruption system (GM1200D, Shunmatech, China; volume of 2,000 ml, frequency of 20 kHz, and power of 1,200 W). The electrical power of the homogenizer with a speed of 24,000 rpm for 500 ml sludge was evaluated (400 W). To ensure the consistency of the electrical power inputs of the homogenizer and the ultrasonic system, the electrical power of the ultrasonic cell disruption system was adjusted.

Table 1 shows the experimental design for the H, U, and H + U methods. The mechanism of sludge disintegration via the H, U, and H + U methods were analyzed according to DD_{COD}, energy disintegration ratio (EDR), particle size distribution, and morphological structure.

Based on the above experiment, RSM was employed to optimize the parameters of sludge disintegration and the central composite design (CCD) with two independent variables (H time–U time). The optimal experiment was further expanded with Design

Table 1
Experimental design for the H, U, and H − U methods

H time (min)	U time (min)	H + U time (min)
3	3	2–1
7	7	2–5
10	10	2–8
15	15	2–13
20	20	2–18
25	25	2–23
30	30	2–28

Expert (Version 8.0.6, Stat-Ease Inc., USA) [18]. The factors and levels are arranged in Table 2. The experimental data obtained from the BBD were analyzed with the following second-order polynomial equation:

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1<}^{k} \sum_{j=2}^{k} b_{ij} x_i x_j \quad (1)$$

where Y is EDR, X is the independent variable (time), and b is the coefficient.

2.3. Energy disintegration ratio (EDR)

Disintegration degree (DD_{COD}) is a key parameter for evaluating the release of soluble organics from sludge solids into the liquid phase. This parameter is calculated as follows [16]:

$$DD_{COD} = \frac{SCOD - SCOD_{raw}}{TCOD - SCOD_{raw}} \times 100\% \quad (2)$$

where $SCOD_{raw}$ is the COD of the sludge supernatant before treatment.

The optimization of the energy consumption of the sludge disintegration process is highly important. Thus, specific energy (Eq. (3)) was considered an essential parameter in the analysis [16].

$$E_S = \frac{P \cdot t}{v \cdot TS_0} \quad (3)$$

where E_S is the specific energy input (kJ g^{-1} TS), P is the electrical power (W), t is the disintegration time (min), v is the sample volume (l), and TS_0 is the initial total solid concentration (g l^{-1}).

Zhang et al. presented kWh kg^{-1} SCOD-increase index, which evaluated the energy efficiency that covered both sludge characteristics and lysis effectiveness [19]. Based on the kWh kg^{-1} SCOD-increase index and considering the influence of TS to SCOD increasing in ultrasonic disintegration, a new index of EDR (Eq. (4)) was introduced to represent the relationship between energy consumption and sludge disintegration ratio in the evaluation process.

$$EDR = \frac{DD_{COD}}{E_S} \times 100\% \quad (4)$$

Table 2
Experimental range and levels of the independent test variables

Variables	Factor	Units	Low	High	$-\alpha$	$+\alpha$
H time	X_1	min	1	3	0.5857	3.4142
U time	X_2	min	5	15	2.929	17.071

2.4. Analytical methods

The sludge sample was centrifuged at 10,000 rpm for 10 min (3H16RI, Hersey, China). The SCOD in the sludge supernatant was measured according to the APHA Standard Methods [20]. The sludge sample was treated with 0.5 mol l^{-1} NaOH for 24 h, and then the SCOD in the sludge supernatant was used to determine the TCOD [21]. DD_{COD} and EDR were calculated with Eqs. (2) and (4), respectively. Particle size distribution was measured with a laser granularity analyzer (Bettersize 2000, Dandong Bettersize, China). The morphological structure of the disintegrated sludge was measured with a transmission electron microscope (TEM; JEM-1200EX, Japan Electron Optics Laboratory, Japan).

3. Results and discussion

3.1. Sludge disintegration of single method

3.1.1. Homogenate method

The influence of H time on sludge disintegration on DD_{COD} and ERD is shown in Fig. 1(a). With an increase in H time, DD_{COD} increased from 6.1 to 18.7% and ERD decreased from 5.8 to 1.6%. In the first 7 min, DD_{COD} increased by 1% and ERD quickly decreased by 2.9%. These results demonstrate that mechanical disintegration can disrupt the cell walls, causing the release of organic materials from the cells. However, energy consumption rapidly increased with the increase in H time.

Microscopic characteristic of sludge disintegration was observed by TEM as intuitive evidence. Raw sludge existed in the form of zoogloea. Different shapes of bacteria gathered in flocs, and EPS filled the void between microorganisms [7]. As shown in Fig. 2(a) and (b), H method can homogenize the sludge, disperse flocs to a great number of zoogloea and bacteria individuals, and partly cut off rod-shaped bacteria and spherical bacteria. With an increase in H time, most rod-shaped bacteria were destroyed, most spherical bacteria were undamaged, and most organic matter remained existing in the bacterial cell.

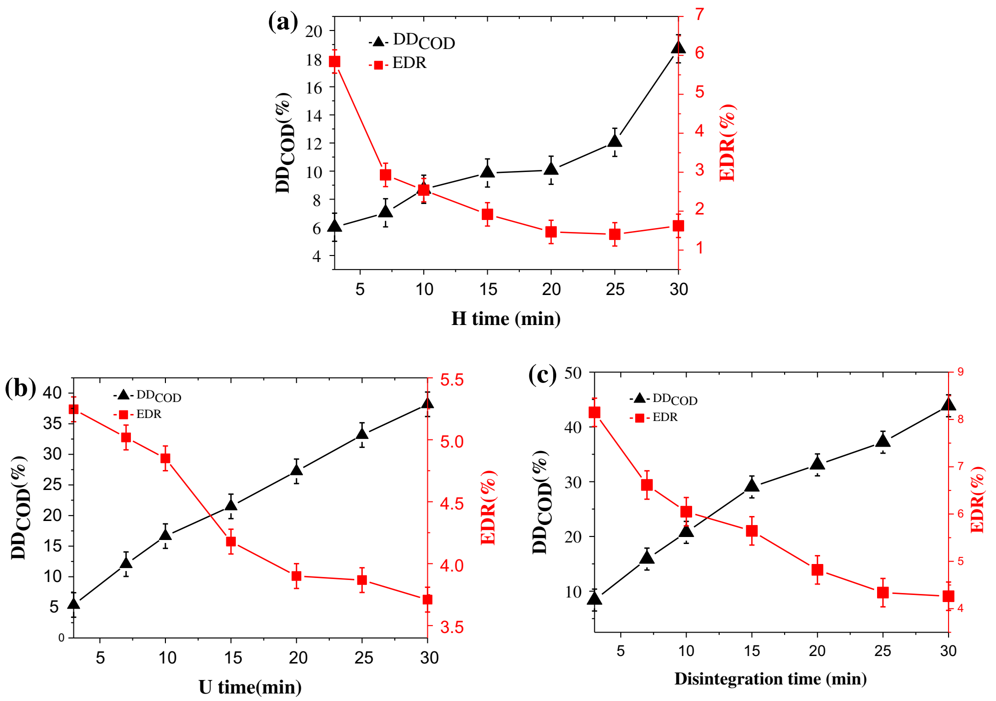


Fig. 1. Changes in DD_{COD} and EDR under the H, U, and H + U method: (a) H method, (b) U method, and (c) H + U method.

In brief, H method can disperse flocs in the sludge and release organic matter (protein and nucleic acid) from weak bacteria through high-speed rotation. T.P. Devi used a disperser (speeds of 4,000–24,000 rpm, similar to that in our study) for sludge disintegration [14]. In that study, mechanical pretreatment was considered costly; thus, excess sludge was disintegrated through a cost-effective method with a dispenser by deflocculating the sludge. The results showed that deflocculated sludge presented a higher SCOD of 26% than flocculated sludge at a specific energy input of 5,013 kJ kg^{-1} TS. These findings reveal that our proposed two-stage process is reasonable. However, the calculation method of energy and homogenizers of various parameters were different, so the results cannot be compared.

3.1.2. Ultrasonic (U) method

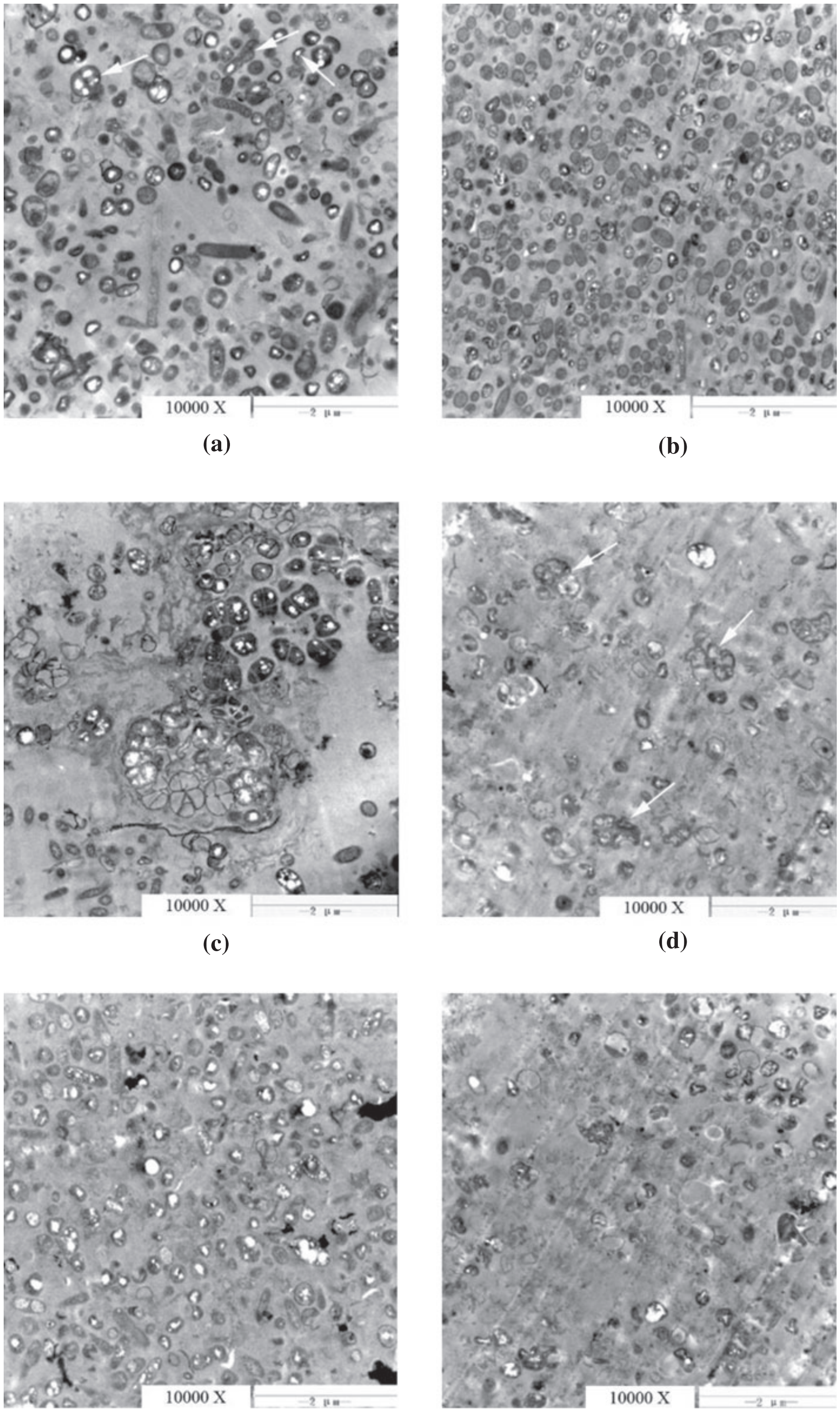
As shown in Fig. 1(b), with an increase in U time, DD_{COD} steadily increased from 5.4 to 38.2% and ERD decreased from 5.2 to 3.7%. EDR was the highest during the first 10 min and then quickly decreased. As shown in Fig. 2(c) and (d), ultrasound irradiation degraded a large number of bacteria and caused the formation of numerous holes; however, the flocs were not damaged thoroughly. A large number of ultrasonic cavitation bubbles were consumed because the flocs and bacteria in the sludge were heterogeneous. These results indicate that ultrasound can effectively disintegrate sludge by solubilizing flocs and destroying bacterial structure; however, ultrasound was inferior in terms of energy consumption [22,23].

DD_{COD} of U method reached 5.4% in 3 min and was lower than that of the H method. Then, DD_{COD} of U method was higher than H method after 3 min. These results indicate that the micro-effect from U method can effortlessly disrupt microscopic bacteria, and that the macroscopic fluid shear stress from the H method was extremely difficult in the sludge.

3.2. Sludge disintegration of combined method

3.2.1. Homogenate + Ultrasonic (H + U) method

As shown in Fig. 1(c), with an increase in disintegration time, DD_{COD} steadily increased from 8.6 to 44.8% and ERD steadily decreased from 8.2 to 4.3%. The macroscopic fluid shear stress fully dispersed the flocs in the sludge. The ultrasonic cavitation bubbles broke the zoogloea and bacteria, causing the formation of numerous holes (Fig. 2(e)). With an increase in disintegration time, nearly all bacteria were destroyed. Many bacterial cell wall fragments were uniformly



(a) (b) (c) (d) (e) (f)

Fig. 2. TEM images of sludge under the H, U, and H + U method: (a) H method for 7 min, (b) H method for 25 min, (c) U method for 7 min, (d) U method for 25 min, (e) H + U method for 7 min, and (f) H + U method for 7 min.

distributed in the visual field and bacterial cytoplasm was released into the aquatic phase (Fig. 2(f)). Combining the results of DD_{COD}, EDR, and TEM reveals that H + U is an efficient pretreatment method for sludge degradation, and that the proposed two-stage process proposed is correct.

3.2.2. Contrastive analysis of single and combined disintegration method

As shown in Fig. 1, at 3 min, the EDR of the U method was the lowest, whereas that of the H + U method was the highest. With an increase in disintegration time, the EDRs of the three methods decreased gradually. The H method showed the fastest decline and the U method showed the slowest decline. At 7 min, the EDR of the three methods (H, U, H + U) reached 2.9, 5.0, and 6.6%, respectively. After 7 min, the EDR of combined H + U method was still the highest, followed by that of U method and H method. In short, the combined H + U method was the most efficient among all the three methods for the sludge disintegration process.

Particle size analysis is unsuitable for characterizing the release of the organic material. However, it can describe the size variation of the sludge [23]. Sludge disintegration can lead to changes of sludge particle size as DD_{COD} increases [24]. Fig. 3(a)–(c) were sludge particle size distribution with the three methods (H, U, H + U) for 3, 10, and 25 min, respectively. As the disintegration time increased, the particle size decreased. During the first few minutes, the change of particles into smaller particles was quick, but eventually, the change slowed down. After 3 min, the efficiency of the U method decreased. After 10 min, the efficiency of the H method decreased. After 25 min, the three methods reached median particle diameters of 7.6, 6.7, and 6.3 μm, respectively. The combined H + U method produced smaller and more homogeneous particle sizes than those produced by either the H method or the U method.

The above results showed that H + U method had the advantages of the H and U methods, thus proving the viability of the two-stage process. The macroscopic fluid shear stress from the H method was efficient in generating homogeneous sludge and small flocs (median particle diameter exceeded 10 μm). Then, microscopic ultrasonic effects were efficient for destructing zoogloea and bacteria in the homogeneous sludge (median particle diameter was approximately

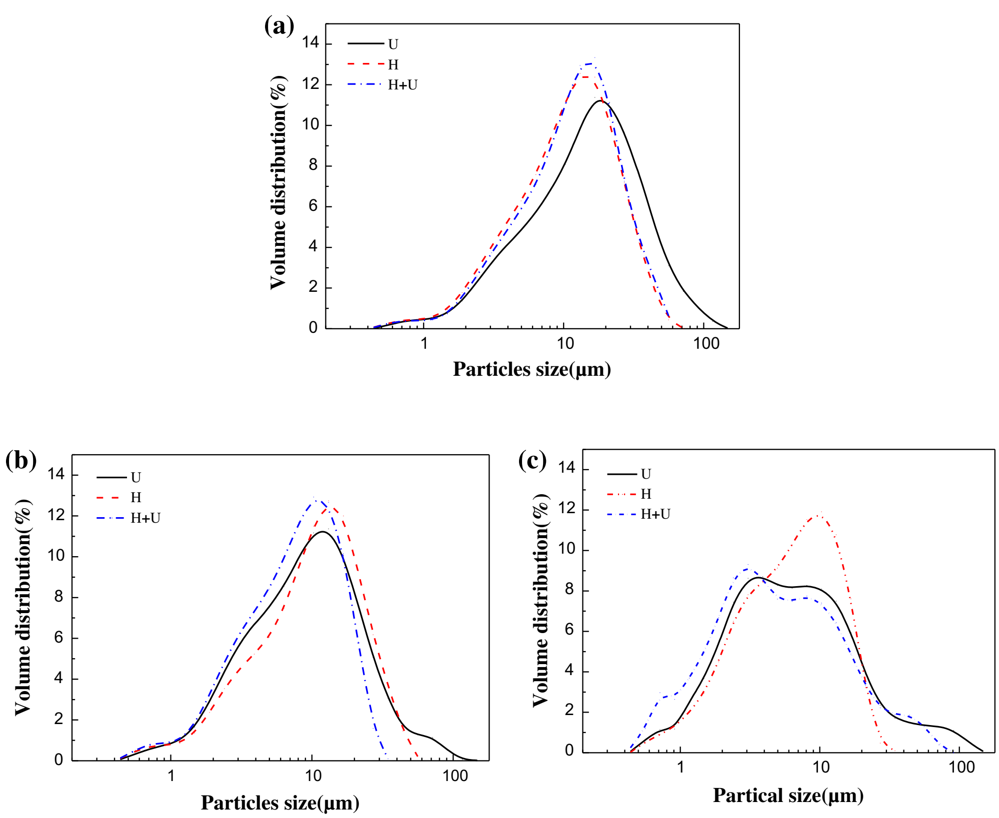


Fig. 3. Sludge particle size distribution under the three methods for 3, 10, and 25 min: (a) three methods for 3 min, (b) three methods for 10 min, and (c) three methods for 25 min.

10 μm). In addition, with an increase in disintegration time, cytoplasm was released into the aquatic phase (median particle diameter was under 10 μm). Furthermore, the effective disintegration methods corresponding to sludge characteristics increased the efficiency and reduced the energy consumption of sludge disintegration.

3.3. Optimization studies on the combined disintegration method

3.3.1. ANOVA and model fitting

By performing multiple regression analysis based on EDR, a second-order polynomial (Eq. (5)) was obtained to describe the correlation of factors.

$$Y = 8.75 + 0.54X_1 - 0.23X_2 + 0.05X_1X_2 - 0.31X_1^2 - 2.66X_2^2 \quad (5)$$

ANOVA was employed for the regression analysis of the experimental data and the RSM results. This step is important in determining the significance of a predictive model [25]. The *F*-value of 37.82 and the "Prob. > *F*" value of less than 0.05 indicated the significance of the model. X_1, X_2, X_1X_2, and X_1^2 were highly significant, indicating the significant effect of the U method, which also demonstrated a considerable influence on the H method. The "Lack of Fit *F*-values" of 10.75 implied that the lack of fit was significant with only a 2.20% chance that a "Lack of Fit *F*-value" this large could occur because of noise (Table 3). In addition, the following results proved the high credibility and precision of the model: $R^2 = 0.9643$, $R^2_{Adj.} - R^2_{Pred.} = 0.17 < 0.2$, Adeq precision = 18.661 > 4, C.V.% = 2.98 < 10. Therefore, the quadratic equation model (Eq. (5)) described the change of the two independent variables in this study. It could be used to predict the increase in EDR within the design range.

3.3.2. Response surface plots

The 2D contour plots describing the tendency of EDR under the H + U method are shown in Fig. 4. In contour plots, oval or saddle contours show significant factor interaction [18]. Fig. 4 shows that contour plots of interactive effects of X_1 and X_2 on RSM. With the increase in U time, EDR steadily decreased. In the first H for 2 min, EDR was consistent, and then EDR steadily decreased. The interactive effects of H method and U method were significant, thus proving the effectiveness of the two-stage process previously described.

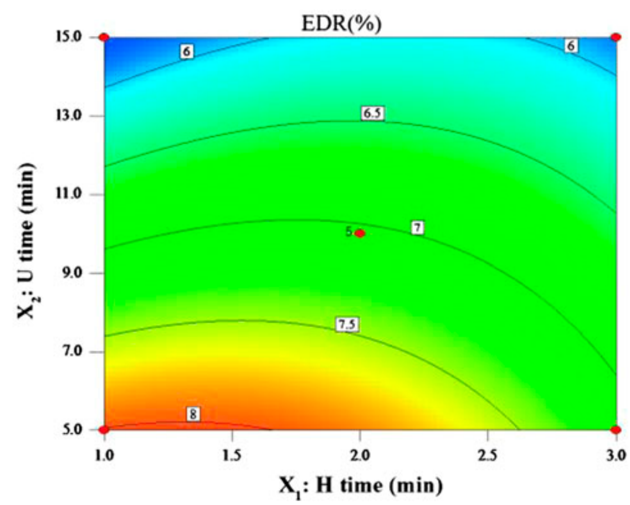


Fig. 4. Contour plots of interactive effects of X_1 and X_2 on RSM.

Table 3
Analysis of AVOVA for a quadratic response surface model of the CCD

Source	Sum of squares	DF	Mean square	*F*-value	Prob. > *F*
Model	7.8	5	1.56	37.82	<0.0001
X_1	0.23	1	0.23	5.62	0.0495
X_2	6.63	1	6.63	160.73	<0.0001
X_1X_2	0.27	1	0.27	6.59	0.0372
X_1^2	0.66	1	0.66	16.03	0.0052
X_2^2	0.031	1	0.031	0.74	0.4168
Residual	0.29	7	0.041		
Lack of fit	0.26	3	0.086	10.75	0.022
Pure error	0.032	4	7.97E-03		
Cor total	8.09	12			

Notes: $R^2 = 0.9643$, Adj. $R^2 = 0.9388$, Pred. $R^2 = 0.768$, Adeq. precision = 18.661, C.V.% = 2.98.

3.3.3. Optimization and verification of the model

According to the CCD–RSM results, at the 12 min (2–10) min of sludge disintegration, EDR was 7.04, as determined by point prediction. At this point, a more interaction between H and U was observed, the sludge disintegration efficiency was relatively high. To confirm the validity of the statistical experimental strategy and to acquire a comprehensive understanding of sludge disintegration by H + U method, repeated experiments were performed under optimal conditions. The DD_{COD}, EDR, and median particle sizes were 28.9, 7.01%, and 7.8 μm, respectively, all of which indicate the correctness of the optimization model. Zhang et al. achieved a statistical formula as $DD_{COD} = 38.7 \times$ power density (W mL^{-1}), where ultrasonic power density was at 0.1–1.5 W mL^{-1} and ultrasonic time was 30 min [26]. Under the ultrasonic power density of 0.8 W mL^{-1} and the ultrasonic time of 30 min, the calculated DD_{COD} was 30.96%. It was very close to the experimental result of 28.9%, but ultrasonic time was shorter (12 min) with the same of ultrasonic power density. Thus, this study presented two-stage process with high efficiency.

4. Conclusions

The analysis of DD_{COD}, EDR, and particle size distribution revealed that the H and U methods were effective sludge pretreatment methods; however, the U method and H method had difficulty in disrupting flocs and small bacteria, respectively. The combined H + U method for sludge disintegration was highly efficient. TEM images showed intuitive evidence for sludge disintegration by the two-stage process. These findings proved the effectiveness of the proposed two-stage process: (1) dispersion of sludge to facilitate homogeneity and to reduce the size of flocs; and (2) destruction of zoogloea and bacterial cells. According to the CCD–RSM results, the second-order response surface model can adequately predict sludge disintegration. The optimal condition was sludge disintegration for 12 min (H of 2 min and U of 10 min). The results showed that DD_{COD}, EDR, and median particle size were 28.9, 7.01%, and 7.8 μm, respectively. These results also prove the effectiveness of the two-stage process proposed.

Acknowledgments

This paper is supported by the National Natural Science Foundation of China (51178089) and the Doctoral Scientific Fund Project of China (20130042110009) and the Fundamental Research Funds for the Central Universities of China (N140306001).

References

[1] W. Fang, P. Zhang, G. Zhang, S. Jin, D. Li, M. Zhang, X. Xu, Effect of alkaline addition on anaerobic sludge digestion with combined pretreatment of alkaline and high pressure homogenization, Bioresour. Technol. 168 (2014) 167–172.

[2] M.S. Shehu, Z.A. Manan, S.R. Wan Alwi, Optimization of thermo-alkaline disintegration of sewage sludge for enhanced biogas yield, Bioresour. Technol. 114 (2012) 69–74.

[3] S. Pilli, P. Bhunia, S. Yan, R.J. LeBlanc, R.D. Tyagi, R.Y. Surampalli, Ultrasonic pretreatment of sludge: A review, Ultrason. Sonochem. 18 (2011) 1–18.

[4] H. Carrère, C. Dumas, A. Battimelli, D.J. Batstone, J.P. Delgenès, J.P. Steyer, I. Ferrer, Pretreatment methods to improve sludge anaerobic degradability: A review, J. Hazard. Mater. 183 (2010) 1–15.

[5] A.K. Janeczko, E.B. Walters, S.J. Schuldt, M.L. Magnuson, S.A. Willison, L.M. Brown, O.N. Ruiz, D.L. Felker, L. Racz, Fate of malathion and a phosphonic acid in activated sludge with varying solids retention times, Water Res. 57 (2014) 127–139.

[6] J. Lu, Y.F. Ma, Y.R. Liu, M.H. Li, Treatment of hypersaline wastewater by a combined neutralization–precipitation with ABR-SBR technique, Desalination 277 (2011) 321–324.

[7] H. Liu, J.K. Yang, N.R. Zhu, H. Zhang, Y. Li, S. He, C.Z. Yang, H. Yao, A comprehensive insight into the combined effects of Fenton's reagent and skeleton builders on sludge deep dewatering performance, J. Hazard. Mater. 258–259 (2013) 144–150.

[8] F. Kara, G.C. Gurakan, F.D. Sanin, Monovalent cations and their influence on activated sludge floc chemistry, structure, and physical characteristics, Biotechnol. Bioeng. 100 (2008) 231–239.

[9] S. Comte, G. Guibaud, M. Baudu, Effect of extraction method on EPS from activated sludge: An HPSEC investigation, J. Hazard. Mater. 140 (2007) 129–137.

[10] A.T. Mielczarek, C. Kragelund, P.S. Eriksen, P.H. Nielsen, Population dynamics of filamentous bacteria in Danish wastewater treatment plants with nutrient removal, Water Res. 46 (2012) 3781–3795.

[11] Z. Zhang, J. Zhang, J. Zhao, S. Xia, Effect of short-time aerobic digestion on bioflocculation of extracellular polymeric substances from waste activated sludge, Environ. Sci. Pollut. Res. 22 (2015) 1812–1818.

[12] J.W. Johnson, J.F. Fisher, S. Mobashery, Bacterial cell-wall recycling, Ann. N.Y. Acad. Sci. 1277 (2013) 54–75.

[13] P. Kampas, S.A. Parsons, P. Pearce, S. Ledoux, P. Vale, J. Churchley, E. Cartmell, Mechanical sludge disintegration for the production of carbon source for biological nutrient removal, Water Res. 41 (2007) 1734–1742.

[14] T.P. Devi, A.V. Ebenezer, S.V. Adish Kumar, S. Kaliappan, J.R. Banu, Effect of deflocculation on the efficiency of disperser induced dairy waste activated sludge disintegration and treatment cost, Bioresour. Technol. 167 (2014) 151–158.

[15] K. Yasui, T. Tuziuti, Y. Iida, H. Mitome, Theoretical study of the ambient-pressure dependence of sonochemical reactions, J. Chem. Phys. 119 (2003) 347–356.
[16] C. Bougrier, H. Carrere, J.P. Delgenes, Solubilisation of waste-activated sludge by ultrasonic treatment, Chem. Eng. J. 106 (2005) 163–169.
[17] R. Wang, J. Liu, Y. Hu, J. Zhou, K. Cen, Ultrasonic sludge disintegration for improving the co-slurrying properties of municipal waste sludge and coal, Fuel Process. Technol. 125 (2014) 94–105.
[18] H. Chen, H.Y. Wu, Optimization of volatile fatty acid production with co-substrate of food wastes and dewatered excess sludge using response surface methodology, Bioresour. Technol. 101 (2010) 5487–5493.
[19] G. Zhang, P. Zhang, J. Yang, H. Liu, Energy-efficient sludge sonication: Power and sludge characteristics, Bioresour. Technol. 99 (2008) 9029–9031.
[20] A.D. Eaton, L.S. Clesceri, E.W. Rice, A.E. Greenberg, Standard Methods for the Examination of Water and Wastewater. Standard Methods for the Examination of Water and Wastewater, 21st ed., American Water Works Association & Water Environment Federation, Washington, DC, 2005.
[21] A. Tiehm, K. Nickel, M. Zellhorn, U. Neis, Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization, Water Res. 35 (2001) 2003–2009.
[22] F. Wang, Y. Wang, M. Ji, Mechanisms and kinetics models for ultrasonic waste activated sludge disintegration, J. Hazard. Mater. 123 (2005) 145–150.
[23] J. Muller, Disintegration as a key-step in sewage sludge treatment, Water Sci. Technol. 41(8) (2000) 123–130.
[24] E. Gonze, S. Pillot, E. Valette, Y. Gonthier, A. Bernis, Ultrasonic treatment of an aerobic activated sludge in a batch reactor, Chem. Eng. Process. 42 (2003) 965–975.
[25] D.H. Kim, E. Jeong, S.E. Oh, H.S. Shin, Combined (alkaline + ultrasonic) pretreatment effect on sewage sludge disintegration, Water Res. 44 (2010) 3093–3100.
[26] P. Zhang, G. Zhang, W. Wang, Ultrasonic treatment of biological sludge: Floc disintegration, cell lysis and inactivation, Bioresour. Technol. 98 (2007) 207–210.