Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.20900

82 (2017) 57–66
July

Process optimization of an ultrasonic technology combining a CASS reactor for excess sludge minimization

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Received 30 October 2016; Accepted 12 May 2017

ABSTRACT

To reduce excess sludge, the MLSS concentration and reaction zone ratio of an ultrasonic lysis-cryptic growth system combined with a CASS reactor (ULG + C) were investigated. Experimental results demonstrated that a high MLSS concentration was adverse to the removal of pollutants but advantageous to sludge reduction on the condition that the bacterial yield coefficient was inhibited, whereas reaction zone ratio had the opposite effect on pollution removal and sludge reduction. Increasing the two parameters increased energy consumption, suggesting that they should be controlled within a suitable range for better performance of the system. With the help of a conventional activated sludge (CAS) process, microbial activity weakened by the sludge lysis process could be recovered in six CASS operation cycles. In addition, the time needed for substrate degradation with the ULG + C process was 4 h, which is more than twice that for a CAS process, because of secondary flocculation. Based on these findings, the optimum conditions of an MLSS concentration of 2640 mg/L and a reaction zone ratio of 8/28 are strongly suggested for ULG + C systems.

Keywords: Ultrasonication; MLSS (mixed liquor suspended solids); Excess sludge reduction; CASS (cyclic activated sludge system); Batch respirometric method; DO (dissolved oxygen)

1. Introduction

With the popularization of municipal wastewater treatment plants (WWTPs) and rising sewage disposal rates, excess sludge in WWTPs has sharply increased, resulting in higher operating consumption and serious environmental problems [1,2]. Accordingly, the issue of excess sludge has received much attention from many researchers interested in saving costs and controlling environmental pollution [3]. Conventional sludge disposal techniques, including the processes of dehydration, digestion, and incineration, cannot reach targets satisfactorily because of high investments, low processing efficiency, and serious secondary pollution [4]. Therefore, it is critical that efficient methods for excess sludge reduction be exploited.

Three main methods have been developed to minimize excess sludge: uncoupling metabolism [5], lysis-cryptic growth [6], and metazoan predation [7]. Among these methods, lysis-cryptic growth seems to be more competitive for highly efficient sludge disintegration [8] and can be easily coupled with other sludge lysis technologies such as acid [9], alkaline [10], chlorine dioxide [11], chlorine [12], thermal [13], ozone [14], ultrasonic waves [15], or a combination of these [16]. Among these technologies, ultrasonication is often regarded as a preferable and promising technology for lysis-cryptic growth, with the merits of sludge treatment efficiency, operational convenience, and environmental security. Hence, the application of lysis-cryptic growth using ultrasonication incorporated with bioreactors (e.g. membrane bioreactor (MBR) and sequencing batch reactor (SBR)) for excess sludge reduction has aroused much attention and research interest recently [17]. Yoon et al. (2004) successfully combined a lab-scale MBR with ultrasonication to achieve zero discharge of excess sludge, with an average organic load rate of 0.91 kg/(m^3·d) and MLSS maintained at 8000 mg/L over one month. However, the combined system showed disadvantages, such as higher effluent pollutants,

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compared with the results of the control experiment [18]. Liu et al. [15] proposed a combination of ultrasonic technology and a continuous flow system, with results showing that 90% reduction in excess sludge could be obtained with ultrasonic density of 0.4 W/mL, ultrasonic time of 5 min, and sludge lysis return ratio of 1/24. The energy consumption induced by the developed technology was intensive and should be investigated, whereas its influence was lacking in their study. Lin et al. [19] incorporated ultrasonic and chlorine dioxide technologies with an SBR process, which achieved a 55% reduction in sludge with 70% recycling of disrupted sludge. The influence of chlorine on the SBR bioreactor was not investigated, but chlorine could erode the bioreactors and increase the cost of the method due to the need to add the chemical. Yang et al. [16] created a continuous flow anaerobic-anoxic-microaerobic-aerobic combining ozone/ultrasound system, and achieved a 55.08% reduction in excess sludge and 14.04% savings in energy cost with their system. Most of these studies found that reducing excess sludge with the ultrasonic sludge lysis-cryptic growth process was possible; however, drawbacks including bad effluent performance, large lysis consumption, and serious side effects were still found. Moreover, the biological nutrient removal process that occurs during biodegradation is an important step in the lysis-cryptic growth process, but has not been paid much attention by previous researchers. Therefore, the influence of the bioreactor behaviour on the lysis-cryptic growth system needs to be explored further.

It is well known that influent water of the lysis-cryptic growth system is characterised by high chemical oxygen demand (COD) concentration, as a sum of the original sewage COD and released COD (introduced during the lysis phase and returned to the bioreactor when the next operational cycle begins), and induces a heavy COD loading on bioreactor operation in biological nutrient removal process, ultimately causing a decrease in the efficiency of nutrient removal and sludge reduction. To resolve these issues simultaneously, a better solution is to couple the lysis-cryptic growth concept with novel high-performance bioreactors for superior pollutant removal efficiency. Compared with an SBR, a CASS reactor has strong pollutant removal ability, easy manipulation, and low investment and running costs, combining anoxic zone and aerobic zone [20]. Due to their ease of operation and good performance of wastewater treatment, CASS reactors are widely used in many WWTPs worldwide [21]. To date, only limited research has been carried out for the purpose of enhancing sludge reduction efficiency, improving effluent quality, and decreasing energy consumption simultaneously by combining an ultrasonic sludge lysis mechanism with a CASS process (ULG + C).

In this study, the primary objectives were to (1) investigate the influence of different operational parameters of an ULG + C system, including MLSS concentration and reaction zone ratios (the volume ratio of anoxic zone to aerobic zone), on sludge reduction, effluent quality, as well as ultrasonic energy efficiency (UE); (2) select the optimal parameters for satisfactory ULG + C operation; and (3) analyse the effect of the ULG + C behavior on microbial activity in activated sludge. We expected to gain a deeper understanding of the ULG + C mechanism, and knowledge of how to further apply of the system for sludge reduction, from this research.

2. Materials and methods

2.1. Experiment setup and operation

A sludge reduction experiment was carried out in a combined system, which incorporated a lab-scale CASS reactor and an ultrasonic device, as illustrated in Fig. 1. One reactor was used for nutrient substrate removal with con-

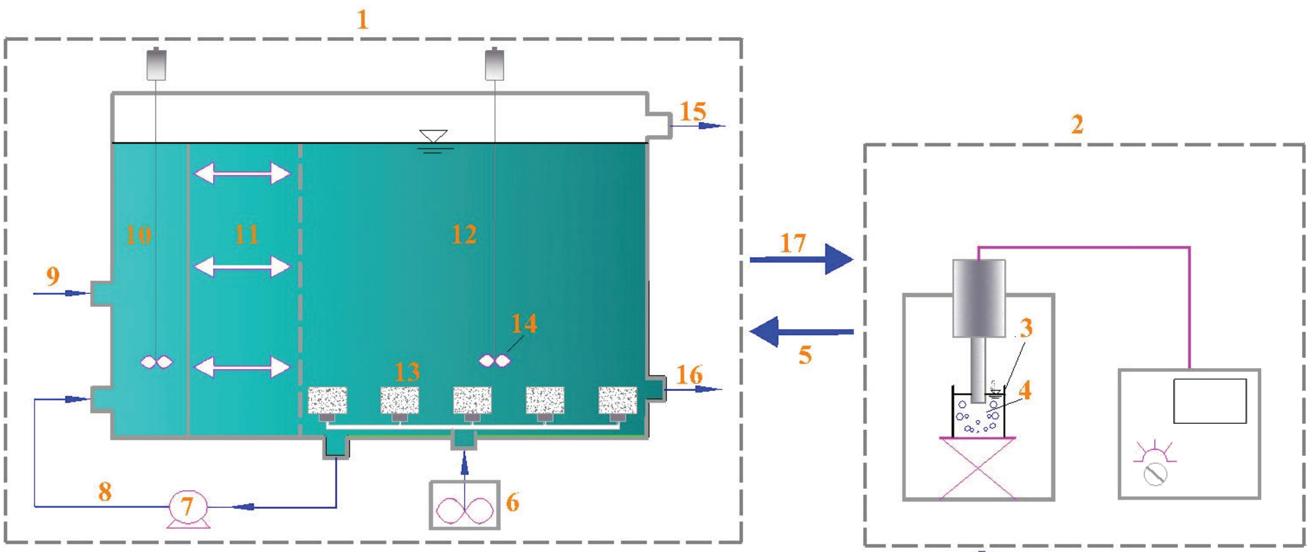

Fig. 1. Schematic of an ultrasonic lysis-cryptic growth combining a CASS reactor process: 1. CASS reactor; 2. Ultrasonic device; 3. Glass beaker; 4. Thickened sludge; 5. Lysed sludge; 6. Air pump; 7. Peristaltic pump; 8. Recycle sludge; 9. Synthetic wastewate; 10. Anoxic zone; 11. Adjustable zone; 12. Aerobic zone; 13. Aerator; 14. Stirring; 15. Effluent water; 16. Excess sludge; 17. Partial excess sludge.

ventional activated sludge (CAS) process (Fig. 1a), whereas a second reactor was employed for sludge lysis with ultrasonic waves (Fig. 1b). During the sludge reduction procedure, 30% of the system sludge was firstly removed from the CASS reactor at the end of settling and then reached a volume of 100 mL through gravity sedimentation. The thickened sludge was eventually poured into a glass beaker that had been placed within the ultrasonic device for ultrasonic lysis.

The CASS was produced using Plexiglas, with an effective volume of 108 L, 90 cm length, 30 cm width, and 45 cm height (Fig. 1b). The device was divided into three zones, i.e. biological selection zone, anoxic zone, and aerobic zone, according to the direction of flow. The reaction zone ratio, namely the volume ratio of the anoxic zone to the aerobic zone, was designed to be changeable. The CASS ran four cycles daily, with each working cycle lasting for 6 h consisting of the following periods: 0.5 h feeding, 4 h aeration, 1 h settling, and 0.5 h decanting. During a typical cycle, lysed sludge was pumped directly back to the CASS reactor alongside synthetic wastewater to feed the microbes when feeding began. The aeration device in the reactor was switched on from the beginning of feeding period to the end of the aeration period; simultaneously, all return sludge pumps were kept open and had a sludge return ratio of 50%. Dissolved oxygen in the aerobic zone was supplied by an air pump controlled at approximately 2–5 mg/L throughout the aeration period. Moreover, as the experimental conditions changed, excess sludge was discharged to obtain different concentrations of MLSS for this study.

Sludge lysis was carried out using an ultrasonic device (JY92-IIN, Shanghai Hao Zhuang Instrument Co., LTD, China) (Fig. 1a), in which ultrasonic waves were generated with the following parameters: 20 kHz ultrasonic frequency, 0–650 W (adjustable) power, 6-mm diameter titanium alloy probe, and continuous ultrasonic radiation mode. In addition, the ultrasonic density of 120 W/mL and ultrasonic time of 10 min were set for sludge disintegration.

2.2. Influent characterization

The synthetic wastewater had a pH of 7.5, temperature of 24.5°C, and composition (per L) of 242–375.7 mg COD, 31.7–52.6 mg total nitrogen (TN), 25.5–40 mg ammonia nitrogen (NH_3–N), and 3.2–4.9 mg total phosphorous (TP).

2.3. Experiments on optimizing the ULG + C system

To propose an optimum operational scheme for desirable performance of the ULG + C system, a series of process parameters, such as MLSS concentration and reaction zone ratio, were systematically investigated in our study. Three experimental modes were carried out to explore the ULG + C system. In mode 1, four ULG + C tests including $A_{1\#}$, $A_{2\#}$, $A_{3\#}$ and $A_{4\#}$ with four different MLSS concentration, i.e. 2059, 2640, 3128 and 3750 mg/L, were operated at the reaction zone ratio of 6/30. In mode 2, the reaction zone ratio was increased to 8/28 and the MLSS concentration for four ULG + C tests, i.e. $B_{1\#}$, $B_{2\#}$, $B_{3\#}$ and $B_{4\#}$, under the increased reaction zone ratio condition were set the same as mode 1. In mode 3, the reaction zone ratio was changed to be 10/26, and the MLSS concentrations for four ULG + C tests numbered $C_{1\#}$, $C_{2\#}$, $C_{3\#}$ and $C_{4\#}$ were 2059, 2640, 3128 and 3750 mg/L, respectively. These experimental conditions for ULG + C system optimization were summarized in Table 1.

2.4. Analysis

2.4.1. Chemical analytical methods

COD, TN, TP, NH_3–N and MLSS in influent and effluent of the CASS reactor were measured daily according to standard methods [22].

2.4.2. Calculation of the sludge yield coefficient

Y (yield coefficient) represents the sludge yielded via COD consumption in ULG + C process and can be determined as shown in Eq. (1):

$$Y = \frac{MLSS_e - MLSS_i}{COD_i - COD_e} \tag{1}$$

where $MLSS_i$ is the mixed liquor volatile suspended solids concentration in a CASS reactor at the beginning of feeding phase, mg/L; $MLSS_e$ is the mixed liquor volatile suspended solids concentration in a CASS reactor at the end of setting phase, mg/L; COD_i is the chemical oxygen demand concentration in influent, mg/L; and COD_e is the chemical oxygen demand concentration in effluent, mg/L.

2.4.3. Estimation of oxygen consumption and substrate degradation rate

There was a strong positive connection between substrate degradation rate (r_s) and OUR (oxygen uptake rate)

Table 1
Summary of the process optimization experiments.

Modes	Tests	Two operating parameters of ULG + C process	
		Reaction zone ratio	MLSS concentration (mg/L)
Mode 1	$A_{1\#}$ test	6/30	2059
	$A_{2\#}$ test		2640
	$A_{3\#}$ test		3128
	$A_{4\#}$ test		3750
Mode 2	$B_{1\#}$ test	8/28	2059
	$B_{2\#}$ test		2640
	$B_{3\#}$ test		3128
	$B_{4\#}$ test		3750
Mode 3	$C_{1\#}$ test	10/26	2059
	$C_{2\#}$ test		2640
	$C_{3\#}$ test		3128
	$C_{4\#}$ test		3750

in biological nutrient removal process. With a given Y, the substrate degradation rate could be determined using the OUR experiment [23]. The OUR experiment comprised an aeration device and a portable dissolved oxygen meter (HQ30D), was conducted in a respirometer by adding acetate as a pulse of readily biodegradable COD and dosing allylthiourea (ATU, 20 mg/L) to inhibit nitrification. To obtain OUR value, dissolved oxygen (DO) data were recorded every second after aeration started and then was applied to perform a linear regression with time. The curve of the DO profile was the OUR or the oxygen consumption. And the r_s of microorganisms can be calculated as shown in Eq. (2):

$$r_S = \frac{\int_0^T OUR(t)dt}{1-Y} \tag{2}$$

where r_s is the degradation rate of substrate, d^{-1}; Y is the yield coefficient of microbes, mg SS/mg COD; OUR is the oxygen uptake rate of microorganisms, mg O_2/(L h); and t is time, d.

2.4.4. Ultrasonication energy efficiency

The ultrasonication energy efficiency (UE) in ULG + C process could be calculated from Eq. (3):

$$UE = \frac{E \times T \times MLSS \times P_u}{\Delta MLSS \times \rho} \tag{3}$$

where UE is the energy consumption per unit in ULG + C process for excess sludge reduction , kwh/kg S_S; E is ultrasonic power density, kw/L (set to 1.2 kw/L in this study); T is total time of using ultrasonication for sludge lysis, s (set to 10 min in this study); MLSS is mixed liquor volatile suspended solids concentration in a CASS reactor, mg/L; P_u is percentage of activated sludge which was taken from a CASS reactor daily and cracked using ultrasonication, % (set at 30% of total sludge); ΔMLSS is the total amount of sludge reduction in the CASS reactor every day, mg/(L d); ρρis concentration of thickened sludge (set at 15 × 10^3 mg/L).

3. Results and discussion

3.1. Effect of MLSS concentration on ULG + C system

To determine the MLSS concentration for good ULG + C performance, we studied the variations of effluent COD and TN. Fig. 2 shows the variations of effluent quality and nutrient removal efficiency in the CASS reactors with the four different MLSS concentrations. As shown in Fig. 2a and Fig. 2b, the average effluent COD concentrations in four tests (Model 1) are 72.86, 88.36, 102.52, and 113.64 mg/L. The average effluent TN concentrations in these tests are 15.93, 21.00, 22.15, and 26.73 mg/L, respectively.

According to Fig. 3a, for A1#, A2#, A3#, and A4#, the sludge yield coefficients (Y) were 0.145, 0.112, 0.097, and 0.083, respectively, corresponding to 43.96%, 59.66%, 67.63%, and 73.83% reductions observed in sludge. These results show that with a certain reaction zone ratio, the greater the MLSS concentration is, the higher the effluent COD concentration is, and the lower the Y will be. The variations of effluent TN for these four tests in the ULG + C system were similar to the changes in effluent COD. This indicates that during the experimental period, high MLSS concentration induced more sludge lysis, through

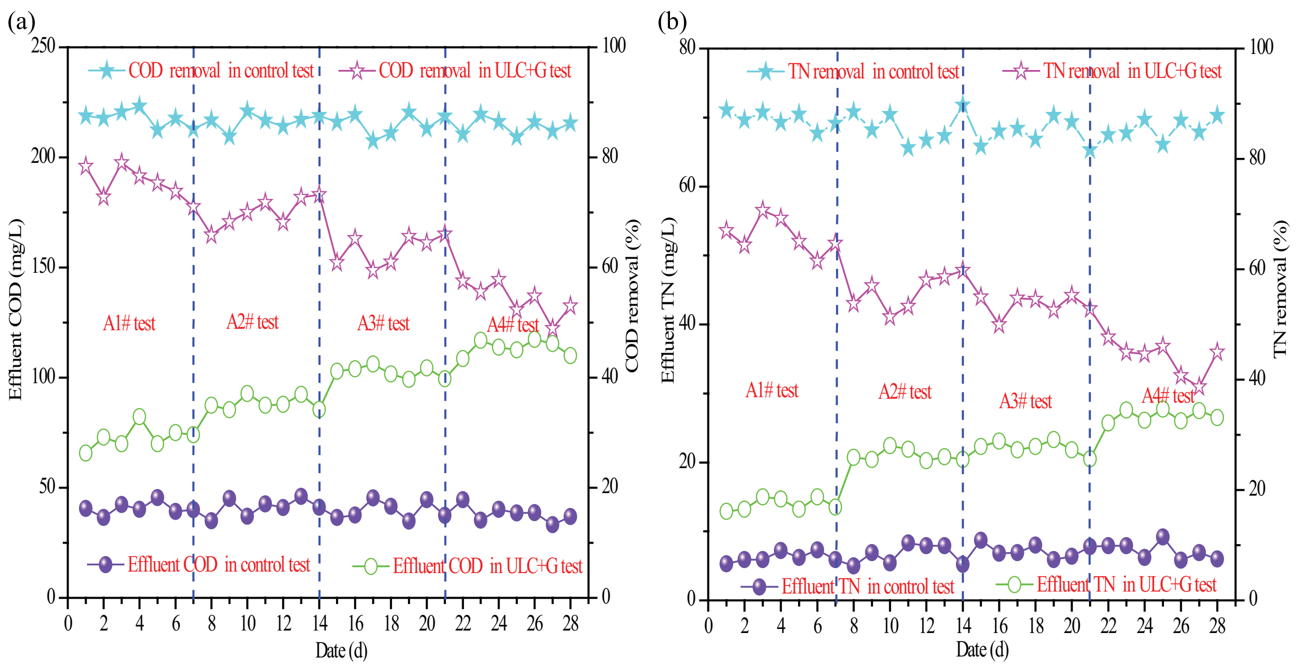

Fig. 2. Variations of effluent quality and nutrient removal efficiency in ULG +C system with different MLSS concentration. (a), COD. (b), TN.

which the broken bacterial cells released their contents as well as extensive refractory materials, e.g. heavy metals, cell wall fragments, and extracellular polymeric substrates (EPSs), into the sludge supernatant. These materials were reabsorbed along with influent substrates by activated sludge in the CASS reactor, not only aggravating the organic loading rate but also shocking the biological system, which resulted in the *Y* and total sludge decreasing distinctly. Inhibition of metabolic activity by the refractory matter released from the sludge disintegration stage has been reported as a potential cause of imbalance between activated sludge generation and dissolution, prohibiting the net sludge in the bioreactor from achieving the original sludge level during a sludge retention time (SRT), and eventually decreasing the *Y* as well as increasing sludge reduction efficiency [24,25].

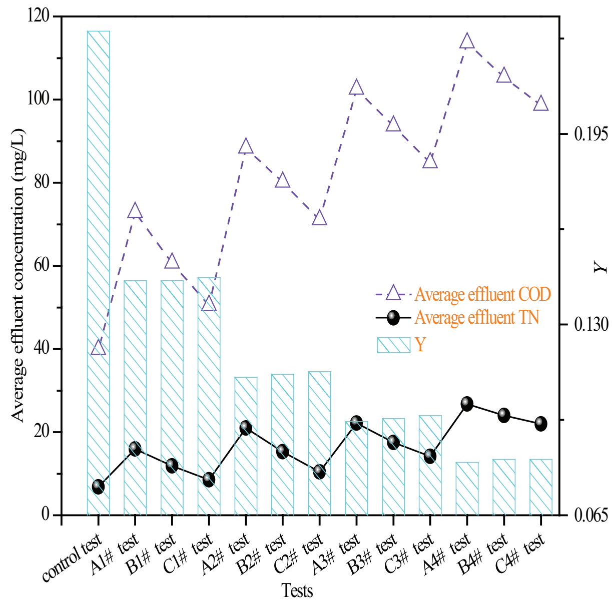

Fig. 3. Variations of effluent COD, TN and sludge yield coefficient in twelve ULG + C tests.

3.2. Effect of MLSS concentration on microbial activity

Based on the results presented in Fig. 4a, increasing the MLSS value in the ULG + C process would deteriorate effluent quality while causing more energy consumption. Noticeably, when the reaction zone ratio was kept at 6/30, the average concentrations of effluent COD and TN in the A4# test run with an MLSS concentration of 3750 mg/L were 113.64 and 26.73 mg/L, respectively, meaning that this test outputs the worst quality effluent among the 12 tests, and thus was regarded as the most unfavourable condition for ULG + C system. To meet sewage discharge standards (100 mg/L COD and 20 mg/L TN), the maximum limit for the MLSS concentration in the ULG + C system should be set to 3750 mg/L when the reaction zone ratio is 6/30, otherwise the effluent quality would be undesirable.

To fully reveal the influence of the highest MLSS concentration (3750 mg/L) on nutrient removal performance, OUR experiments were carried out to investigate the relationship between microbial activity in the A4# test and nutrient degradation, according to Eq. (2). Prior to the OUR experiments, sludge was taken from the A4# test and put in a respirometer to determine its oxygen uptake rate. For more detailed information about this experimental procedure, please refer to section 2.4.3. As shown

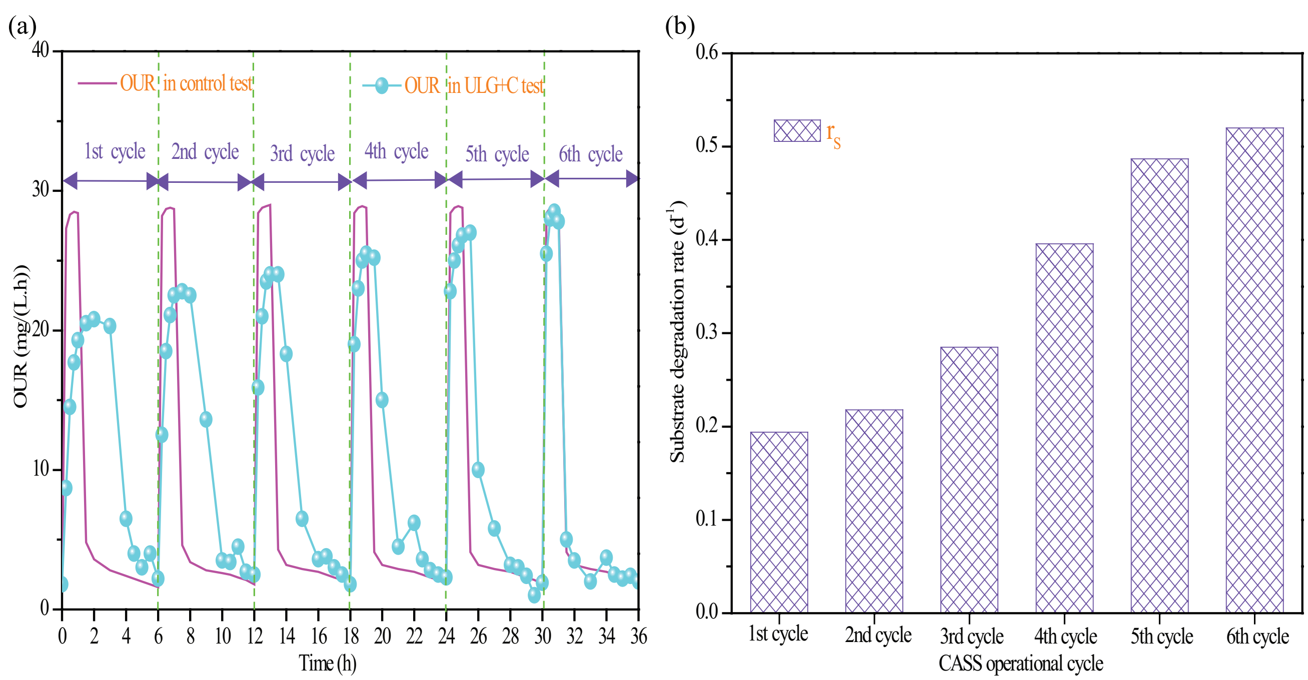

Fig. 4. Variations of OUR data (a) and substrate degradation rate (b) in $A_{4\#}$ test and control test during six CASS operational cycles.

in Fig. 4a and Fig. 4b, in the first working cycle, the A4# test is monitored with ULG + C process; the ΔOUR data for its sludge sample was 0.178 mg O_2/(L·h), and the corresponding substrate degradation rate (r_s) was 0.194 d^{-1}. After the following five working cycles, the A4# test was conducted without the sludge reduction process as a control. The ΔOUR data increased gradually to 0.236 mg O_2/(L·h), 0.278 mg O_2/(L·h), 0.320 mg O_2/(L·h), 0.359 mg O_2/(L·h), and 0.402 mg O_2/(L·h), with corresponding substrate degradation rate (r_s) rising to 0.218 d^{-1}, 0.285 d^{-1}, 0.396 d^{-1}, 0.487 d^{-1}, and 0.520 d^{-1}, indicating that during the five cycles, the r_s increased as the CASS operational cycles increased, despite the bioreactor only operating the CAS process. These results are most likely due to the fact that with the CAS process, running the CASS working cycle from the 2nd to the 6th cycle could consecutively supply a favourable environment and sufficient influent nutrients for microorganisms in the system to fix cellular injuries, caused by ultrasonic radiation during an ULG + C process, and ultimately regain full metabolism and proliferation rates. Liao et al. (2000) also found that when facing adverse environmental factors, bacteria in bioreactors had the ability to adapt and rehabilitate gradually using physiological mechanisms including dormant periods and polysaccharide capsules [26].

In another way, it could be seen from Fig. 4a that the CASS reactor combined with ultrasonication needs to run 4 h to completely consume organic substrates using oxygen before achieving its maximum during an operational cycle, whereas control testing peaked in 2 h under conventional activated sludge process. These phenomena are attributable to secondary flocculation, which is induced by ultrasonic radiation during ultrasonic lysis-cryptic growth processes and results in increasing the size of sludge flocs and extending the time of substrate adsorption by activated sludge [27].

3.3. Effect of reaction zone ratio on ULG + C system

To determine the effects of reaction zone ratio on the ULG + C system, three variations of the reaction zone ratio, i.e. 6/30, 8/28, and 10/26, were implemented by varying the volume ratio of the anoxic zone to the aerobic zone when MLSS concentration was controlled at 2059 mg/L, 2640 mg/L, 3128 mg/L, and 3750 mg/L. The relative results are shown in Fig. 5 and Fig. 6. Initially, the MLSS concentration was set at 2059 mg/L, with average concentrations of effluent COD for the three tests $A_{1\#}$, $B_{1\#}$, and $C_{1\#}$ being 72.86 mg/L, 60.64 mg/L, and 50.50 mg/L, respectively, and the average concentrations of effluent TN being 15.93 mg/L, 11.85 mg/L, and 8.53 mg/L, respectively. The average concentrations of effluent COD and TN in the remaining tests when the MLSS concentration was increased from 2640 to 3750 mg/L were also dependent on reaction zone ratio.

Based on these experimental results, it can be concluded that a high reaction zone ratio is favoured for COD and TN removal whereas a high MLSS concentration is harmful to substrate removal. Lower effluent COD and TN concentrations occurred with the increase of reaction zone ratio at a given MLSS concentration, which were caused by the following two reasons: firstly, a more anoxic environment could have been created for denitrifiers living in the ULG + C system, with the increase of the reaction zone ratio. Secondly, the anoxic zone was installed at the front of the CASS reactor and was dominated by denitrifiers, thus the denitrifiers were able to obtain food from the influent sewage and lysed cells much easier than heterotrophs could in the aerobic zone. Consequently, the larger the ratio of anoxic zone to aerobic zone (supplying more volume for the anoxic zone), the higher the quantity of denitrifying bacteria contained in its volume, and hence more nutrient substrates were consumed. As most previous ultrasonic lysis-cryptic growth procedures are typically coupled with CAS processes, i.e. sequencing batch reactor (SBR) and membrane bio-reactor (MBR), most nutrients in these procedures will be utilized by aerobic heterotrophs and autotrophs with high dissolved oxygen (DO) first, whereby the remaining substrates cannot meet the requirements for denitrification. This would limit the nitrate or TN removal efficiencies, increasing the demand for oxygen, and eventually leading to heavier financial burden [28,29]. Therefore, with the help of a CASS reactor, external nutrient substrates originated from the lysis process and the relatively wide volume of the anoxic zone developed by adjusting the ratio of anoxic zone to aerobic zone could be introduced into an ultrasonic lysis-cryptic growth system, serving as a combination strategy to strengthen bacterial activities and enhance bacterial metabolic abilities. As a result, such a combined technology must be a preferable alternative for wastewater treatment because high pollutant removal, sludge minimization, and energy saving can be achieved simultaneously.

3.4. Economic assessment on the two operational parameters

To facilitate the application of the ULG + C system, an economic analysis was conducted to quantitatively assess the interaction between energy consumption and MLSS concentration and reaction zone ratio, the two key operational parameters. Based on a previous study [30], the price of energy in the industrial market is \$0.07/kWh. Thus, the economic assessments for the 12 tests in this study were calculated according to Eq. (3) and are listed in Table 2. Moreover, to visually demonstrate how the four study objects like COD, TN removal efficiency, sludge reduction efficiency, and UE were influenced by the two parameters, a graph illustrating dependency of the above four objects on the two parameters is presented in Fig. 7.

According to results shown in Table 2 and Fig. 7, at the initial value of MLSS concentration (2059 mg/L), the UE rose from \$5.7/kg SS to \$6.64/kg SS and the sludge reduction efficiency dropped from 43.96% to 37.76% when the reaction zone ratio increased from 6/30 to 10/26 and the average removal for COD and TN increased to 82.27 and 78.28 mg/L, respectively. At the MLSS concentrations of 2640, 3128, and 3750 mg/L, the efficiency of UE, sludge reduction, COD removal, and TN removal all exhibited the same regularity as those at the MLSS concentration of 2059 mg/L. Based on these experimental results, it can be concluded that both the MLSS concentration and reaction zone ratio affected UE adversely, although the trend of reaction zone ratio was slightly weaker than that of MLSS concentration. In other words, higher MLSS concentration and reaction zone ratio in the ULG + C system means

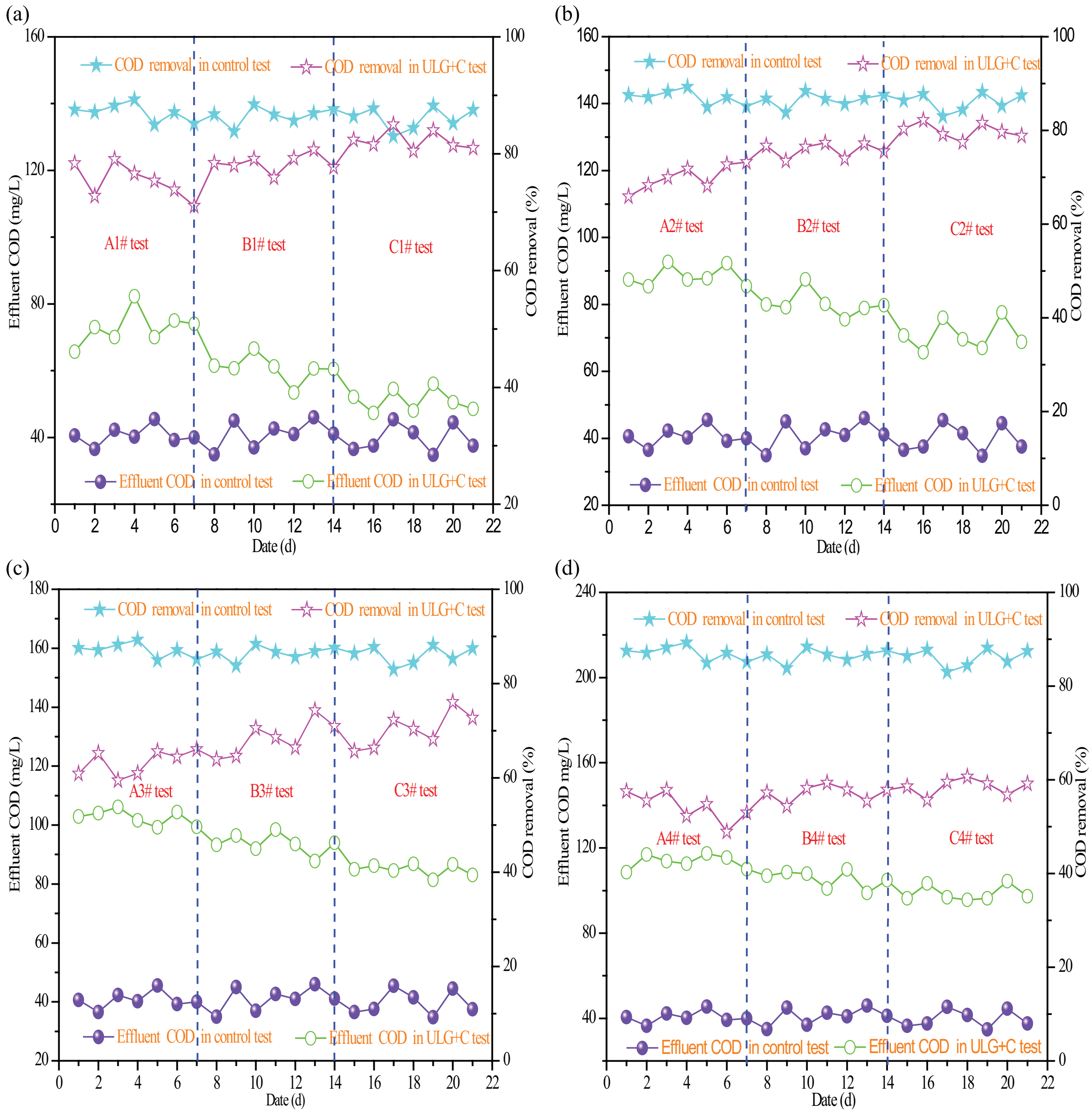

Fig. 5. Variations of effluent COD and its removal efficiency in ULG +C system with different reaction zone ratio. (a), when MLSS is 2059 mg/L. (b), when MLSS is 2640 mg/L. (c), when MLSS is 3128 mg/L. (d), when MLSS is 3750 mg/L.

greater electricity consumption. Simultaneously taking into account UE, sludge reduction, and pollutant removal performance, adjusting MLSS concentration and reaction zone ratio to 2640 mg/L and 8/28, respectively, leading to efficiency of COD and TN removal are 75.83% and 66.03%, respectively, achieving a 57.69% sludge reduction and a \$5.57/kg SS energy efficiency, which would be an optimal choice for an ULG + C system. As a result, three superior characteristics including notable energy conservation, moderate sludge reduction, and effective pollutant removal were all possessed in the system under the condition.

4. Conclusion

In this work, the influence of MLSS concentration and reaction zone ratio on an ULG + C system was studied successfully. It is concluded that at a certain value of

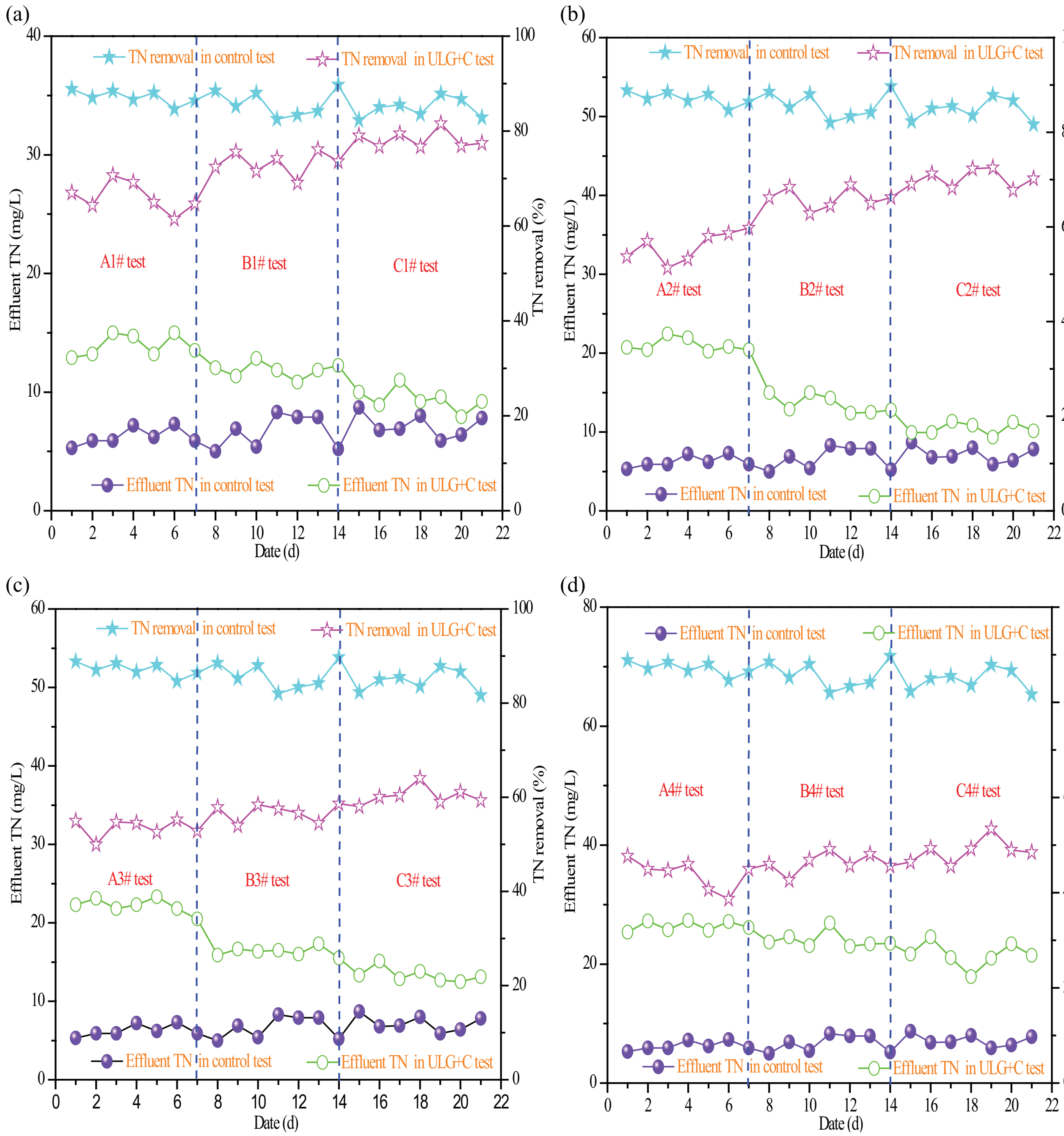

Fig. 6. Variations of effluent TN and its removal efficiency in ULG +C system with different reaction zone ratio. (a), when MLSS is 2059 mg/L. (b), when MLSS is 2640 mg/L. (c), when MLSS is 3128 mg/L. (d), when MLSS is 3750 mg/L.

reaction zone ratio, increasing MLSS concentration in the system would diminish sludge production, but limit pollutant removal efficiency and UE. With respect to reaction zone ratio, the ratio showed an adverse effect on UE and sludge reduction, but a positive effect on effluent quality. In addition, it was found that with a reaction zone ratio of 6/30, MLSS concentration in the ULG + C system should not exceed 3750 mg/L, otherwise system performance will be reduced to unacceptable levels. Additionally, OUR experimental results showed that with a CAS process, running a CASS working cycle to the 6th cycle could restore injured microbial cells that lose their activity in an ULG + C system. Substrate degradation with a CAS system takes 2 h, whereas with an ULG + C process, it takes 4 h because of secondary flocculation. Therefore, to obtain an excellent ULG + C system, MLSS concentration and reaction zone ratio values were optimized from 2059 mg/L to 2640 mg/L and from 6/30 to 8/28, respectively.

Table 2
Nutrient removal efficiency, sludge reduction efficiency and energy efficiency in ULG+C system[a]

Tests	Average effluent (mg/L)		Removal efficiency (%)		Y	Sludge production (g/d)	Sludge reduction efficiency (%)	UE ($/kg S_S)
	COD	TN	COD	TN				
Control test	39.89	6.81	86.34	85.80	0.230	24.84	–	–
$A_{1\#}$ test	72.86	15.93	75.29	66.60	0.145	13.92	43.96	5.70
$B_{1\#}$ test	60.64	11.85	78.44	73.25	0.145	14.72	40.74	6.15
$C_{1\#}$ test	50.50	8.53	82.27	78.28	0.146	15.46	37.76	6.64
$A_{2\#}$ test	88.36	21.00	70.04	55.97	0.112	10.02	59.66	5.39
$B_{2\#}$ test	80.13	15.25	75.83	66.03	0.113	10.51	57.69	5.57
$C_{2\#}$ test	71.07	10.40	79.90	70.20	0.114	10.99	55.76	5.76
$A_{3\#}$ test	102.52	22.15	63.24	53.56	0.097	8.04	67.63	5.63
$B_{3\#}$ test	93.62	17.50	68.50	56.80	0.098	8.53	65.66	5.80
$C_{3\#}$ test	84.79	14.17	70.25	60.29	0.099	8.96	63.93	5.96
$A_{4\#}$ test	113.64	26.73	54.46	43.96	0.083	6.5	73.83	6.18
$B_{4\#}$ test	105.40	24.01	57.22	46.30	0.084	6.85	72.42	6.30
$C_{4\#}$ test	98.60	22.00	58.53	48.78	0.084	7.15	71.22	6.41

[a]Average influent COD and TN in the above tests are 294.9 mg/L and 47.7 mg/L , respectively.

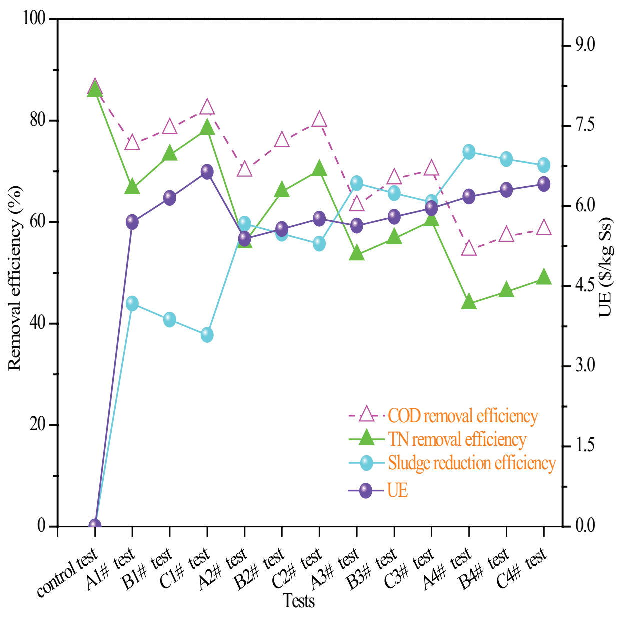

Fig. 7. Variations of COD, TN removal efficiency, sludge reduction efficiency, and ultrasonic electricity efficiency (UE) in twelve ULG + C tests.

Acknowledgements

This research was supported by the National Water Pollution Control and Management Technology Special Project of China (No. 2014ZX07201-012-2) and the State Key Laboratory of Urban Water Resource and Environment (Harbin Institute of Technology) (No. 2012DX07).

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