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Reduction of excess sludge production by microwave/activated carbon fibre pretreatment process based on lysis-cryptic growth

Dedong Sun*, Ke Zhang, Yina Wang, Hongchao Ma, Chun Ma

School of Light Industry and Chemistry Engineering, Dalian Polytechnic University, Dalian 116034, China, Tel. +86-411-86323508; Fax: +86-411-86323736; emails: sundedong@sina.com (D. Sun), ke_zhang95@163.com (K. Zhang), wangyn1985@yeah.net (Y. Wang), hongchaom@126.com (H. Ma), mchuchum@yeah.net (C. Ma)

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ABSTRACT

In this study, the effect of microwave (MW)/activated carbon fiber (ACF) pretreatment for excess sludge reduction was investigated. The results showed that MW/ACF can effectively lyse the sludge. When the ACF dose was 0.19 g gSS^{-1}, the supernatant total organic carbon increased by 483.6% after MW irradiation at 800 W for 70 s. In order to study the influence of MW/ACF pretreatment on sludge reduction and the quality of the effluent, two parallel lab-scale sequencing batch reactors were operated. The study has shown that the observed sludge production yield (Y_{obs}) of the test and control systems averaged 0.22 and 0.39 $mgSS/mgSCOD_{removed}$ (SCOD: soluble chemical oxygen demand), respectively. The incorporation of MW/ACF pretreatment resulted in a 43.6% reduction of sludge production. Slight increases in effluent SCOD, total phosphorus and NH_4^+–N were observed, but biological treatment efficiencies were maintained.

Keywords: Excess activated sludge; Microwave; Activated carbon fiber; Cryptic growth; Sludge reduction; Effluent quality

1. Introduction

With the processing of fast urbanization and industrialization, huge amounts of wastewater have been produced in China. For example, China produced 73.53 billion metric tonnes of wastewater in 2015 [1]. The activated sludge process has been widely employed to treat wastewater but produced large amounts of excess sludge that is composed mostly of microorganisms. Excess sludge is the main by-product of the biological wastewater treatment process. In addition, as the rate of wastewater treatment goes up, the amount of excess sludge generated in the treatment process increases significantly. In 2015, there were approximately 43 million metric tonnes of excess sludge (at a moisture content of 80%) produced in China [2]. Many technologies such as dewatering, landfilling, anaerobic digestion, aerobic composting and incineration have been used for the ultimate disposal of excess sludge from wastewater treatment plants. However, treatment and disposal of sludge are extremely costly, which constitutes about 50%–60% of total operating costs for wastewater treatment [3,4]. Therefore, the treatment and disposal of sludge are a serious challenge for wastewater treatment plants.

The principles of the 3Rs (reduce, reuse, and recycle) have been applied in sludge treatment [5]. Among the 3Rs, reducing excess sludge production is considered as the ideal way of solving sludge-associated problems [6]. The reduction of sludge production can be achieved through the cryptic growth of microorganisms [7]. The lysis of sludge cells releases extracellular and intracellular biopolymers into sludge mixed liquor, thus providing an organic autochthonous substrate that can be reused by a microorganism. The activated sludge biomass growth based on this autochthonous substrate is called "cryptic growth" [8]. This growth results in reduced

* Corresponding author.

excess sludge production [9,10]. Cell lysis-cryptic growth consists of two stages: lysis and biodegradation [11]. The lysis of sludge cells is a rate-limiting step in lysis-cryptic growth [9] because extracellular polymeric substances produced by the sludge cells surround them, and offer protection for the sludge cells [5]. Therefore, cryptic growth can be amplified by increasing lysis efficiency, which contributes to reducing excess sludge production. To enhance cryptic growth, many cell lysis techniques have been studied, including electrical treatment [12], mechanical disintegration [13], ultraviolet disintegration [6], ultrasonic disintegration [14], thermo-chemical treatments [15], biological methods [16,17] and chemical oxidation such as ozonation [18], chlorination [4] and sulfate radical-based oxidation [19]. All the existing cell lysis methods have their shortcomings, therefore, an economical and effective cell-lysing technique is still required [5,20].

Microwave (MW) irradiation has been widely applied in the field of environmental engineering [21]. Compared with conventional thermal treatment, MW heating possesses many advantages such as ease of control, rapid heating, energy savings and low overall cost [22]. High heating rates and direct heating inside the bulk are the unique characteristics of MW heating [23]. In recent years, MW heating has gained popularity as an effective heating technique for sludge treatment [24]. It has been regarded as an alternative to carrying out the cell pyrolysis. In general, sludge cells cannot be heated by the MW directly up to the high temperatures required to attain pyrolysis, because they are poor receptors of microwave energy. Studies have indicated that if the sludge is mixed with an effective microwave absorber such as carbon, MW-induced pyrolysis is possible [25]. In this work, activated carbon fiber (ACF) was used as an effective receptor of microwave energy. To the best of the authors' knowledge, there have been no reports related to MW/ACF-assisted excess sludge reduction in the literature. This study investigated the sludge solubilization ability of MW/ACF, the effect of subsequent sludge reduction and the effluent quality of the sequencing batch reactor (SBR).

2. Materials and methods

2.1. Cultures of activated sludge

The activated sludge taken from the Lingshui river municipal sewage treatment plant in Dalian (Liaoning, China) was applied as inoculums for an SBR. The SBR which had an active volume of 2L was operated on two cycles per day, and each cycle consisted of 5 phases: instantaneous feeding, aeration period (10 h), settling period (55 min), effluent discharge period (5 min) and an idle period (1.0 h). The sludge retention time (SRT) was 10 d during steady operation. The dissolved oxygen level was approximately 4 mg L^{-1} during the aerobic stage. Characteristics of synthetic wastewater fed to the SBR are displayed in Table 1. The main sources of nitrogen and carbon were ammonium chloride and glucose, respectively.

2.2. Microwave-induced pyrolysis of waste activated sludge

Microwave furnace (KD21B-C, 2,450 MHz, 800 W, Shantou Huanhai Co. Ltd ., Longhu District, Shantou City, Guangdong Province, China) with Teflon vessels was used for heating sludge. Microwave-induced pyrolysis of sewage sludge was performed by batch tests. An ACF dose of 0.19 g ACF/g SS was mixed by sewage sludge according to the study before [26]. Sludge samples with ACF were subjected to closed Teflon vessel. All test samples were irradiated by MW at 800 W MW power and the MW irradiating time was varied from 10–70 s. After the treatment, samples were removed from the microwave furnace immediately and cooled to room temperature in air. Commercial ACF was (thickness: 3–4 mm; diameter: 10–20 μm) supplied by Sutong Carbon Fiber Co. Ltd., (China).

2.3. Impact of cell lysis on sludge production and treatment performance

Fig. 1 shows a schematic representation of the MW/ACF-activated sludge process combined system. Two previously described identical SBRs worked in parallel. One was provided with an MW/ACF pretreatment unit (test system) and the other (control system) was operated without MW/ACF pretreatment for the comparison of sludge yield and effluent quality. In the test system, every day 10% of the sludge from the SBR was subjected to the MW/ACF pretreatment unit in which the sludge was disintegrated. Then the pretreated sludge was returned to the SBR system. Both SBRs worked at room temperature for 12 d and were fed with the same synthetic wastewater (Table 1). During operation, the effluent quality from SBR was monitored daily. The observed sludge yield (Y_{obs}) coefficient was used as the ratio of the number of suspended solids (SS) produced to the amount of soluble chemical oxygen demand (SCOD) removed (mg SS/mg $SCOD_{removed}$) [27]. This parameter is widely used for evaluating the sludge reduction potential of a biological wastewater treatment process.

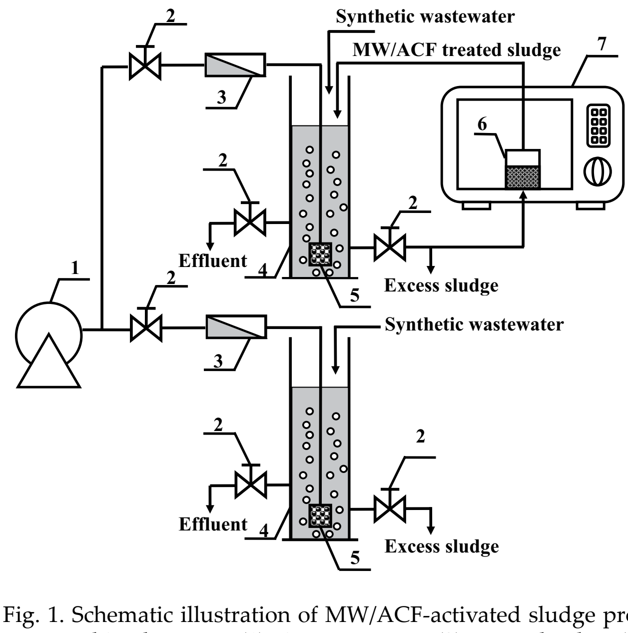

Fig. 1. Schematic illustration of MW/ACF-activated sludge process combined system: (1) air compressor; (2) manual valve; (3) flow meter; (4) SBR system; (5) micro-porous aerator; (6) Teflon vessel with ACF; (7) Microwave furnace.

Table 1
Characteristics of synthetic wastewater

Parameter	Average
COD, mg L^{-1}	494
NH_4^+–N, mg L^{-1}	26.7
P, mg L^{-1}	5.55
$CaCl_2 \cdot 2H_2O$, mg L^{-1}	9.4
$MgSO_4 \cdot 7H_2O$, mg L^{-1}	6.25

2.4. Samples analysis and calculations

Samples of effluent from the SBR system were filtered through a 0.45 μm membrane using vacuum filtration and soluble substance contents in the filtrate were measured. SS, SCOD, total phosphorus (TP), and ammonia nitrogen (NH_4^+–N) were measured based on Standard Methods [28]. A Shimadzu TOC analyzer (model TOC-V_{CPH}, Japan) was used for measuring total organic carbon (TOC).

Biosolids mass balance can be written as follows [29]:

$$W = Q_{purge}SS_{purge} + V_{react}\frac{\Delta SS}{\Delta t} + Q_{out}SS_{out} \quad (1)$$

where W is the daily sludge production, mg SS d^{-1}; Q_{purge} is the volume of sludge daily draw off, L d^{-1}; SS_{purge} is the SS concentration for the waste sludge, mg L^{-1};$\Delta SS/\Delta t$ is the daily accumulation of sludge, mg SS d^{-1}; V_{react} is the volume of the biological reactor, L; Q_{out} is the effluent flow, l d^{-1}; SS_{out} is the SS concentration of the effluent, mg L^{-1}.

This mass balance equation takes into account the accumulation within the biological reactor, the quantity of purged sludge and the sludge loss with treated effluent. Eq. (1) can be rewritten as follows for steady-state conditions:

$$W = Q_{purge}SS_{purge} + Q_{out}SS_{out} \quad (2)$$

The Y_{obs} coefficient was calculated using Eq. (3) [30]:

$$Y_{obs}\left(\text{mgSS / mgSCOD}_{removed}\right) = \frac{W}{Q \times \left(S_0 - S_e\right)} \quad (3)$$

where Q (L d^{-1}) is the flow rate of the wastewater influent to the SBR system, and S_0 (mg L^{-1}) and S_e (mg L^{-1}) are the SCOD concentrations of the influent and effluent of the SBR system, respectively.

The sludge reduction efficiency (SRE) of the test system can be calculated using Eq. (4) [5]:

$$\text{SRE}(\%) = \left(1 - \frac{Y_{obs\ Test}}{Y_{obs\ Control}}\right) \times 100 \quad (4)$$

where $Y_{obs\ Test}$ (mg SS/mg $SCOD_{removed}$) is the observed sludge yield of the SBR operated with excess sludge pretreatment, $Y_{obs\ Control}$ (mg SS/mg $SCOD_{removed}$) is the observed sludge yield of the SBR operated without excess sludge pretreatment.

3. Results and discussions

3.1. Sludge disintegration by the MW/ACF process

In our previous work, we reported that sludge was effectively decomposed by microwave combined with ACF [31]. The Supernatant TOC change of MW/ACF-treated sludge is shown in Fig. 2. TOC represents the content of carbon bound in an organic matter and its increase means that sludge lysis transfers organic matters from sludge cells into sludge mixed liquor, which contributes to subsequent cryptic growth. As shown in Fig. 2, the TOC concentration benefited from sludge disintegration and therefore showed a relatively linear increase with irradiation time. The supernatant TOC concentration rose from 67 to 391 mg L^{-1} for 70 s and increased by 483.6%. Table 2 shows the changes of supernatant SCOD, TP, total nitrogen (TN), ammonia nitrogen, polysaccharide and protein. After MW/ACF pretreatment, there were significant increases in all these indexes. The supernatant SCOD, TP, TN, ammonia nitrogen, polysaccharide and protein increased by 1,701; 16.7; 76.1; 46.7; 89.4; and 117.3 mg L^{-1}, respectively. Menéndez et al. [25] reported when the excess sludge is mixed with carbonaceous adsorbents, high temperatures can be achieved so that sewage sludge disintegration takes place rather than drying. Fig. 3 shows the scanning electron microscopy (SEM) images of the raw sludge and MW/ACF pretreated sludge. Fig. 3a indicates that the raw sludge was fully compacted, whereas, after 50 s of irradiation, the structural integrity of the treated samples was disrupted (Fig. 3b), the pretreated sludges were loose and highly porous. This lysis demonstrates indirectly that extracellular and intracellular biopolymers were released from within the sludge cells.

On the other hand, the temperature of the microwave absorber surface might be high enough to generate •OH. Quan et al. [32] used salicylic acid as a molecular probe to determine •OH in aqueous solutions, where activated carbon (AC) existed and MW radiation was involved. Results showed that •OH was generated indirectly by MW irradiation. Fortuny et al. [33] proved that AC was an excellent catalyst in catalytic wet air oxidation (CWAO). Because free radicals dominate in CWAO reaction, Quan et al. [32] supposed that AC should be a catalytic effect on •OH formation.

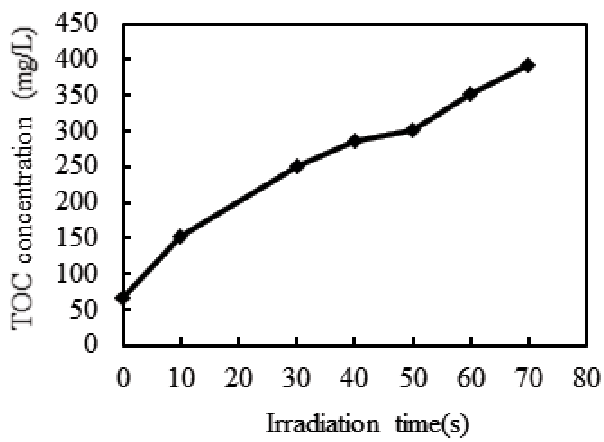

Fig. 2. Supernatant TOC under MW/ACF treatment.

Table 2
Variations of SCOD, TP, TN, ammonia nitrogen, polysaccharide and protein in the mixed liquid before and after MW/ACF pretreatment

Parameter	Raw sludge	MW/ACF
SCOD, mg L^{-1}	99	1,800
TP, mg L^{-1}	3.4	20.1
TN, mg L^{-1}	23.5	99.6
NH_4^+–N, mg L^{-1}	8.3	55. 0
Polysaccharide, mg L^{-1}	20.6	110
Protein, mg L^{-1}	22.7	140

The AC is a very good microwave absorber that can easily be heated by MW to temperatures above 1,000°C (this value is the external temperature measured by an optical pyrometer, and yet the internal temperature is probably higher [23]), so such high temperature of the micro-surfaces of AC might induce catalytic generation of •OH. Booske et al [34] made a similar suggestion, they supposed that a portion of electromagnetic energy could be focused on hot spots by the localized resonant coupling of electromagnetic energy to weak surface bonds or point defects of solid materials. The hot spot could conduce to the generation of •OH. Like AC, ACF is also an effective microwave receptor and thus plays an important role in •OH generation during MW heating. We proposed that •OH destroys the zoogloea structures and the cell walls, and then the extracellular and intracellular biopolymers are released into the supernatant. This process benefits SS disintegration, resulting in a significant increase in TOC.

3.2. SBR performance after incorporation of MW/ACF pretreatment

3.2.1. Excess sludge production

To investigate the effect of MW/ACF pretreatment on the performance of the biological wastewater treatment process, MW/ACF pretreatment was incorporated into an SBR system (test system). In the test system, 10% of the sludge was irradiated daily at an ACF dose of 0.19 g ACF/g SS for 50 s under MW power of 800 W in the MW/ACF pretreatment unit, and then it was returned to the SBR system. In order to compare the excess sludge generated from the control system and test system, the Y_{obs} were calculated. The yield coefficients for the control and the test system are presented as box plots in Fig. 4. As shown in Fig. 4, the incorporation of MW/ACF pretreatment decreased excess sludge production in the SBR system. During operation, the mean yield coefficients of the test and control system were 0.22 mg SS/mg $SCOD_{removed}$ and 0.39 mg SS/mg $SCOD_{removed}$, respectively, and the SRE was 43.6%. The microbial cryptic growth consists of lysis and biodegradation, where the lysis does not occur under ordinary conditions but once lysed, it becomes easy for other microorganisms to biodegrade the lysed cells, therefore an increase of the lysis efficiency contributes to a reduction of sludge production [10]. The lysis releases the cell contents into sludge mixed liquor and provides an autochthonous substrate for other living cells. The organic autochthonous substrate is reused by the living cells and a portion of autochthonous carbonaceous matter is liberated as products of respiration, which can lead to an overall reduction of biomass production [8,9,30]. The decrease in the sludge yield shows the incorporation of MW/ACF pretreatment into an activated sludge process is effective during excess sludge reduction and the MW/ACF pretreatment has the potential for sludge reduction.

3.2.2. Effluent quality

To investigate MW/ACF pretreatment on the effluent quality of bioreactor, SCOD, TP, and NH_4^+–N in the effluent was measured every day. Fig. 5 presents the variations of these parameters plotted against time in both the test system and control system. As is shown in Fig. 5, returning of the pretreated sludge to the test system induced a slight increase in effluent SCOD, TP and NH_4^+–N, but the biological treatment performance of the test system was

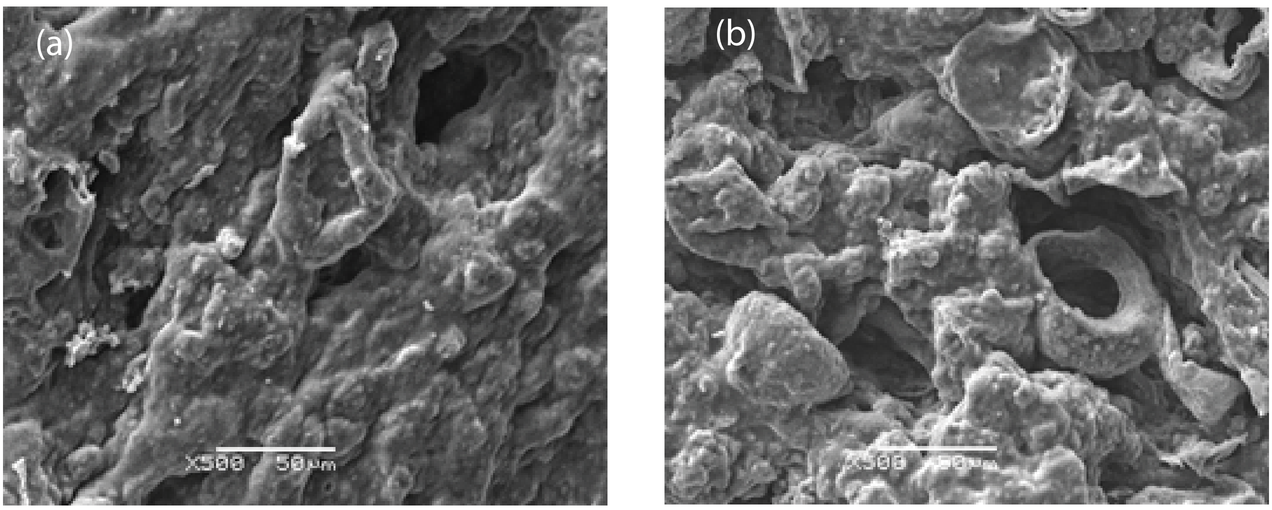

Fig. 3. SEM images of sludge before (a) and after MW/ACF pretreatment (b).

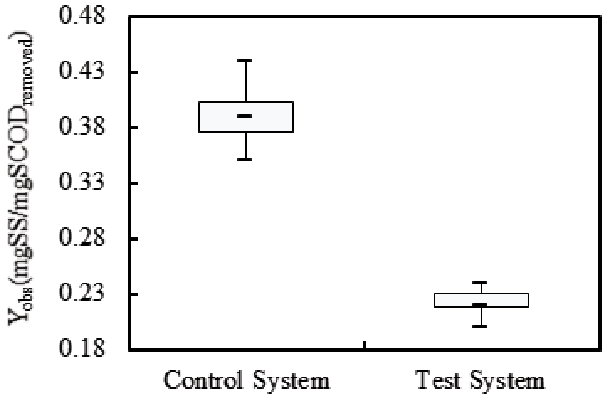

Fig. 4. Statistical analysis of the Y_{obs} coefficients.

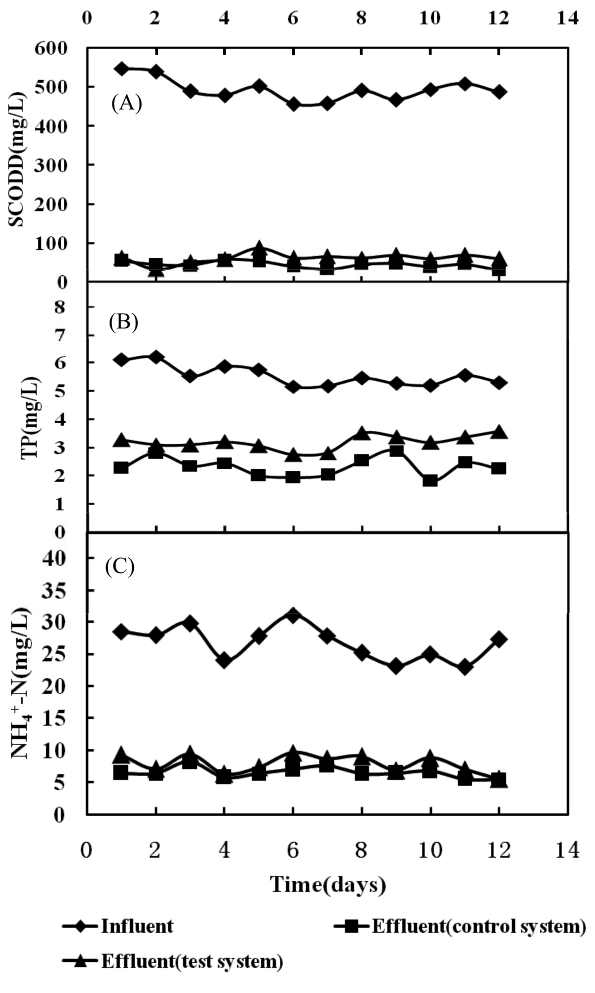

Fig. 5. Variations of the SCOD (a), TP (b) and NH_4^+–N (c) in the effluent of the control system and test system.

maintained. Soluble chemical oxygen demand (COD) in the effluent was not obviously affected by pretreatment according to the study before [26]. Fig. 5a shows that the average SCOD concentration in the effluent of the test system increased by 37.8% compared with the control system. Due to MW/ACF pretreatment, the sludge was lysed and the cell contents were released into the supernatant, which caused the increase of SCOD in the effluent. However, the total removal rate of SCOD was not affected by the pretreatment of MW/ACF. Similar SCOD removal rates of 87.4% and 90.8% were observed in the test system and the control system, respectively. Besides, a portion of SCOD generated by MW/ACF pretreatment could potentially be used as an additional carbon source for denitrification [35].As shown in Fig. 5b, the average TP concentration of the effluent was lower in the control system (2.3 mg L^{-1}) than in the test system (3.2 mg L^{-1}). The biological removal of phosphorus from wastewaters mainly depends on the bioaccumulation and bioabsorption, so the phosphorus was unavoidably released. Similar phenomena have also been reported by others in ClO_2 oxidation-activated sludge and ozonation-activated sludge systems [36–38]. The ammonia nitrogen concentrations in the influent and effluent are plotted in Fig. 5c. As seen in Fig. 5c, the nitrification process was not significantly altered by the MW/ACF pretreatment. The average NH_4^+–N concentration in the effluent of the test system increased by 21.5% compared with the control system. The decrease of the SRT of the nitrifiers due to MW/ACF pretreatment can be compensated by the increased apparent SRT due to excess sludge reduction [39]. Therefore, The nitrification process is not significantly affected by MW/ACF treatment.

4. Conclusions

MW/ACF pretreatment for the disintegration of excess sludge was tested and introduced into SBR for sludge reduction. When the ACF dose was 0.19 g/gSS and MW irradiation time was 70 s under MW power of 800 W, the supernatant TOC increased by 483.6%. The incorporation of MW/ACF pretreatment reduced significantly excess sludge production in the test system. The results indicated that the Y_{obs} of the control and test systems averaged 0.39 and 0.22 mgSS/mgSCOD$_{removed}$, respectively. The test system achieved a 43.6% reduction in sludge production compared with the control, and biological treatment efficiencies were not significantly affected.

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