STATIC MIXER APPLICATION IN ENHANCING BIOGRANULES TREATMENT THROUGH HYDRODYNAMIC SHEAR FORCE IN SEQUENCING BATCH REACTOR

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DEDICATION

To my pillar of strength

Abdul Syukor bin Abd Razak

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ABSTRACT

Biogranulation is considered a promising technology in biological wastewater treatment due to its high effluent treatment quality, strong ability to withstand organic loading, strong microbial structure and high capability to remove organics, nitrogen and phosphate. Hydrodynamic shear force in terms of superficial air velocity (SAV) is known as one of the significant factors in biogranulation process. High SAV would lead to the requirement of high aeration energy in biogranulation system while lowering the SAV will not be able to form biogranules of desired characteristics. The main objective of this study was to determine the effect of static mixer at low SAV on physical properties and removal performance of biogranules in treating synthetic textile wastewater. Experiments were divided into initial, development and post-development stages. Four static mixers namely SM1, SM2, SM3 and SM4 were designed and tested in the initial phase of the study. The best static mixer was chosen based on the mixing time study. The experiments were carried out in Sequencing Batch Reactor (SBR) made of acrylic with a height of 100 cm, diameter of 8 cm and a working volume of 1.5 L, at an exchange ratio of 50%. Three reactors with static mixer and another three operating without static mixer (R1-0.5N, R1-0.5Y, R2-1.4N, R2-1.4Y, R3-21.N and R3-2.1Y) were used during development stage to investigate the properties and performance of developed granules under influence of static mixers and SAVs of 0.5, 1.4 and 2.1 cm/s. The influence of hydraulic retention time (HRT) and organic loading rate (OLR) on the properties and performance of aerobic granules were investigated during post development stage. Two reactors named as R4Y and R4N were used, where R4Y was a reactor with static mixer and R4N was without the static mixer. The mixing study revealed that SM1 was the best static mixer as compared to SM2, SM3 and SM4 due to the shortest mixing time of 8 sec. The results in development stage disclosed that the granules could be developed at low SAV using static mixer (R1-0.5Y) with integrity coefficient (IC) of 40.5%, sludge volume index (SVI) of 107.5 mL/g, settling velocity (SV) of 70.3 m/h, chemical oxygen demand (COD) removal of 94.6% and color removal of 53.8%. The results also showed that the developed granules in others reactors with static mixer improved the physical properties and reactor performance. Reactor R2-1.4Y was the best with an IC of 27.5%, SVI of 29.6 mL/g, SV of 80.4 m/h, COD removal of 94.2% and color removal of 63.1%. The study also demonstrated that HRT and OLR affected the performance of biogranules. Again, the physical characteristics of biogranules and removal efficiencies of the reactor with static mixer seemed to be better as compared to the reactor without static mixer with increasing of HRT and OLR. The increase of HRT in the system resulted in decreasing of SRT (R4N-95.1 days, R4Y-96.8 days) with increasing of overall specific biomass growth rate ($\mu_{overall}$) (R4N-0.011 per day, R4Y-0.010 per day), endogenous decay rate (k_d) (R4N-0.178 per day, R4Y-0.241 per day), observed biomass yield (Y_{obs}) (R4N-0.052 mg VSS/mg COD, R4Y-0.051 mg VSS/mg COD) and theoretical biomass yield (Y) (R4N-0.938 mg VSS/mg COD, R4Y-1.230 mg VSS/mg COD). Meanwhile, the higher OLR of the system increased the SRT (R4N-96.2 days, R4Y-100 days) which led to the decreasing of $\mu_{overall}$ (R4N-0.010 per day, R4Y-0.010 per day), k_d (R4N-0.179 per day, R4Y-0.197 per day), Y_{obs} (R4N-0.027 mg VSS/mg COD, R4Y-0.028 mg VSS/mg COD) and Y (R4N-0.497 mg VSS/mg COD, R4Y-0.587 mg VSS/mg COD). At lower SAV, the use of static mixer provided shorter SRT which resulted in higher $\mu_{overall}$, k_d, Y_{obs} and Y compared to the reactor without static mixer. The findings proved that static mixer is capable to enhance hydrodynamic shear force at low SAV in biogranulation system and therefore, will lower the energy consumption and operational cost.

ABSTRAK

Biogranulasi dikenal pasti sebagai salah satu teknologi berkeupayaan tinggi bagi sistem olahan air sisa secara biologi disebabkan keupayaan menghasilkan effluen berkualiti tinggi, daya tahanan terhadap beban organik, struktur mikrob yang kuat serta keupayaan yang tinggi untuk menyingkirkan bahan organik, nitrogen dan fosfat. Daya ricih hidrodinamik dalam bentuk halaju udara permukaan (SAV) dikenal pasti sebagai salah satu faktor utama di dalam proses biogranulasi. Nilai SAV yang tinggi akan menyebabkan keperluan tenaga pengudaraan yang tinggi manakala nilai SAV yang rendah tidak akan dapat membentuk biogranul yang mempunyai ciri-ciri yang dikehendaki. Objektif utama kajian ini adalah untuk mengenal pasti kesan pengaduk statik pada SAV rendah terhadap ciri-ciri fizikal dan prestasi penyingkiran biogranul di dalam mengolah air sisa tekstil. Ujikaji dibahagikan kepada peringkat permulaan, pembentukan dan pasca pembentukan. Empat pengaduk statik iaitu SM1, SM2, SM3 dan SM4 direka bentuk dan diuji semasa peringkat permulaan kajian. Pengaduk statik terbaik telah dipilih berdasarkan ujian masa pembauran. Semua ujikaji dijalankan menggunakan Reaktor Kelompok Berjujukan (SBR) yang diperbuat daripada akrilik dengan ketinggian 100 cm, diameter 8 cm dan isipadu kerja 1.5 L serta nisbah pertukaran 50%. Tiga reaktor dengan pengaduk statik dan tiga lagi tanpa pengaduk statik (R1-0.5N, R1-0.5Y, R2-1.4N, R2-1.4Y, R3-21.N dan R3-2.1Y) di bawah SAVs 0.5, 1.4 dan 2.1 cm/s telah digunakan semasa peringkat pembentukan bagi mengenal pasti ciri-ciri dan prestasi granul yang terbentuk. Di peringkat pasca pembentukan, pengaruh masa tahanan hidraulik (HRT) dan kadar beban organik (OLR) telah dikenal pasti. Dua reaktor yang dinamakan sebagai R4Y dan R4N telah digunakan, di mana R4Y adalah reaktor dengan pengaduk statik manakala R4N adalah reaktor tanpa pengaduk statik. Ujian masa pembauran menunjukkan bahawa SM1 adalah pengaduk statik terbaik kerana mempunyai masa pembauran terpantas iaitu 8 saat jika dibandingkan dengan SM2, SM3 dan SM4. Keputusan kajian peringkat pembentukan mendapati bahawa reaktor yang mempunyai pengaduk statik (R1-0.5Y) dan nilai SAV yang rendah menghasilkan biogranul dengan nilai pekali integriti (IC) sebanyak 40.5%, indeks isipadu enapcemar (SVI) sebanyak 107.5 mL/g, halaju pengenapan (SV) sebanyak 70.3 m/h, penyingkiran permintaan oksigen kimia (COD) sebanyak 94.6% dan penyingkiran warna sebanyak 53.8%. Hasil ujikaji juga mendapati reaktor lain yang mempunyai pengaduk statik mampu menghasilkan biogranul yang mempunyai ciri-ciri fizikal dan kadar prestasi yang lebih baik. Reaktor R2-1.4Y merupakan reaktor yang terbaik dengan IC serendah 27.5%, SVI sebanyak 29.6 mL/g, SV sebanyak 80.4 m/h, penyingkiran COD sebanyak 94.2% dan penyingkiran warna sebanyak 63.1%. Kajian juga mendapati bahawa HRT dan OLR mempengaruhi prestasi biogranul. Dengan peningkatan HRT dan OLR juga, ciri-ciri fizikal dan kadar kecekapan penyingkiran bagi reaktor mempunyai pengaduk statik didapati lebih baik berbanding reaktor tanpa pengaduk statik. Peningkatan HRT memendekkan masa tahanan pepejal (SRT) (R4N-95.1 hari, R4Y-96.8 hari) yang mengakibatkan peningkatan nilai keseluruhan kadar pertumbuhan biojisim spesifik ($\mu_{overall}$) (R4N-0.011 per hari, R4Y-0.010 per hari), kadar kematian (k_d) (R4N-0.178 per hari, R4Y-0.241 per hari), hasil biojisim yang diperhatikan (Y_{obs}) (R4N-0.052 mg VSS/mg COD, R4Y-0.051 mg VSS/mg COD) dan hasil biojisim teori (Y) (R4N-0.938 mg VSS/mg COD, R4Y-1.230 mg VSS/mg COD). Sementara itu, peningkatan nilai OLR meningkatkan SRT (R4N-96.2 hari, R4Y-100 hari) yang menyebabkan penurunan $\mu_{overall}$ (R4N-0.010 per hari, R4Y-0.010 per hari), k_d (R4N-0.179 per hari, R4Y-0.197 per hari), Y_{obs} (R4N-0.027 mg VSS/mg COD, R4Y-0.028 mg VSS/mg COD) and Y (R4N-0.497 mg VSS/mg COD, R4Y-0.587 mg VSS/mg COD). Pada nilai SAV yang rendah, penggunaan pengaduk statik menghasilkan nilai SRT yang lebih pendek dan seterusnya meningkatkan nilai $\mu_{overall}$, k_d, Y_{obs} dan Y jika dibandingkan dengan reaktor tanpa pengaduk statik. Hasil ujikaji membuktikan bahawa pengaduk statik mampu meningkatkan daya ricih hidrodinamik di dalam sistem biogranulasi walaupun pada nilai SAV yang rendah, dan oleh itu akan menurunkan penggunaan tenaga dan kos operasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADMI	-	American Dye Manufacturing Index
BOD	-	Biochemical oxygen demand
CAS	-	Conventional activated sludge
COD	-	Chemical oxygen demand
DGGE	-	Denaturing gradient gel electrophoresis
DO	-	Dissolved oxygen
EPS	-	Extracellular polymeric substances
FESEM	-	Field emission scanning electron microscope
FISH	-	Fluorescence in situ hybridization
HRT	-	Hydraulic retention time
IC	-	Integrity coefficient
LB-EPS	-	Loosely bound EPS
MLSS	-	Mixed liquor suspended solid
MLVSS	-	Mixed liquor volatile suspended solid
N	-	Nitrogen
NaCl	-	Sodium chloride
NH_4	-	Ammonia nitrogen
OLR	-	Organic loading rate
OUR	-	Oxygen utilization rate
P	-	Phosphorus
POME	-	Palm oil effluent mill
SAV	-	Superficial air velocity
SBBGR	-	Sequencing batch biofilter granular reactor
SBR	-	Sequencing batch reactor
SEM	-	Scanning electron microscopic
SPSS	-	Statistical Package for Social Sciences
SV	-	Settling velocity
SVI	-	Sludge volume index
TB-EPS	-	Tightly bound EPS
TDS	-	Total dissolved solids

TN	-	Total nitrogen
TP	-	Total phosphorus
TS	-	Total solids
UASB	-	Upflow anaerobic sludge blanket
VER	-	Volume exchange ratio

LIST OF SYMBOLS

k_d	-	Endogenous decay rate
m	-	Mean
P	-	Significance difference
t_c	-	cycle time of SBR operation
V_d	-	manually discharged mixture volume
V_e	-	effluent volume of the SBR operating cycle
V_r	-	working volume of SBR reactor
X_d	-	biomass concentration of manually discharged
X_e	-	effluent volatile solid concentrations
X_{VSS}	-	volatile solid concentration in reactor
Y_{obs}	-	Observed biomass yield
Y	-	Theoretical biomass yield
$\mu_{overall}$	-	Overall specific biomass growth rate
θ_c	-	solid retention time

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Preamble

Water is the most essential requirement for all life but in recent years the availability becoming limited due to the increasing contamination and human activities around the world. According to statistics, currently there are 7.6 billion people living without safe drinking water, two million people die annually due to diarrhoea and about one third of the world's population have poor sanitation systems (Tee et al., 2016). Based on reported cases around the world, water pollution is one of the issues that are becoming serious every year. The main sources of water pollution are not limited to but mainly include industrial and domestic wastewaters. Untreated or improperly treated wastewater which is discharged to the environment pollutes the receiving water and threatens the environment and human health. Hence, various technologies have been developed and used since decades to ensure the wastewater is being properly treated.

During the past hundred years, the conventional activated sludge (CAS) processes have been established in biological wastewater treatment. The first generation of activated sludge systems was built in the 1920's by Ardern and Lockett (De Kreuk & Loosdrecht, 2006). The basic idea behind the CAS system was to reduce the treatment of wastewater to a one-reactor system. Generally, the system consists of an aeration tank in which a mixed culture of suspended biomass is growing. Along with the removal of organic carbon and nutrients from the influent and a settling tank, the treated effluent is separated from the biomass (Metcalf & Eddy, 2003). Conventional activated sludge process produce surplus sludge. Part of the settled activated sludge is recycled to the aeration tank and the remainder is usually treated and later disposed or used as fertilizer. One of the major drawback of CAS is the poor solid-liquid separation between biomass and the treated effluent

(Gobi, Mashitah, & Vadivelu, 2011). To be specific, this treatment plants generally require large surface area in order to provide large aeration tanks. In fact as the available ground area to build the treatment plant is limited especially in dense populated regions, there is a need for a more compact treatment. According to (de Bruin, de Kreuk, van der Roest, Uijterlinde, & van Loosdrecht, 2004), this need directed to the development of systems based on biogranulation technology which is an alternative to the existing technology, as the footprint of this technology is only 25% compared to that of the CAS.

Biogranulation technology is considered as one of the novel advanced biological treatment technologies developed for wastewater treatment. Biogranulation process involves cell-to-cell attachment in which granules are formed through self-immobilization of microorganisms. As compared to CAS flocs, biogranules are dense, compact and has strong structure with good settling properties. Biogranulation is a complex process with many factors affecting the structure and composition of the granules. Biogranulation for methanogenic sludge was first reported by Lettinga, van Velsen, Hobma, de Zeeuw, & Klapwijk, (1980) where biogranules were formed in upflow anaerobic sludge blanket (UASB) reactors. However it exhibits several drawbacks, which include the need of a long start-up period, a relatively high operating temperature, incapability to treat low strength organic wastewater and less efficient in removing nutrients from the wastewater (Adav, Lee, Show, & Tay, 2008). Mishima and Nakamura (1991) began a study on aerobic granulation to overcome these weaknesses.

Most aerobic granules have been cultured in sequencing batch reactors (SBRs). Sequencing batch reactors is a fill and draw activated sludge system where the suspended biomass is grown to remove organics and nutrients from the influent. Sequencing batch reactors saves more than 60% of the expenses required for conventionally activated sludge process in terms of operating cost and in achieving high effluent quality within a very short aeration time (Singh & Srivastava, 2011). The system is a repetitive system, which basically comprises of filling, reaction, settling, decanting and idling within a single bioreactor.

Several conditions such as organic loading rate (OLR), composition of substrate, settling time, hydraulic retention time (HRT), reactor configuration, volume exchange ratio (VER), mineral cations, cell hydrophobicity, extracellular polymeric substances (EPS), dissolved oxygen and hydrodynamic shear force affect the formation of the granules. One of the most influencing factors that have received consideration is the hydrodynamic shear force, quantified by superficial air velocity (SAV). The general agreement is that high shear force forms compact and dense granules. High shear force encourages bacteria to produce more EPS that contribute to the cells attachments and maintain the microorganisms structure (Liu, Liu, Wang, Yang, & Tay, 2005). In addition, the high detachment force resulted from the high hydrodynamic shear force can further shape aggregate surface forming dense and smooth granules (Chen, Jiang, Liang, & Tay, 2007), which also leads to stronger and smaller aerobic granules (Tay, Liu, & Liu, 2004). Hydrodynamic shear force has been proven to have a signifance influence to the formation of compact, stable and dense aerobic granules (Liu & Tay, 2002).

In most of the earlier studies, it has been observed that hydrodynamic shear force in terms of SAV used in reactor was found to be much higher than 1.2 cm/s; therefore, high aeration rate is necessary to ensure the granular sludge formation and successful of the granulation process. Beun et al. (1999) reported that at high SAV of 4.1 cm/s, smooth granules were formed whereas at lower SAV of 1.4 cm/s and 2.0 cm/s, loose and poor settling ability of granules were developed. Tay, Liu and Liu, (2001) also found that regular, rounder and more compact granules could be formed at SAV of above 1.2 cm/s only. Sturm and Irvine (2008) observed that granules disintegrated into flocs when SAV was lower than 1.0 cm/s. Chen, Jiang, Liang and Tay (2008) reported that a high SAV of 3.2 cm/s was used to develop stable granules with good settling properties. In another study, Lochmatter, Gonzalez-Gil, & Holliger (2013) applied air velocities of 2.1 to 2.8 cm/s to obtain stable granules. Lochmatter and Holliger (2014) also carried out an experiment at SAV of 2.8 cm/s and proved biogranulation process reliability under high shear force. However, in more recent studies, different observations were reported. Henriet, Meunier, Henry, and Mahillon (2016) observed that under low SAV of 0.42 cm/s, stable granules could be obtained using SBR in treating acetate. Additionally, Devlin, di Biase, Kowalski & Oleszkiewicz, (2016) successfully developed stable granules treating low-strength wastewater under SAV of 0.41 cm/s.

1.2 Problem Statement

Hydrodynamic shear force was proven to be one of the significant factors for the stability of biogranules. There have been number of attempts to develop strategies for improving the biogranulation process. Experimental evidences show that a wide range of SAVs has been successfully used to develop the biogranules. Different SAVs from as low as 0.41 cm/s to 3.4 cm/s were experimented by different researchers to find the best conditions for the biogranulation. A high SAV increases the attrition of granules and shifts granule size distribution towards smaller size but with higher density, however, a relatively low SAV favors the growth of granules size but with lower density. One of the challenges in the biogranulation process in providing the optimum SAV is cost. Such SAVs normally require high aeration rates which results in high energy consumption and eventually operational cost. Producing hydrodynamic shear force at lower SAV is a challenge and should be the way forward. Therefore, a strategy to favor the granules development and enhance the performance of biogranulation process is worthy to explore. Apparently, no study has been carried out on the use of static mixer in enhancing the hydrodynamic shear force. In this study, a static mixer was introduced in the reactor to enhance the hydrodynamic shear force even at low SAV. Static mixer provides well-mixed condition as it is very important in the process. The main objective of this work was to study the effect of static mixer combination with low SAV in the reactor on the properties of developed biogranules and reactor performance. The findings would provide a cheaper promising alternative for aerobic biogranulation system.

Different operational strategies have led to the different biogranules characteristics and removal performance. Hydraulic retention time is an important parameter that controls the contact time between biomass and the wastewater in a reactor system. The range of HRT among the previous studies was 1 to 36 hours. Liu, Moy & Tay, (2007) reported that granules were formed within 16 days under

HRT of 3 hours while it took 21 days under HRT of 16 hours. Pan, Tay, He, and Tay (2004) claimed that an HRT of 6 hours is most appropriate for biogranulation since the granules possessed higher cell hydrophobicity. A short HRT is favorable for rapid granulation process while too long HRT may cause the disintegration of the granules and lead to granulation system failure (Liu & Tay, 2015). Therefore, choice of HRT is very important in biogranulation process.

Organic loading rate is another crucial factor in any biological system. It was reported in many previous study that aerobic granules was able to withstand OLR range 2.5 to 15 kg/m^3.day. The low OLR probably did not enhance the granulation as many researchers have pointed out (Liu & Tay, 2015; Nguyen, Van Nguyen, Truong, & Bui, 2016). A moderate OLR was found to favor the development of stable aerobic granules (Tay, Pan, He, Tiong, & Tay, 2004). It has been reported that high OLR is beneficial for accumulating biomass by secreting more EPS. However, Long et al., (2015) demonstrate that aerobic granules disintegrated and eventually led to the collapse of the aerobic granule system when OLR increased to 18 kg/m^3.day. As observed from the experiment, disintegration of AGS mainly ascribed to instability of granule's inner core. Additionally, study on evaluating the effect of static mixer under influence of different HRTs and OLRs in the biogranulation system has never been reported. Thus, this study sought to investigate the effects of granules properties and reactor performance under combination of various HRTs and OLRs with the addition of static mixer into the reactor system. Moreover, kinetics study on aerobic granule growth at the steady state is also carried out to correlate sludge production, sludge growth, and sludge retention time with HRT and OLR.

1.3 Objectives of Study

The main aim of this study is to enhance the biogranulation treatment in terms of energy requirement and characteristics of the biogranules with the use of static mixer. Hence, the objectives of the study are as follows:

1. To design and identify a suitable static mixer based on mixing intensity study.

2. To investigate the development of aerobic granules and their performance in treating synthetic textile wastewater in the SBR under different SAVs and influence of static mixer.
3. To evaluate the effect of static mixer on the properties and performance of aerobic granules under different HRTs and OLRs.
4. To determine the biokinetic properties of the SBR system under different HRTs and OLRs

1.4 Scope of Study

This study was carried out using a lab-scale SBR system under intermittent anaerobic and aerobic phase. A glass column with a working volume of 1.5L was used. Synthetic wastewater was used as the feed influent and the seed sludge was obtained from Taman Harmoni IWK Sewage Treatment Plant (STP). Four types of static mixers were designed and custom-made to suit the laboratory-scale reactor system. In this study, two stages of experimental works were involved which are the development and the post-development stage. The SAVs of 0.5, 1.4 and 2.1 cm/s have been applied during the development stage while HRT and OLR were set at 8 hours and 2.0 kg/m^3.day, respectively. Samples of granules were collected and examined for their morphology and physical properties such as mixed liquor suspended solid (MLSS), sludge volume index (SVI), settling velocity (SV) and integrity coefficient (IC). The formed granules were also tested for performance in treating textile wastewater in terms of chemical oxygen demand (COD) and color removal. The effects of HRT and OLR on the performance of biogranules were investigated in post-development stage. Furthermore, the relationship between the biokinetic parameters at different HRT and OLR were also explored. Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) 21 to determine the significant difference between reactor with and without static mixer.

1.5 Significance of Study

Previous studies have proven that hydrodynamic shear force has a significant effect on the formation and stability of aerobic granules (Tay et al., 2001; Liu & Tay, 2002; Chen et al., 2008; Lochmatter et al., 2013; Devlin et al., 2016). The hydrodynamic shear force triggers the production of EPS, which is important in bacterial cells attachment. A high hydrodynamic shear force generally needs big amounts of energy, which raises the applications cost. Therefore, a static mixer was added to the reactor to enhance the shear force at low SAV. Apparently, the influence of static mixer in manipulating the hydrodynamic shear force in the process of aerobic granules development has not been studied. Several significant contributions of this study are identified as follows:

i. Hydrodynamic shear force is one the most influencing factor in biogranulation. This study is regarded as the pioneer study on the influence of static mixer in manipulating the hydrodynamic shear force to develop the biogranules treating textile wastewater.

ii. This study provides the suitable SAVs together with static mixer for developing aerobic granules especially for degradation of textile wastewater.

iii. This study contributes to the knowledge of the properties of biogranules under influence of static mixer.

iv. Aerobic granules are known to have strong and dense microstructure and ability to withstand high OLRs. This study provides information on the effect of various HRT and OLR to the profile of aerobic granules under influence of static mixer.

v. For the design and operation of aerobic granular system for biological treatment process, the underlying biological growth kinetics is important to be understood. This study provides the kinetics of biomass growth parameters including overall specific biomass growth rate ($\mu_{overall}$), endogenous decay rate (k_d), observed biomass yield (Y_{obs}) and theoretical biomass yield (Y), which followed the Monod's model.

1.6 Thesis Organization

The thesis is organised into five chapters. Chapter 1 introduces the application of biogranulation technology in wastewater treatment. This chapter also provides an overview on the factors affecting the performance of biogranulation technology. It also presents the statement of research problems, research objectives and significance of the study.

Chapter 2 is dedicated for the literature reviews on the background of biogranulation technology, factors affecting the process and application of the technology. The basic principles of biogranulation technology which include the theory of granulation process and various application of biogranulation technology in treating different types of wastewater are also highlighted. A review of previous studies in the related topics is also given in this chapter.

Chapter 3 explains the methodology used in the study. This chapter details out the laboratory materials and equipment, analytical method as well as experimental procedures including wastewater feed and seed sludge used throughout the study. The reactor description, operational strategies are also illustrated in details in this chapter.

Chapter 4 reports and discusses the results obtained from the study, which include the findings during the development stage and post-development stage of the aerobic granules. Finally, Chapter 5 summarizes the conclusions of the findings from this study, embracing the specific achievement and recommendations for the future studies. General conclusions are also drawn based on the outcomes and experiences gained throughout the study.

REFERENCES

Ab Halim, M. H., Nor Anuar, A., Abdul Jamal, N. S., Azmi, S. I., Ujang, Z., & Bob, M. M. (2016). Influence of high temperature on the performance of aerobic granular sludge in biological treatment of wastewater. *Journal of Environmental Management*, *184*, 271–280. https://doi.org/10.1016/j.jenvman.2016.09.079

Ab Halim, M. H., Nor Anuar, A., Azmi, S. I., Jamal, N. S. A., Wahab, N. A., Ujang, Z., … Bob, M. M. (2015). Aerobic sludge granulation at high temperatures for domestic wastewater treatment. *Bioresource Technology*, *185*, 445–449. https://doi.org/10.1016/j.biortech.2015.03.024

Abdullah, N., Ujang, Z., & Yahya, A. (2011). Aerobic granular sludge formation for high strength agro-based wastewater treatment. *Bioresource Technology*, *102*(12), 6778–6781. https://doi.org/10.1016/j.biortech.2011.04.009

Abdullah, N., Yuzir, A., Curtis, T. P., Yahya, A., & Ujang, Z. (2013). Characterization of aerobic granular sludge treating high strength agro-based wastewater at different volumetric loadings. *Bioresource Technology*, *127*, 181–187. https://doi.org/10.1016/j.biortech.2012.09.047

Abou Hweij, K., & Azizi, F. (2015). Hydrodynamics and residence time distribution of liquid flow in tubular reactors equipped with screen-type static mixers. *Chemical Engineering Journal*, *279*, 948–963. https://doi.org/10.1016/j.cej.2015.05.100

Adav, S. S., Lee, D.J., & Lai, J.Y. (2009). Aerobic granulation in sequencing batch reactors at different settling times. *Bioresource Technology*, *100*(21), 5359–5361. https://doi.org/10.1016/j.biortech.2009.05.058

Adav, S. S., Lee, D.J., & Lai, J.Y. (2010). Potential cause of aerobic granular sludge breakdown at high organic loading rates. *Applied Microbiology and Biotechnology*, *85*(5), 1601–1610. https://doi.org/10.1007/s00253-009-2317-9

Adav, S. S., Lee, D.J., & Lai, J. Y. (2007). Effects of aeration intensity on formation of phenol-fed aerobic granules and extracellular polymeric substances. *Applied Microbiology and Biotechnology*, *77*(1), 175–182. https://doi.org/10.1007/s00253-007-1125-3

Adav, S. S., Lee, D.J., Show, K.Y., & Tay, J.H. (2008). Aerobic granular sludge: recent advances. *Biotechnology Advances*, *26*(5), 411–423. https://doi.org/10.1016/j.biotechadv.2008.05.002

Adav, S. S., Lee, D.J., & Tay, J.H. (2008). Extracellular polymeric substances and structural stability of aerobic granule. *Water Research*, *42*(6–7), 1644–1650. https://doi.org/10.1016/j.watres.2007.10.013

Ahmad, A., Mohd-Setapar, S. H., Chuong, C. S., Khatoon, A., Wani, W. A., Kumar, R., & Rafatullah, M. (2015). Recent advances in new generation dye removal technologies: Novel search for approaches to reprocess wastewater. *RSC Advances*, *5*(39), 30801–30818. https://doi.org/10.1039/c4ra16959j

Al-busafi, A., Al-harrasi, B., Al-shidhani, I., & Al-dallal, A. J. A. (2016). Study on Mixing Time and Gas Hold-up in an Airlift Bioreactor, (September).

Al-Malack, M. H. (2006). Determination of biokinetic coefficients of an immersed membrane bioreactor. *Journal of Membrane Science*, *271*(1–2), 47–58. https://doi.org/10.1016/j.memsci.2005.07.008

Anderson, P., & Meijer, H. E. H. (2000). Chaotic mixing analysis by distribution matrices. *Applied {R}heology*, *10*(3), 119–133.

André, C., Demeyre, J. F., Gatumel, C., Berthiaux, H., & Delaplace, G. (2012). Dimensional analysis of a planetary mixer for homogenizing of free flowing powders: Mixing time and power consumption. *Chemical Engineering Journal*, *198–199*, 371–378. https://doi.org/10.1016/j.cej.2012.05.069

Arrojo, B., Mosquera-Corral, A., Garrido, J. M., & Méndez, R. (2004). Aerobic granulation with industrial wastewater in sequencing batch reactors. *Water Research*, *38*(14–15), 3389–3399. https://doi.org/10.1016/j.watres.2004.05.002

Awomeso, J. A., Taiwo, A. M., Gbadebo, A. M., & Arimoro, A. O. (2010). Waste disposal and pollution management in urban areas: A workable remedy for the environment in developing countries. *American Journal of Environmental Sciences*, *6*(1), 26–32. https://doi.org/10.3844/ajessp.2010.26.32

Banerjee, P., Sau, S., Das, P., & Mukhopadhayay, A. (2015). Optimization and modelling of synthetic azo dye wastewater treatment using Graphene oxide nanoplatelets: Characterization toxicity evaluation and optimization usingArtificial Neural Network. *Ecotoxicology and Environmental Safety*, *119*, 47–57. https://doi.org/10.1016/j.ecoenv.2015.04.022

Bashiri, B., Fallah, N., Bonakdarpour, B., & Elyasi, S. (2018). The development of aerobic granules from slaughterhouse wastewater in treating real dyeing wastewater by Sequencing Batch Reactor (SBR). *Journal of Environmental Chemical Engineering*, *6*(4), 5536–5543. https://doi.org/10.1016/j.jece.2018.05.020

Bassin, J. P., Pronk, M., Kraan, R., Kleerebezem, R., & Van Loosdrecht, M. C. M. (2011). Ammonium adsorption in aerobic granular sludge, activated sludge and anammox granules. *Water Research*, *45*(16), 5257–5265. https://doi.org/10.1016/j.watres.2011.07.034

Bauman, I. (2001). Solid-solid mixing with static mixers. *Chemical and Biochemical Engineering Quarterly*, *15*(4), 159–165. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0035699694&partnerID=tZOtx3y1

Beun, J. ., Hendriks, a, van Loosdrecht, M. C. ., Morgenroth, E., Wilderer, P. ., & Heijnen, J. . (1999). Aerobic granulation in a sequencing batch reactor. *Water Research*, *33*(10), 2283–2290. https://doi.org/10.1016/S0043-1354(98)00463-1

Beun, J. J., van Loosdrecht, M. C. M., & Heijnen, J. J. (2002). Aerobic granulation in a sequencing batch airlift reactor. *Water Research*, *36*(3), 702–712. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11831218

Bilińska, L., Gmurek, M., & Ledakowicz, S. (2016). Comparison between industrial and simulated textile wastewater treatment by AOPs – Biodegradability, toxicity and cost assessment. *Chemical Engineering Journal*, *306*, 550–559.

https://doi.org/10.1016/j.cej.2016.07.100

Bindhu, B. K., & Madhu, G. (2013). Influence of Organic Loading Rates on Aerobic Granulation Process for the Treatment of Wastewater. *Journal of Clean Energy Technologies*, *1*(2), 84–87. https://doi.org/10.7763/JOCET.2013.V1.20

Bindhu, B. K., & Madhu, G. (2015). Influence of three selection pressures on aerobic granulation in sequencing batch reactor, *22*(September), 241–247.

Bindhu, B. K., & Madhu, G. (2017). Application of grey system theory on the influencing parameters of aerobic granulation in SBR. *Environmental Technology (United Kingdom)*, *38*(17), 2143–2152. https://doi.org/10.1080/09593330.2016.1246617

Bonvillani, P., Ferrari, M. P., Ducros, E. M., & Orejas, J. A. (2006). Theoretical and experimental study of the effects of scale-up on mixing time for a stirred-tank bioreactor. *Brazilian Journal of Chemical Engineering*, *23*(1), 1–7. https://doi.org/10.1590/S0104-66322006000100001

Bren, A., Hart, Y., Dekel, E., Koster, D., & Alon, U. (2013). The last generation of bacterial growth in limiting nutrient. *BMC Systems Biology*, *7*(1), 27. https://doi.org/10.1186/1752-0509-7-27

Brillas, E., & Martínez-Huitle, C. A. (2015). Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. An updated review. *Applied Catalysis B: Environmental*, *166–167*, 603–643. https://doi.org/10.1016/j.apcatb.2014.11.016

Bumbac, C., Ionescu, I. A., Tiron, O., & Badescu, V. R. (2015). Continuous flow aerobic granular sludge reactor for dairy wastewater treatment. *Water Science and Technology*, *71*(3), 440–445. https://doi.org/10.2166/wst.2015.007

Caluwé, M., Dobbeleers, T., D'aes, J., Miele, S., Akkermans, V., Daens, D., … Dries, J. (2017). Formation of aerobic granular sludge during the treatment of petrochemical wastewater. *Bioresource Technology*, *238*, 559–567. https://doi.org/10.1016/j.biortech.2017.04.068

Campo, R., Corsino, S. F., Torregrossa, M., & Di Bella, G. (2018). The role of extracellular polymeric substances on aerobic granulation with stepwise increase of salinity. *Separation and Purification Technology*, *195*(August 2017), 12–20. https://doi.org/10.1016/j.seppur.2017.11.074

Campos, J. L., Figueroa, M., & Rı, A. V. (2011). Treatment of high loaded swine slurry in an aerobic granular reactor, 1808–1814. https://doi.org/10.2166/wst.2011.381

Campos, J. L., Garrido-Fernández, J. M., Méndez, R., & Lema, J. M. (1999). Nitrification at high ammonia loading rates in an activated sludge unit. *Bioresource Technology*, *68*(2), 141–148. https://doi.org/10.1016/S0960-8524(98)00141-2

Cardoso, J. C., Bessegato, G. G., & Boldrin Zanoni, M. V. (2016). Efficiency comparison of ozonation, photolysis, photocatalysis and photoelectrocatalysis methods in real textile wastewater decolorization. *Water Research*, *98*, 39–46. https://doi.org/10.1016/j.watres.2016.04.004

Carneiro, P. A., Umbuzeiro, G. A., Oliveira, D. P., & Zanoni, M. V. B. (2010). Assessment of water contamination caused by a mutagenic textile effluent/dyehouse effluent bearing disperse dyes. *Journal of Hazardous Materials*, *174*(1–3), 694–699. https://doi.org/10.1016/j.jhazmat.2009.09.106

Caşcaval, D., Matran, R. M., Turnea, M., Blaga, A. C., & Galaction, A. I. (2015). Distribution of mixing efficiency in a split-cylinder gas-lift bioreactor for *Yarrowia lipolytica* suspensions. *The Canadian Journal of Chemical Engineering*, *93*(1), 18–28. https://doi.org/10.1002/cjce.22107

Cassidy, D. P., & Belia, E. (2005). Nitrogen and phosphorus removal from an abattoir wastewater in a SBR with aerobic granular sludge. *Water Research*, *39*(19), 4817–4823. https://doi.org/10.1016/j.watres.2005.09.025

Caudan, C., Filali, A., Spérandio, M., & Girbal-Neuhauser, E. (2014). Multiple EPS interactions involved in the cohesion and structure of aerobic granules. *Chemosphere*,*117*(1),262–270. https://doi.org/10.1016/j.chemosphere.2014.07.020

Cetin, E., Karakas, E., Dulekgurgen, E., Ovez, S., Kolukirik, M., & Yilmaz, G. (2018). Effects of high-concentration influent suspended solids on aerobic granulation in pilot-scale sequencing batch reactors treating real domestic wastewater. *Water Research*, *131*, 74–89. https://doi.org/10.1016/j.watres.2017.12.014

Chen, C., Ming, J., Yoza, B. A., Liang, J., Li, Q. X., Guo, H., … Wang, Q. (2019). Characterization of aerobic granular sludge used for the treatment of petroleum wastewater. *Bioresource Technology*, *271*(September 2018), 353–359. https://doi.org/10.1016/j.biortech.2018.09.132

Chen, F., Liu, Y., & Tay, J. (2015). Rapid formation of nitrifying granules treating high-strength ammonium wastewater in a sequencing batch reactor. https://doi.org/10.1007/s00253-014-6363-6

Chen, Y., Jiang, W., Liang, D. T., & Tay, J. H. (2007). Structure and stability of aerobic granules cultivated under different shear force in sequencing batch reactors. *Applied Microbiology and Biotechnology*, *76*(5), 1199–1208. https://doi.org/10.1007/s00253-007-1085-7

Chen, Y., Jiang, W., Liang, D. T., & Tay, J. H. (2008). Aerobic granulation under the combined hydraulic and loading selection pressures. *Bioresource Technology*, *99*(16), 7444–7449. https://doi.org/10.1016/j.biortech.2008.02.028

Chiu, Z. C., Chen, M. Y., Lee, D. J., Tay, S. T., Tay, J. H., & Show, K. Y. (2006). Diffusivity of Oxygen in Aerobic Granules, (3). https://doi.org/10.1002/bit

Coma, M., Verawaty, M., Pijuan, M., Yuan, Z., & Bond, P. L. (2012). Enhancing aerobic granulation for biological nutrient removal from domestic wastewater. *Bioresource Technology*, *103*(1), 101–108. https://doi.org/10.1016/j.biortech.2011.10.014

Corsino, S. F., di Biase, A., Devlin, T. R., Munz, G., Torregrossa, M., & Oleszkiewicz, J. A. (2016). Effect of Extended Famine Conditions on Aerobic Granular Sludge Stability in the Treatment of Brewery Wastewater. *Bioresource Technology*, *226*, 150–157. https://doi.org/10.1016/j.biortech.2016.12.026

Corsino, S. F., Di Trapani, D., Torregrossa, M., & Viviani, G. (2018). Aerobic granular sludge treating high strength citrus wastewater: Analysis of pH and organic loading rate effect on kinetics, performance and stability. *Journal of Environmental Management*, *214*, 23–35. https://doi.org/10.1016/j.jenvman.2018.02.087

Couto, C. F., Moravia, W. G., & Amaral, M. C. S. (2017). Integration of microfiltration and nanofiltration to promote textile effluent reuse. *Clean Technologies and Environmental Policy*, *19*(8), 2057–2073. https://doi.org/10.1007/s10098-017-1388-z

Cui, F., Park, S., & Kim, M. (2014). Bioresource Technology Characteristics of aerobic granulation at mesophilic temperatures in wastewater treatment. *Bioresource Technology*, *151*, 78–84. https://doi.org/10.1016/j.biortech.2013.10.025

Dangcong, P., Bernet, N., Delgenes, J., & Moletta, R. (1999). Rapid Communication Aerobic Granular Sludge - A Case Report, *33*(3), 890–893.

de Bruin, L. M. M., de Kreuk, M. K., van der Roest, H. F. R., Uijterlinde, C., & van Loosdrecht, M. C. M. (2004). Aerobic granular sludge technology: an alternative to activated sludge? *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *49*(11–12), 1–7. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15303716

de Kreuk, M K, Pronk, M., & van Loosdrecht, M. C. M. (2005). Formation of aerobic granules and conversion processes in an aerobic granular sludge reactor at moderate and low temperatures. *Water Research*, *39*(18), 4476–4484. https://doi.org/10.1016/j.watres.2005.08.031

Deng, S., Wang, L., & Su, H. (2016). Role and influence of extracellular polymeric substances on the preparation of aerobic granular sludge. *Journal of Environmental Management*, *173*, 49–54. https://doi.org/10.1016/j.jenvman.2016.03.008

Devlin, T. R., di Biase, A., Kowalski, M., & Oleszkiewicz, J. A. (2016). Granulation of activated sludge under low hydrodynamic shear and different wastewater characteristics. *Bioresource Technology*, *224*, 1–7. https://doi.org/10.1016/j.biortech.2016.11.005

Di Bella, G., & Torregrossa, M. (2014). Aerobic Granular Sludge for Leachate Treatment. *Chemical Engineering Transactions*, *38*, 493–498. https://doi.org/10.3303/CET1438083

Di Iaconi, C., Ramadori, R., Lopez, A., & Passino, R. (2006). Influence of hydrodynamic shear forces on properties of granular biomass in a sequencing batch biofilter reactor. *Biochemical Engineering Journal*, *30*(2), 152–157. https://doi.org/10.1016/j.bej.2006.03.002

Dobbeleers, T., Daens, D., Miele, S., D'aes, J., Caluwé, M., Geuens, L., & Dries, J. (2017). Performance of aerobic nitrite granules treating an anaerobic pre-treated wastewater originating from the potato industry. *Bioresource Technology*, *226*. https://doi.org/10.1016/j.biortech.2016.11.117

Dong, C., & Lv, B. (2018). Granulation for Coking Wastewater Treatment in a Coupled Anaerobic-Aerobic Reactor, *01052*, 1–6.

dos Santos, A. B., Cervantes, F. J., & van Lier, J. B. (2007). Review paper on current technologies for decolourisation of textile wastewaters: Perspectives for anaerobic biotechnology. *Bioresource Technology*, *98*(12), 2369–2385. https://doi.org/10.1016/j.biortech.2006.11.013

Eom, H., Kim, J., Kim, S., & Lee, S.-S. (2018). Treatment of Saline Wastewater Containing a High Concentration of Salt Using Marine Bacteria and Aerobic Granule Sludge. *Journal of Environmental Engineering (United States)*, *144*(5), 1–8. https://doi.org/10.1016/S0143-974X(01)00044-X

Ergüder, T. H., & Demirer, G. N. (2005). Investigation of granulation of a mixture of suspended anaerobic and aerobic cultures under alternating anaerobic/microaerobic/aerobic conditions. *Process Biochemistry*, *40*(12), 3732–3741. https://doi.org/10.1016/j.procbio.2005.05.005

Etterer, T., & Wilderer, P. a. (2001). Generation and properties of aerobic granular sludge. *Water Science and Technology : A Journal of the International* treating a low-strength wastewater. *Chemical Engineering Journal*, *198–199*, 163–170. https://doi.org/10.1016/j.cej.2012.05.066

Jegatheesan, V., Pramanik, B. K., Chen, J., Navaratna, D., Chang, C. Y., & Shu, L. (2016). Treatment of textile wastewater with membrane bioreactor: A critical review. *Bioresource Technology*, *204*, 202–212. https://doi.org/10.1016/j.biortech.2016.01.006

Ji, G., Zhai, F., Wang, R., & Ni, J. (2010). Sludge granulation and performance of a low superficial gas velocity sequencing batch reactor (SBR) in the treatment of prepared sanitary wastewater. *Bioresource Technology*, *101*(23), 9058–9064. https://doi.org/10.1016/j.biortech.2010.07.045

Ji, M., Wei, Y., Lu, S., Wang, F., & Cheng, L. (2009). Characteristics and Stability of Aerobic Granules Treating Domestic Sewage. *2009 3rd International Conference on Bioinformatics and Biomedical Engineering*, 1–5. https://doi.org/10.1109/ICBBE.2009.5162490

Jiang, H. L., Tay, J. H., Maszenan, A. M., & Tay, S. T. L. (2004). Bacterial diversity and function of aerobic granules engineered in a sequencing batch reactor for phenol degradation. *Applied and Environmental Microbiology*, *70*(11), 6767. https://doi.org/10.1128/AEM.70.11.6767

Jiang, H. L., Tay, J. H., & Tay, S. T. L. (2002). Aggregation of immobilized activated sludge cells into aerobically grown microbial granules for the aerobic biodegradation of phenol. *Letters in Applied Microbiology*, *35*(5), 439–445. https://doi.org/10.1046/j.1472-765X.2002.01217.x

Jiang, Y., Wei, L., Yang, K., & Wang, H. (2019). Investigation of rapid granulation in SBRs treating aniline-rich wastewater with different aniline loading rates. *Science of the Total Environment*, *646*, 841–849. https://doi.org/10.1016/j.scitotenv.2018.07.313

Kang, A. J., & Yuan, Q. (2017). Long-term Stability and Nutrient Removal Efficiency of Aerobic Granules at Low Organic Loads. *Bioresource Technology*, *234*, 336–342. https://doi.org/10.1016/j.biortech.2017.03.057

Kant, R. (2012). Textile dyeing industry an environmental hazard, *4*(1), 22–26.

Kapdan, I. K., & Ozturk, R. (2005). Effect of operating parameters on color and COD removal performance of SBR: Sludge age and initial dyestuff concentration. *Journal of Hazardous Materials*, *123*(1–3), 217–222. https://doi.org/10.1016/j.jhazmat.2005.04.013

Khan, T. A., Nazir, M., & Khan, E. A. (2013). Adsorptive removal of rhodamine B from textile wastewater using water chestnut (Trapa natans L.) peel: Adsorption dynamics and kinetic studies. *Toxicological and Environmental Chemistry*, *95*(6), 919–931. https://doi.org/10.1080/02772248.2013.840369

Khan, T. A., Rahman, R., Ali, I., Khan, E. A., & Mukhlif, A. A. (2014). Removal of malachite green from aqueous solution using waste pea shells as low-cost adsorbent – adsorption isotherms and dynamics. *Toxicological and Environmental Chemistry*, *96*(4), 569–578. https://doi.org/10.1080/02772248.2014.969268

Kim, I. S., Kim, S.-M., & Jang, A. (2008). Characterization of aerobic granules by microbial density at different COD loading rates. *Bioresource Technology*, *99*(1), 18–25. https://doi.org/10.1016/j.biortech.2006.11.058

Konopacki, M., Kordas, M., Fijałkowski, K., & Rakoczy, R. (2015). Computational Fluid Dynamics and Experimental Studies of a New Mixing Element in a Static Mixer as a Heat Exchanger. *Chemical and Process Engineering*, *36*(1), 59–72. https://doi.org/10.1515/cpe-2015-0005

Kreuk, Merle K De, & Loosdrecht, M. C. M. Van. (2006). Formation of Aerobic Granules with Domestic Sewage, (June), 694–697.

Kumar, K., Singh, G. K., Dastidar, M. G., & Sreekrishnan, T. R. (2014). Effect of mixed liquor volatile suspended solids (MLVSS) and hydraulic retention time (HRT) on the performance of activated sludge process during the biotreatment of real textile wastewater. *Water Resources and Industry*, *5*, 1–8. https://doi.org/10.1016/j.wri.2014.01.001

Kwok, W. K., Picioreanu, C., Ong, S. L., Van Loosdrecht, M. C. M., Ng, W. J., &

Heijnen, J. J. (1998). Influence of biomass production and detachment forces on biofilm structures in a biofilm airlift suspension reactor. *Biotechnology and Bioengineering*, *58*(4), 400–407. https://doi.org/10.1002/(SICI)1097-0290(19980520)58:4<400::AID-BIT7>3.0.CO;2-N

Lashkarizadeh, M., Munz, G., & Oleszkiewicz, J. A. (2016). Impacts of variable pH on stability and nutrient removal efficiency of aerobic granular sludge. *Water Science and Technology*, *73*(1), 60–68. https://doi.org/10.2166/wst.2015.460

Lee, D. J., Chen, Y. Y., Show, K. Y., Whiteley, C. G., & Tay, J. H. (2010). Advances in aerobic granule formation and granule stability in the course of storage and reactor operation. *Biotechnology Advances*, *28*(6), 919–934. https://doi.org/10.1016/j.biotechadv.2010.08.007

Lemaire, R., Yuan, Z., Blackall, L. L., & Crocetti, G. R. (2008). Microbial distribution of Accumulibacter spp. and Competibacter spp. in aerobic granules from a lab-scale biological nutrient removal system. *Environmental Microbiology*, *10*(2), 354–363. https://doi.org/10.1111/j.1462-2920.2007.01456.x

Lettinga, G., van Velsen, A. F. M., Hobma, S. W., de Zeeuw, W., & Klapwijk, A. (1980). Use of the upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment. *Biotechnology and Bioengineering*, *22*(4), 699–734. https://doi.org/10.1002/bit.260220402

Li, A., Yang, S., Li, X., & Gu, J. (2008). Microbial population dynamics during aerobic sludge granulation at different organic loading rates, *42*, 3552–3560. https://doi.org/10.1016/j.watres.2008.05.005

Li, A., Zhang, T., & Li, X. (2010). Fate of aerobic bacterial granules with fungal contamination under different organic loading conditions. *Chemosphere*, *78*(5), 500–509. https://doi.org/10.1016/j.chemosphere.2009.11.040

Li, D., Lv, Y., Cao, M., Zeng, H., & Zhang, J. (2016). Optimized hydraulic retention time for phosphorus and COD removal from synthetic domestic sewage with granules in a continuous-flow reactor. *Bioresource Technology*, *216*, 1083–1087. https://doi.org/10.1016/j.biortech.2016.05.061

Li, J., Ding, L., Cai, A., Huang, G., & Horn, H. (2014). Aerobic Sludge Granulation in a Full-Scale Sequencing Batch Reactor, *2014*.

Li, X. Y., & Yuan, Y. (2002). Settling velocities and permeabilities of microbial aggregates. *Water Research*, *36*(12), 3110–3120. https://doi.org/10.1016/S0043-1354(01)00541-3

Li, Y., Liu, Y., Shen, L., & Chen, F. (2008). DO diffusion profile in aerobic granule and its microbiological implications. *Enzyme and Microbial Technology*, *43*(4–5), 349–354. https://doi.org/10.1016/j.enzmictec.2008.04.005

Li, Z. H., Kuba, T., & Kusuda, T. (2006). The influence of starvation phase on the properties and the development of aerobic granules. *Enzyme and Microbial Technology*, *38*(5), 670–674. https://doi.org/10.1016/j.enzmictec.2005.07.020

Liang, C. Z., Sun, S. P., Li, F. Y., Ong, Y. K., & Chung, T. S. (2014). Treatment of highly concentrated wastewater containing multiple synthetic dyes by a combined process of coagulation/flocculation and nanofiltration. *Journal of Membrane Science*, *469*, 306–315. https://doi.org/10.1016/j.memsci.2014.06.057

Lim, V., Hobby, A. M., Mccarthy, M. J., & Mccarthy, K. L. (2015). Laminar mixing of miscible fl uids in a SMX mixer evaluated by magnetic resonance imaging (MRI). *Chemical Engineering Science*, *137*, 1024–1033. https://doi.org/10.1016/j.ces.2015.07.003

Linlin, H., Jianlong, W., Xianghua, W., & Yi, Q. (2005). The formation and characteristics of aerobic granules in sequencing batch reactor (SBR) by seeding anaerobic granules. *Process Biochemistry*, *40*(1), 5–11. https://doi.org/10.1016/j.procbio.2003.11.033

Liu, L., Wang, Z., Lin, K., & Cai, W. (n.d.). Microbial degradation of polyacrylamide by aerobic granules. *Environmental Technology*, *33*(7–9), 1049–1054. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22720433

Liu, L., Wang, Z., Yao, J., Sun, X., & Cai, W. (2005). Investigation on the formation and kinetics of glucose-fed aerobic granular sludge. *Enzyme and Microbial*

Technology, *36*(5–6), 712–716. https://doi.org/10.1016/j.enzmictec.2004.12.024

Liu, W. R., Yang, Y. Y., Liu, Y. S., Zhang, L. J., Zhao, J. L., Zhang, Q. Q., … Ying, G. G. (2017). Biocides in wastewater treatment plants: Mass balance analysis and pollution load estimation. *Journal of Hazardous Materials*, *329*, 310–320. https://doi.org/10.1016/j.jhazmat.2017.01.057

Liu, Y. Q., Kong, Y., Tay, J. H., & Zhu, J. (2011). Enhancement of start-up of pilot-scale granular SBR fed with real wastewater. *Separation and Purification Technology*, *82*, 190–196. https://doi.org/10.1016/j.seppur.2011.09.014

Liu, Y. Q., Moy, B., Kong, Y. H., & Tay, J. H. (2010). Formation, physical characteristics and microbial community structure of aerobic granules in a pilot-scale sequencing batch reactor for real wastewater treatment. *Enzyme and Microbial Technology*, *46*(6), 520–525. https://doi.org/10.1016/j.enzmictec.2010.02.001

Liu, Y. Q., Moy, B. Y. P., & Tay, J. H. (2007). COD removal and nitrification of low-strength domestic wastewater in aerobic granular sludge sequencing batch reactors. *Enzyme and Microbial Technology*, *42*(1), 23–28. https://doi.org/10.1016/j.enzmictec.2007.07.020

Liu, Y. Q., & Tay, J. H. (2007a). Cultivation of aerobic granules in a bubble column and an airlift reactor with divided draft tubes at low aeration rate. *Biochemical Engineering Journal*, *34*(1), 1–7. https://doi.org/10.1016/j.bej.2006.11.009

Liu, Y. Q., & Tay, J. H. (2007b). Influence of cycle time on kinetic behaviors of steady-state aerobic granules in sequencing batch reactors. *Enzyme and Microbial Technology*, *41*(4), 516–522. https://doi.org/10.1016/j.enzmictec.2007.04.005

Liu, Y. Q., & Tay, J. H. (2015). Fast formation of aerobic granules by combining strong hydraulic selection pressure with overstressed organic loading rate. *Water Research*, *80*, 256–266. https://doi.org/10.1016/j.watres.2015.05.015

Liu, Yali, Kang, X., Li, X., & Yuan, Y. (2015). Performance of aerobic granular sludge in a sequencing batch bioreactor for slaughterhouse wastewater treatment. *Bioresource Technology*. https://doi.org/10.1016/j.biortech.2015.03.008

Liu, Yong-qiang, & Tay, J. (2008). Influence of starvation time on formation and stability of aerobic granules in sequencing batch reactors, *99*, 980–985. https://doi.org/10.1016/j.biortech.2007.03.011

Liu, Yu, & Liu, Q. S. (2006). Causes and control of filamentous growth in aerobic granular sludge sequencing batch reactors. *Biotechnology Advances*, *24*(1), 115–127. https://doi.org/10.1016/j.biotechadv.2005.08.001

Liu, Yu, Liu, Y. Q., Wang, Z. W., Yang, S. F., & Tay, J. H. (2005). Influence of substrate surface loading on the kinetic behaviour of aerobic granules. *Applied Microbiology and Biotechnology*, *67*(4), 484–488. https://doi.org/10.1007/s00253-004-1785-1

Liu, Yu, & Tay, J. H. (2002). The essential role of hydrodynamic shear force in the formation of biofilm and granular sludge. *Water Research*, *36*(7), 1653–1665. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12044065

Liu, Yu, & Tay, J. H. (2004). State of the art of biogranulation technology for wastewater treatment. *Biotechnology Advances*, *22*(7), 533–563. https://doi.org/10.1016/j.biotechadv.2004.05.001

Liu, Yu, Xu, H. L., Yang, S. F., & Tay, J. H. (2003). Mechanisms and models for anaerobic granulation in upflow anaerobic sludge blanket reactor. *Water Research*, *37*(3), 661–673. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12688701

Liu, Yu, Yang, S. F., Tay, J. H., Liu, Q. S., Qin, L., & Li, Y. (2004). Cell hydrophobicity is a triggering force of biogranulation. *Enzyme and Microbial Technology*, *34*(5), 371–379. https://doi.org/10.1016/j.enzmictec.2003.12.009

Lobry, E., Theron, F., Gourdon, C., Le Sauze, N., Xuereb, C., & Lasuye, T. (2011). Turbulent liquid-liquid dispersion in SMV static mixer at high dispersed phase concentration. *Chemical Engineering Science*, *66*(23), 5762–5774. https://doi.org/10.1016/j.ces.2011.06.073

Lochmatter, S., Gonzalez-Gil, G., & Holliger, C. (2013). Optimized aeration strategies for nitrogen and phosphorus removal with aerobic granular sludge. *Water Research*, *47*(16), 6187–6197. https://doi.org/10.1016/j.watres.2013.07.030

Lochmatter, S., & Holliger, C. (2014). Optimization of operation conditions for the startup of aerobic granular sludge reactors biologically removing carbon, nitrogen, and phosphorous. *Water Research*, *59*, 58–70. https://doi.org/10.1016/j.watres.2014.04.011

Lodha, B., & Chaudhari, S. (2007). Optimization of Fenton-biological treatment scheme for the treatment of aqueous dye solutions. *Journal of Hazardous Materials*, *148*(1–2), 459–466. https://doi.org/10.1016/j.jhazmat.2007.02.061

Long, B., Yang, C., Pu, W., Yang, J., Jiang, G., Dan, J., … Liu, F. (2014). Bioresource Technology Rapid cultivation of aerobic granular sludge in a pilot scale sequencing batch reactor. *BIORESOURCE TECHNOLOGY*, *166*, 57–63. https://doi.org/10.1016/j.biortech.2014.05.039

Long, B., Yang, C., Pu, W., Yang, J., Liu, F., Zhang, L., … Cheng, K. (2015). Tolerance to organic loading rate by aerobic granular sludge in a cyclic aerobic granular reactor. *Bioresource Technology*, *182*, 314–322. https://doi.org/10.1016/j.biortech.2015.02.029

Lotito, A. M., De Sanctis, M., Di Iaconi, C., & Bergna, G. (2014). Textile wastewater treatment: aerobic granular sludge vs activated sludge systems. *Water Research*, *54*, 337–346. https://doi.org/10.1016/j.watres.2014.01.055

Lotito, A. M., Di Iaconi, C., Fratino, U., Mancini, A., & Bergna, G. (2011). Sequencing batch biofilter granular reactor for textile wastewater treatment. *New Biotechnology*, *29*(1), 9–16. https://doi.org/10.1016/j.nbt.2011.04.008

Lotito, A. M., Fratino, U., Mancini, A., Bergna, G., & Di Iaconi, C. (2012). Effective aerobic granular sludge treatment of a real dyeing textile wastewater. *International Biodeterioration & Biodegradation*, *69*, 62–68. https://doi.org/10.1016/j.ibiod.2012.01.004

Lourenço, N. D., Franca, R. D. G., Moreira, M. A., Gil, F. N., Viegas, C. A., & Pinheiro, H. M. (2015). Comparing aerobic granular sludge and flocculent sequencing batch reactor technologies for textile wastewater treatment. *Biochemical Engineering Journal*, *104*, 57–63. https://doi.org/10.1016/j.bej.2015.04.025

Ma, J., Quan, X., & Li, H. (2013). Application of high OLR-fed aerobic granules for the treatment of low-strength wastewater: Performance, granule morphology and microbial community. *Journal of Environmental Sciences*, *25*(8), 1549–1556. https://doi.org/10.1016/S1001-0742(12)60243-5

Manavi, N., Kazemi, A. S., & Bonakdarpour, B. (2017). The development of aerobic granules from conventional activated sludge under anaerobic-aerobic cycles and their adaptation for treatment of dyeing wastewater. *Chemical Engineering Journal*, *312*, 375–384. https://doi.org/10.1016/j.cej.2016.11.155

Martins, A. M. P., Pagilla, K., Heijnen, J. J., & Van Loosdrecht, M. C. M. (2004). Filamentous bulking sludge - A critical review. *Water Research*, *38*(4), 793–817. https://doi.org/10.1016/j.watres.2003.11.005

Mata, a M. T., Pinheiro, H. M., & Lourenço, N. D. (2015). Effect of Sequencing Batch Cycle Strategy on the Treatment of a Simulated Textile Wastewater with Aerobic Granular Sludge. *Elsevier B.V.* https://doi.org/10.1016/j.bej.2015.04.005

McClure, D. D., Aboudha, N., Kavanagh, J. M., Fletcher, D. F., & Barton, G. W. (2015). Mixing in bubble column reactors: Experimental study and CFD modeling. *Chemical Engineering Journal*, *264*, 291–301. https://doi.org/10.1016/j.cej.2014.11.090

Mcswain, B. S. (2005). Molecular Investigation Of Aerobic Granular Sludge Formation A Dissertation Submitted to the Graduate School of the University of Notre Dame in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy by Robert L . Irvine , Director , (February).

McSwain, B. S., Irvine, R. L., & Wilderer, P. a. (2004a). The effect of intermittent feeding on aerobic granule structure. *Water Science and Technology : A Journal* *of the International Association on Water Pollution Research*, *49*(11–12), 19–25. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15303718

McSwain, B. S., Irvine, R. L., & Wilderer, P. a. (2004b). The influence of settling time on the formation of aerobic granules. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *50*(10), 195–202. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15656313

Meijer, H. E. H., Singh, M. K., & Anderson, P. D. (2012). On the performance of static mixers: A quantitative comparison. *Progress in Polymer Science*, *37*(10), 1333–1349. https://doi.org/10.1016/j.progpolymsci.2011.12.004

Meunier, C., Henriet, O., Schroonbroodt, B., Boeur, J. M., Mahillon, J., & Henry, P. (2016). Influence of feeding pattern and hydraulic selection pressure to control filamentous bulking in biological treatment of dairy wastewaters. *Bioresource Technology*, *221*, 300–309. https://doi.org/10.1016/j.biortech.2016.09.052

Miladi, B., El, A., Smaali, I., Ben, A., Hamdi, M., & Bouallagui, H. (2016). Industrial textile ef fl uent decolourization in stirred and static batch cultures of a new fungal strain Chaetomium globosum IMA1 KJ472923, *170*, 8–14. https://doi.org/10.1016/j.jenvman.2015.12.038

Milia, S., Malloci, E., & Carucci, A. (2016). Aerobic granulation with petrochemical wastewater in a sequencing batch reactor under different operating conditions. *Desalination and Water Treatment*, *3994*(September), 1–10. https://doi.org/10.1080/19443994.2016.1191778

Miralles-Cuevas, S., Oller, I., Agüera, A., Sánchez Pérez, J. A., Sánchez-Moreno, R., & Malato, S. (2016). Is the combination of nanofiltration membranes and AOPs for removing microcontaminants cost effective in real municipal wastewater effluents? *Environmental Science: Water Research and Technology*, *2*(3), 511–520. https://doi.org/10.1039/c6ew00001k

Mishima, K., & Nakamura, M. (1991). Self-Immobilization of Aerobic Activated Sludge-a Pilot Study of the Aerobic Upflow Municipal Sewage Treatment. *Water Science Technology*, *23 (4-6)*(August), 981–990.

Mohammadi, A., Moghaddas, J., & Ariamanesh, A. (2015). Residence Time and Concentration Distribution in a Kenics Static Mixer. *Chemical Engineering Communications*, *202*(2), 144–150. https://doi.org/10.1080/00986445.2013.832225

Mohebali, S., Bastani, D., & Shayesteh, H. (2019). Equilibrium, kinetic and thermodynamic studies of a low-cost biosorbent for the removal of Congo red dye: Acid and CTAB-acid modified celery (Apium graveolens). *Journal of Molecular Structure*, *1176*, 181–193. https://doi.org/10.1016/j.molstruc.2018.08.068

More, T. T., Yadav, J. S. S., Yan, S., Tyagi, R. D., & Surampalli, R. Y. (2014). Extracellular polymeric substances of bacteria and their potential environmental applications. *Journal of Environmental Management*, *144*, 1–25. https://doi.org/10.1016/j.jenvman.2014.05.010

Morgenroth, E., Sherden, T., Van Loosdrecht, M. C. M., Heijnen, J. J., & Wilderer, P. A. (1997). Aerobic granular sludge in a sequencing batch reactor. *Water Research*, *31*(12), 3191–3194. https://doi.org/10.1016/S0043-1354(97)00216-9

Moy, B. Y. P., Tay, J. H., Toh, S. K., Liu, Y., & Tay, S. T. L. (2002). High organic loading influences the physical characteristics of aerobic sludge granules. *Letters in Applied Microbiology*, *34*(6), 407–412. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12028420

Muda, K., Aris, A., Salim, M. R., Ibrahim, Z., van Loosdrecht, M. C. M., Ahmad, A., & Nawahwi, M. Z. (2011). The effect of hydraulic retention time on granular sludge biomass in treating textile wastewater. *Water Research*, *45*(16), 4711–4721. https://doi.org/10.1016/j.watres.2011.05.012

Muda, K., Aris, A., Salim, M. R., Ibrahim, Z., Yahya, A., van Loosdrecht, M. C. M., … Nawahwi, M. Z. (2010). Development of granular sludge for textile wastewater treatment. *Water Research*, *44*(15), 4341–4350. https://doi.org/10.1016/j.watres.2010.05.023

Najib, M. Z. M., Salmiati, Ujang, Z., Salim, M. R., & Ibrahim, Z. (2017). Developed microbial granules containing photosynthetic pigments for carbon dioxide reduction in palm oil mill effluent. *International Biodeterioration and Biodegradation*, *116*, 163–170. https://doi.org/10.1016/j.ibiod.2016.10.031

Nancharaiah, Y. V, Joshi, H. M., Mohan, T. V. K., Venugopalan, V. P., & Narasimhan, S. V. (2008). Formation of aerobic granules in the presence of a synthetic chelating agent, *153*, 37–43. https://doi.org/10.1016/j.envpol.2007.11.017

Nguyen, P. T. T., Van Nguyen, P., Truong, H. T. B., & Bui, H. M. (2016). The formation and stabilization of aerobic granular sludge in a sequencing batch airlift reactor for treating tapioca-processing wastewater. *Polish Journal of Environmental Studies*, *25*(5), 2077–2084. https://doi.org/10.15244/pjoes/62736

Ni, B. J., Xie, W. M., Liu, S. G., Yu, H. Q., Wang, Y. Z., Wang, G., & Dai, X. L. (2009). Granulation of activated sludge in a pilot-scale sequencing batch reactor for the treatment of low-strength municipal wastewater. *Water Research*, *43*(3), 751–761. https://doi.org/10.1016/j.watres.2008.11.009

Nidheesh, P. V., Gandhimathi, R., & Ramesh, S. T. (2013). Degradation of dyes from aqueous solution by Fenton processes: A review. *Environmental Science and Pollution Research*, *20*(4), 2099–2132. https://doi.org/10.1007/s11356-012-1385-z

Nor-Anuar, a, Ujang, Z., van Loosdrecht, M. C. M., de Kreuk, M. K., & Olsson, G. (2012). Strength characteristics of aerobic granular sludge. *Water Science & Technology*, *65*(2), 309. https://doi.org/10.2166/wst.2012.837

Nor Anuar, a, Ujang, Z., van Loosdrecht, M. C. M., & de Kreuk, M. K. (2007). Settling behaviour of aerobic granular sludge. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *56*(7), 55–63. https://doi.org/10.2166/wst.2007.671

Obaja, D., MacÉ, S., & Mata-Alvarez, J. (2005). Biological nutrient removal by a sequencing batch reactor (SBR) using an internal organic carbon source in digested piggery wastewater. *Bioresource Technology*, *96*(1), 7–14. https://doi.org/10.1016/j.biortech.2004.03.002

Ong, S. A., Toorisaka, E., Hirata, M., & Hano, T. (2005). Treatment of azo dye Orange II in aerobic and anaerobic-SBR systems. *Process Biochemistry*, *40*, 2907–2914. https://doi.org/10.1016/j.procbio.2005.01.009

Otero, M., Rozada, F., Calvo, L. F., García, A. I., & Morán, A. (2003). Kinetic and equilibrium modelling of the methylene blue removal from solution by adsorbent materials produced from sewage sludges. *Biochemical Engineering Journal*, *15*(1), 59–68. https://doi.org/10.1016/S1369-703X(02)00177-8

Othman, I., Anuar, A. N., Ujang, Z., Rosman, N. H., Harun, H., & Chelliapan, S. (2013). Livestock wastewater treatment using aerobic granular sludge. *Bioresource Technology*, *133*, 630–634. https://doi.org/10.1016/j.biortech.2013.01.149

Ou, D., Li, H., Li, W., Wu, X., Wang, Y., & Liu, Y. (2018). Salt-tolerance aerobic granular sludge: Formation and microbial community characteristics. *Bioresource Technology*, *249*(July 2017), 132–138. https://doi.org/10.1016/j.biortech.2017.07.154

Oyanedel-Craver, V. A., Smith, J. A., Roosta, M., Ghaedi, M., Mohammadi, M., Wu, T., … Gray, D. G. (2014). Optimization of the ultrasonic assisted removal of methylene blue by gold nanoparticles loaded on activated carbon using experimental design methodology. *Environmental Science and Technology*, *21*(6), 2069–2079. https://doi.org/10.1007/s11051-009-9766-z

Pan, S., Tay, J. H., He, Y. X., & Tay, S. T. L. (2004). The effect of hydraulic retention time on the stability of aerobically grown microbial granules. *Letters in Applied Microbiology*, *38*(2), 158–163. https://doi.org/10.1111/j.1472-765X.2003.01479.x

Pan, Y., Wang, Y., Zhou, A., Wang, A., Wu, Z., Lv, L., … Zhu, T. (2017). Removal of azo dye in an up-flow membrane-less bioelectrochemical system integrated with bio-contact oxidation reactor. *Chemical Engineering Journal*, *326*, 454–461. https://doi.org/10.1016/j.cej.2017.05.146

Pandey, A., Singh, P., & Iyengar, L. (2007). Bacterial decolorization and degradation of azo dyes. *International Biodeterioration and Biodegradation*, *59*(2), 73–84.

https://doi.org/10.1016/j.ibiod.2006.08.006

Pang, Y. L., & Abdullah, A. Z. (2013). Current status of textile industry wastewater management and research progress in malaysia: A review. *Clean - Soil, Air, Water*, *41*(8), 751–764. https://doi.org/10.1002/clen.201000318

Panswad, T., Iamsamer, K., & Anotai, J. (2001). Decolorization of azo-reactive dye by polyphosphate- and glycogen-accumulating organisms in an anaerobic-aerobic sequencing batch reactor. *Bioresource Technology*, *76*(2), 151–159. https://doi.org/10.1016/S0960-8524(00)00073-0

Pearce, C. I., Lloyd, J. R., & Guthrie, J. T. (2003). The removal of colour from textile wastewater using whole bacterial cells: A review. *Dyes and Pigments*, *58*(3), 179–196. https://doi.org/10.1016/S0143-7208(03)00064-0

Peyong, Y. N., Zhou, Y., Abdullah, A. Z., & Vadivelu, V. (2012). The effect of organic loading rates and nitrogenous compounds on the aerobic granules developed using low strength wastewater. *Biochemical Engineering Journal*, *67*, 52–59. https://doi.org/10.1016/j.bej.2012.05.009

Pezo, M., Pezo, L., Jovanović, A., Lončar, B., & Čolović, R. (2016). DEM/CFD approach for modeling granular flow in the revolving static mixer. *Chemical Engineering Research and Design*, *109*, 317–326. https://doi.org/10.1016/j.cherd.2016.02.003

Praveen Kumar, G.N & Bhat Sumngala, K. (2012). Decolorization of Azo dye Red 3BN by Bacteria. *International Research Journal of Biological Sciences*, *1*(5), 46–52.

Pronk, M., de Kreuk, M. K., de Bruin, B., Kamminga, P., Kleerebezem, R., & van Loosdrecht, M. C. M. (2015). Full scale performance of the aerobic granular sludge process for sewage treatment. *Water Research*, *84*, 207–217. https://doi.org/10.1016/j.watres.2015.07.011

Qin, L., Liu, Y., & Tay, J.-H. (2004). Effect of settling time on aerobic granulation in sequencing batch reactor. *Biochemical Engineering Journal*, *21*(1), 47–52. https://doi.org/10.1016/j.bej.2004.03.005

Rahmani, R. K., Keith, T. G., & Ayasoufi, A. (2005). Three-Dimensional Numerical Simulation and Performance Study of an Industrial Helical Static Mixer. *Journal of Fluids Engineering*, *127*(3), 467. https://doi.org/10.1115/1.1899166

Rahmani, R. K., Keith, T. G., & Ayasoufi, A. (2008). Numerical simulation of turbulent flow in an industrial helical static mixer. *International Journal of Numerical Methods for Heat & Fluid Flow*, *18*(6), 675–696. https://doi.org/10.1108/09615530810885515

Raju, M. D., Joseph, P., Kavitha, E., Dhanasekaran, N., Grahadurai, H. M., & Mohan, T. (2014). Remediation of textile effluents by membrane based treatment techniques: A state of the art review. *Journal of Chemical and Pharmaceutical Sciences*, *2014-Decem*, 296–299. https://doi.org/10.1016/j.jenvman.2014.08.008

Rampure, M. R., Kulkarni, A. A., & Ranade, V. V. (2007). Hydrodynamics of bubble column reactors at high gas velocity: Experiments and computational fluid dynamics CFD simulations. *Industrial and Engineering Chemistry Research*, *46*(25), 8431–8447. https://doi.org/10.1021/ie070079h

Ramsay, J., Simmons, M. J. H., Ingram, A., & Stitt, E. H. (2016). Mixing performance of viscoelastic fluids in a Kenics KM in-line static mixer. *Chemical Engineering Research and Design*, *115*, 310–324. https://doi.org/10.1016/j.cherd.2016.07.020

Ren, T., Liu, L., Sheng, G., Liu, X., Yu, H., Zhang, M., & Zhu, J. (2008). Calcium spatial distribution in aerobic granules and its effects on granule structure , strength and bioactivity, *42*, 3343–3352. https://doi.org/10.1016/j.watres.2008.04.015

Revathi, D., & Saravanan, K. (2014). Studies on mixing characteristics of non newtonian fluids using static mixer. *International Journal of ChemTech Research*, *6*(10).

Rondon, H., El-Cheikh, W., Boluarte, I. A. R., Chang, C. Y., Bagshaw, S., Farago, L., … Shu, L. (2015). Application of enhanced membrane bioreactor (eMBR) to treat dye wastewater. *Bioresource Technology*, *183*, 78–85.

https://doi.org/10.1016/j.biortech.2015.01.110

Rosman, N. H., Nor Anuar, A., Chelliapan, S., Md Din, M. F., & Ujang, Z. (2014). Characteristics and performance of aerobic granular sludge treating rubber wastewater at different hydraulic retention time. *Bioresource Technology*, *161*, 155–161. https://doi.org/10.1016/j.biortech.2014.03.047

Rosman, N. H., Nor Anuar, A., Othman, I., Harun, H., Sulong Abdul Razak, M. Z., Elias, S. H., … Ujang, Z. (2013). Cultivation of aerobic granular sludge for rubber wastewater treatment. *Bioresource Technology*, *129*, 620–623. https://doi.org/10.1016/j.biortech.2012.12.113

Sadri Moghaddam, S., & Alavi Moghaddam, M. R. (2016). Aerobic Granular Sludge for Dye Biodegradation in a Sequencing Batch Reactor With Anaerobic/Aerobic Cycles. *Clean - Soil, Air, Water*, *44*(4), 438–443. https://doi.org/10.1002/clen.201400855

Sadrzadeh, F., & Dulekgurgen, E. (2014). Improving the settling properties of activated sludge by gradually decreasing the settling time. *Desalination and Water Treatment*, *52*(13–15), 2465–2471. https://doi.org/10.1080/19443994.2013.795874

Şahinkaya, S. (2013). COD and color removal from synthetic textile wastewater by ultrasound assisted electro-Fenton oxidation process. *Journal of Industrial and Engineering Chemistry*, *19*(2), 601–605. https://doi.org/10.1016/j.jiec.2012.09.023

Sarvajith, M., Reddy, G. K. K., & Nancharaiah, Y. V. (2018). Textile dye biodecolourization and ammonium removal over nitrite in aerobic granular sludge sequencing batch reactors. *Journal of Hazardous Materials*, *342*, 536–543. https://doi.org/10.1016/j.jhazmat.2017.08.064

Schwarzenbeck, N., Borges, J. M., & Wilderer, P. A. (2005). Treatment of dairy effluents in an aerobic granular sludge sequencing batch reactor. *Applied Microbiology and Biotechnology*, *66*(6), 711–718. https://doi.org/10.1007/s00253-004-1748-6

Sharma, S., Kapoor, S., & Christian, R. A. (2017). Effect of Fenton process on treatment of simulated textile wastewater: optimization using response surface methodology. *International Journal of Environmental Science and Technology*, *14*(8), 1665–1678. https://doi.org/10.1007/s13762-017-1253-y

Shi, J., Zhang, B., Liang, S., Li, J., & Wang, Z. (2018). Simultaneous decolorization and desalination of dye wastewater through electrochemical process. *Environmental Science and Pollution Research*, *25*(9), 8455–8464. https://doi.org/10.1007/s11356-017-1159-8

Sirianuntapiboon, S., & Srisornsak, P. (2007). Removal of disperse dyes from textile wastewater using bio-sludge. *Bioresource Technology*, *98*, 1057–1066. https://doi.org/10.1016/j.biortech.2006.04.026

Smolders, G. J., Klop, J. M., van Loosdrecht, M. C., & Heijnen, J. J. (1995). A metabolic model of the biological phosphorus removal process: I. Effect of the sludge retention time. *Biotechnology and Bioengineering*, *48*(3), 222–233. https://doi.org/10.1002/bit.260480309

Song, Z., Pan, Y., Zhang, K., Ren, N., & Wang, A. (2010). Effect of seed sludge on characteristics and microbial community of aerobic granular sludge. *Journal of Environmental Sciences*, *22*(9), 1312–1318. https://doi.org/10.1016/S1001-0742(09)60256-4

Sturm, B. S. M., & Irvine, R. L. (2008). Dissolved oxygen as a key parameter to aerobic granule formation, 781–787. https://doi.org/10.2166/wst.2008.393

Su, B., Cui, X., & Zhu, J. (2012). Optimal cultivation and characteristics of aerobic granules with typical domestic sewage in an alternating anaerobic/aerobic sequencing batch reactor. *Bioresource Technology*, *110*, 125–129. https://doi.org/10.1016/j.biortech.2012.01.127

Su, K. Z., & Yu, H. Q. (2005). Gas holdup and oxygen transfer in an aerobic granule-based sequencing batch reactor. *Biochemical Engineering Journal*, *25*(3), 201–207. https://doi.org/10.1016/j.bej.2005.05.004

Sulyman, M., Namiesnik, J., & Gierak, A. (2017). Low-cost adsorbents derived from agricultural by-products/wastes for enhancing contaminant uptakes from wastewater: A review. *Polish Journal of Environmental Studies*, *26*(2), 479–510. https://doi.org/10.15244/pjoes/66769

Szabó, E., Hermansson, M., Modin, O., Persson, F., & Wilén, B. M. (2016). Effects of wash-out dynamics on nitrifying bacteria in aerobic granular sludge during start-up at gradually decreased settling time. *Water (Switzerland)*, *8*(5). https://doi.org/10.3390/w8050172

Szabó, E., Liébana, R., Hermansson, M., Modin, O., Persson, F., & Wilén, B. M. (2017). Microbial population dynamics and ecosystem functions of anoxic/aerobic granular sludge in sequencing batch reactors operated at different organic loading rates. *Frontiers in Microbiology*, *8*(MAY), 1–14. https://doi.org/10.3389/fmicb.2017.00770

Talansier, E., Dellavalle, D., Loisel, C., Desrumaux, A., & Legrand, J. (2012). Elaboration of Controlled Structure Foams with the SMX Static Mixer, *00*(0), 34–36. https://doi.org/10.1002/aic

Tay, J. H., Ivanov, V., Pan, S., & Tay, S. T. L. (2002). Specific layers in aerobically grown microbial granules. *Letters in Applied Microbiology*, *34*(4), 254–257. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11940154

Tay, J. H., Liu, Q. S., & Liu, Y. (2004). The effect of upflow air velocity on the structure of aerobic granules cultivated in a sequencing batch reactor. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *49*(11–12), 35–40. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15303720

Tay, J. H., Pan, S., Tay, S. T. L., Ivanov, V., & Liu, Y. (2003). The effect of organic loading rate on the aerobic granulation: the development of shear force theory. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *47*(11), 235–240. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12906295

Tay, J. H., Liu, Q. S., & Liu, Y. (2001). The effects of shear force on the formation, structure and metabolism of aerobic granules. *Applied Microbiology and*

Biotechnology, *57*(1–2), 227–233. https://doi.org/10.1007/s002530100766

Tay, J., Liu, Q., Liu, Y., Show, K., Ivanov, V., & Tay, S. T. (2005). A Comparative Study of Aerobic Granulation in Pilot- and Laboratory-Scale SBRs, *4*(8).

Tay, J., Pan, S., He, Y., Tiong, S., & Tay, L. (2004). Effect of Organic Loading Rate on Aerobic Granulation . I : Reactor Performance, (October), 1094–1101.

Tee, P. F., Abdullah, M. O., Tan, I. A. W., Rashid, N. K. A., Amin, M. A. M., Nolasco-Hipolito, C., & Bujang, K. (2016). Review on hybrid energy systems for wastewater treatment and bio-energy production. *Renewable and Sustainable Energy Reviews*, *54*, 235–246. https://doi.org/10.1016/j.rser.2015.10.011

Thakur, R. K., Vial, C., Nigam, K. D. P., Nauman, E. B., & Djelveh, G. (2003). Static mixers in the process industries - a review. *Chemical Engineering Research and Design*, *81*(7), 787–826. https://doi.org/10.1205/026387603322302968

Thanh, B. X., Visvanathan, C., & Aim, R. Ben. (2009). Characterization of aerobic granular sludge at various organic loading rates. *Process Biochemistry*, *44*(2), 242–245. https://doi.org/10.1016/j.procbio.2008.10.018

Theron, F., & Sauze, N. Le. (2011). Comparison between three static mixers for emulsification in turbulent flow. *International Journal of Multiphase Flow*, *37*(5), 488–500. https://doi.org/10.1016/j.ijmultiphaseflow.2011.01.004

Tian, X., Xiao, Y., Zhou, P., Zhang, W., Chu, Z., & Zheng, W. (2015). Study on the mixing performance of static mixers in selective catalytic reduction (SCR) systems. *Journal of Marine Engineering & Technology*, *14*(2), 57–60. https://doi.org/10.1080/20464177.2015.1096615

Tijhuis, L., Huisman, J. L., Hekkelman, H. D., van Loosdrecht, M. C. M., & Heijnen, J. J. (1995). Formation of nitrifying biofilms on small suspended particles in airlift reactors. *Biotechnology and Bioengineering*, *47*(5), 585–595. https://doi.org/10.1002/bit.260470511

Toh, S. K., Tay, J. H., Moy, B. Y. P., Ivanov, V., & Tay, S. T. L. (2003). Size-effect on the physical characteristics of the aerobic granule in a SBR. *Applied Microbiology and Biotechnology*, *60*(6), 687–695. https://doi.org/10.1007/s00253-002-1145-y

Tomar, S. K., & Chakraborty, S. (2018). Characteristics of aerobic granules treating phenol and ammonium at different cycle time and up flow liquid velocity. *International Biodeterioration and Biodegradation*, *127*(July 2017), 113–123. https://doi.org/10.1016/j.ibiod.2017.11.024

Truong, H. T. B., Nguyen, P. Van, Nguyen, P. T. T., & Bui, H. M. (2018). Treatment of tapioca processing wastewater in a sequencing batch reactor: Mechanism of granule formation and performance. *Journal of Environmental Management*, *218*, 39–49. https://doi.org/10.1016/j.jenvman.2018.04.041

Umar, M., Aziz, H. A., & Yusoff, M. S. (2010). Trends in the use of Fenton , electro-Fenton and photo-Fenton for the treatment of landfill leachate. *Waste Management*, *30*(11), 2113–2121. https://doi.org/10.1016/j.wasman.2010.07.003

Val del Río, A., Figueroa, M., Mosquera-Corral, A., Campos, J. L., & Méndez, R. (2013). Stability of Aerobic Granular Biomass Treating the Effluent from A Seafood Industry. *Environmenta Research*, *7*(2), 265–276.

Venkata Mohan, S., Lalit Babu, V., & Sarma, P. N. (2007). Anaerobic biohydrogen production from dairy wastewater treatment in sequencing batch reactor (AnSBR): Effect of organic loading rate. *Enzyme and Microbial Technology*, *41*(4), 506–515. https://doi.org/10.1016/j.enzmictec.2007.04.007

Vikrant, K., Giri, B. S., Raza, N., Roy, K., Kim, K. H., Rai, B. N., & Singh, R. S. (2018). Recent advancements in bioremediation of dye: Current status and challenges. *Bioresource Technology*, *253*(November 2017), 355–367. https://doi.org/10.1016/j.biortech.2018.01.029

Wagner, J., & da Costa, R. H. R. (2013). Aerobic Granulation in a Sequencing Batch Reactor Using Real Domestic Wastewater. *Journal of Environmental Engineering*, *139*, 1391–1396. https://doi.org/10.1061/(ASCE)EE.1943-

7870.0000760

Wang, F., Yang, F., Zhang, X., Liu, Y., Zhang, H., & Zhou, J. (2005). Effects of Cycle Time on Properties of Aerobic Granules in Sequencing Batch Airlift Reactors. *World Journal of Microbiology and Biotechnology*, *21*(8–9), 1379–1384. https://doi.org/10.1007/s11274-005-5451-2

Wang, Q., Du, G., & Chen, J. (2004). Aerobic granular sludge cultivated under the selective pressure as a driving force. *Process Biochemistry*, *39*(5), 557–563. https://doi.org/10.1016/S0032-9592(03)00128-6

Wang, S. G., Liu, X. W., Gong, W. X., Gao, B. Y., Zhang, D. H., & Yu, H. Q. (2007). Aerobic granulation with brewery wastewater in a sequencing batch reactor. *Bioresource Technology*, *98*(11), 2142–2147. https://doi.org/10.1016/j.biortech.2006.08.018

Wang, Y., Guo, G., Wang, H., Stephenson, T., Guo, J., & Ye, L. (2013). Long-term impact of anaerobic reaction time on the performance and granular characteristics of granular denitrifying biological phosphorus removal systems. *Water Research*, *47*(14), 5326–5337. https://doi.org/10.1016/j.watres.2013.06.013

Wang, Z., Gao, M., Wang, S., Xin, Y., Ma, D., She, Z., … Ren, Y. (2014). Effect of hexavalent chromium on extracellular polymeric substances of granular sludge from an aerobic granular sequencing batch reactor. *Chemical Engineering Journal*, *251*, 165–174. https://doi.org/10.1016/j.cej.2014.04.078

Weber, S. D., Ludwig, W., Schleifer, K. H., & Fried, J. (2007). Microbial composition and structure of aerobic granular sewage biofilms. *Applied and Environmental Microbiology*, *73*(19), 6233–6240. https://doi.org/10.1128/AEM.01002-07

Wei, D., Shi, L., Yan, T., Zhang, G., Wang, Y., & Du, B. (2014). Bioresource Technology Aerobic granules formation and simultaneous nitrogen and phosphorus removal treating high strength ammonia wastewater in sequencing batch reactor. *BIORESOURCE TECHNOLOGY*, *171*, 211–216. https://doi.org/10.1016/j.biortech.2014.08.001

Wichern, M., Lu, M., & Horn, H. (2008). Optimizing sequencing batch reactor (SBR) reactor operation for treatment of dairy wastewater with aerobic granular sludge, 1199–1206. https://doi.org/10.2166/wst.2008.486

Winkler, M. K. H., Meunier, C., Henriet, O., Mahillon, J., Suárez-Ojeda, M. E., Del Moro, G., … Weissbrodt, D. G. (2018). An integrative review of granular sludge for the biological removal of nutrients and recalcitrant organic matter from wastewater. *Chemical Engineering Journal*, *336*(December 2017), 489–502. https://doi.org/10.1016/j.cej.2017.12.026

Xu, G., Xu, X., Yang, F., & Liu, S. (2011). Selective inhibition of nitrite oxidation by chlorate dosing in aerobic granules. *Journal of Hazardous Materials*, *185*(1), 249–254. https://doi.org/10.1016/j.jhazmat.2010.09.025

Yagub, M. T., Sen, T. K., Afroze, S., & Ang, H. M. (2014). Dye and its removal from aqueous solution by adsorption: A review. *Advances in Colloid and Interface Science*, *209*, 172–184. https://doi.org/10.1016/j.cis.2014.04.002

Yan, L. K. Q., Fung, K. Y., & Ng, K. M. (2017). Aerobic sludge granulation for simultaneous anaerobic decolorization and aerobic aromatic amines mineralization for azo dye wastewater treatment. *Environmental Technology (United Kingdom)*, *3330*(May), 1–8. https://doi.org/10.1080/09593330.2017.1329354

Yang, B., Xu, H., Yang, S., Bi, S., Li, F., Shen, C., & Ma, C. (2018). Bioresource Technology Treatment of industrial dyeing wastewater with a pilot-scale strengthened circulation anaerobic reactor. *Bioresource Technology*, *264*(April), 154–162. https://doi.org/10.1016/j.biortech.2018.05.063

Yang, S. F., Tay, J. H., & Liu, Y. (2003). A novel granular sludge sequencing batch reactor for removal of organic and nitrogen from wastewater. *Journal of Biotechnology*, *106*(1), 77–86. https://doi.org/10.1016/j.jbiotec.2003.07.007

Yang, Y. C., Liu, X., Wan, C., Sun, S., & Lee, D. J. (2014). Accelerated aerobic granulation using alternating feed loadings: Alginate-like exopolysaccharides. *Bioresource Technology*, *171*, 360–366. https://doi.org/10.1016/j.biortech.2014.08.092

Yeap, K. L., Teng, T. T., Poh, B. T., Morad, N., & Lee, K. E. (2014). Preparation and characterization of coagulation/flocculation behavior of a novel inorganic-organic hybrid polymer for reactive and disperse dyes removal. *Chemical Engineering Journal*, *243*, 305–314. https://doi.org/10.1016/j.cej.2014.01.004

Zhan, M., Sun, G., Lu, Y., Wang, X., & Zhang, Y. (2016). Characterization of mixing of binary particles in a continuous colliding static mixer. *Powder Technology*, *291*, 448–455. https://doi.org/10.1016/j.powtec.2016.01.005

Zhang, Dalei, Wang, Y., Li, H., Wang, S., & Jing, Y. (2013). Aerobic Granulation in a Sequencing Batch Reactor for the Treatment of Piggery Wastewater. *Water Environment Research*, *85*, 239–245. https://doi.org/10.2175/106143012X13560205145136

Zhang, Dejin, Li, W., Hou, C., Shen, J., Jiang, X., Sun, X., … Liu, X. (2017). Aerobic granulation accelerated by biochar for the treatment of refractory wastewater. *Chemical Engineering Journal*, *314*, 88–97. https://doi.org/10.1016/j.cej.2016.12.128

Zhang, H., Dong, F., Jiang, T., Wei, Y., Wang, T., & Yang, F. (2011). Aerobic granulation with low strength wastewater at low aeration rate in A/O/A SBR reactor. *Enzyme and Microbial Technology*, *49*, 215–222. https://doi.org/10.1016/j.enzmictec.2011.05.006

Zhang, L., Feng, X., Zhu, N., & Chen, J. (2007). Role of extracellular protein in the formation and stability of aerobic granules. *Enzyme and Microbial Technology*, *41*(5), 551–557. https://doi.org/10.1016/j.enzmictec.2007.05.001

Zhang, Y., An, X., & Quan, X. (2011). Enhancement of sludge granulation in a zero valence iron packed anaerobic reactor with a hydraulic circulation. *Process Biochemistry*, *46*(2), 471–476. https://doi.org/10.1016/j.procbio.2010.09.021

Zheng, Y. M., Yu, H. Q., Liu, S. J., & Liu, X. Z. (2006). Formation and instability of aerobic granules under high organic loading conditions. *Chemosphere*, *63*(10), 1791–1800. https://doi.org/10.1016/j.chemosphere.2005.08.055