Specific Moving Bed Biofilm Reactor For Organic Removal from Synthetic Municipal Wastewater

By

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and it has not been previously submitted as part of the requirements for any other degree at UTS or any other education institution except where acknowledgment is made in the text.
I also declare that this thesis has been written by me. Any help I have received in my research work, preparation of this thesis, and all the information sources used have been acknowledged in this thesis.

Signature of Candidate

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NOMENCLATURE

AFBR	anaerobic fluidized bed reactors
AHR	anaerobic hybrid reactor
AMBBR	anaerobic moving bed biofilm reactor
AOB	autotrophic bacteria
BOD	biochemical oxygen demand
COD	chemical oxygen demand
DAF	dissolved air flotation
DO	dissolved oxygen
DOC	dissolved organic carbon
F	flow rate
FBBR	fluidised bed bioreactor
HABR	hybrid anaerobic baffled reactor
HBR	hybrid biological reactor
HRT	hydraulic retention time
MBBR	moving bed biofilm reactor
MBR	membrane bioreactor
MF	microfiltration
MLSS	mixed liquor suspended solid
MLVSS	mixed liquor volatile suspended solid
MW	molecular weight
NF	nanofiltration
OLR	organic loading rate
OM	organic matter
OUR	oxygen uptake rate
PAC	powdered activated carbon

PAO	phosphorous accumulation organism
PIP	pharmaceutical industrial park
PTSE	primary treated sewage effluent
RBC	rotating biological contactor
RO	reverse osmosis
ROC	reverse osmosis concentrate
SBBR	sequencing batch biofilm reactor
SBR	sequencing batch reactor
SOUR	specific oxygen uptake rate
SS	suspended solid
TDS	total dissolved solid
T-N	total nitrogen
TOC	total organic carbon
TSS	total suspended solid
UASB	up-flow anaerobic sludge blanket
UF	ultrafiltration
UF-PAC	ultrafiltration-powered activated carbon
UF-RO	ultrafiltration-reverse osmosis
WWTP	wastewater treatment plant

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ABSTRACT

Due to the rapid urbanization, wastewater has been continuously and excessively released into the environment, causing significant impacts on human and wild life. Many organic compounds in municipal wastewater are detected in different types of wastewater, affecting water quality, human health and biodiversity in the ecosystems. These compounds have significant impacts on receiving water bodies so as finding an appropriate treatment technology to effectively remove organic matters (OMs) in wastewater is very essential. Recently, moving bed biofilm reactor (MBBR) has brought increasing research interest in practice for removal of biodegradable organic matter and its application have undergone various degrees of modification and development. Moreover, as the carrier using in the MBBR is playing a crucial role in system performance, choosing the most efficient carrier could enhance the MBBR performance. Hence, scientists have been looking for an appropriate carrier which is not costly and has a suitable surface for microbial growth. The main aim of this study is to evaluate a specific MBBR with polyethylene media as biofilm support carrier in terms of OMs removal along with nutrient removal and microbial growth and activity.

The optimization study for its practical application was conducted through a series of the investigations on the effect of carrier's filling rate, organic loading rate (OLR) and hydraulic retention time (HRT). The carrier used in this study was made of Poly Ethylene (PE) with a density of about 0.95 g/cm^3. The experimental results show that although increasing carrier filling rate from 10 to 40% resulted in augment of attached biomass from 0.95 to 5.0 mg/g, microbial activity was dramatically decreased from 2.22 to 0.25 mg O_2/g MLVSS.h. Thus, the best MBBR performance was achieved when the SOUR was at the peak of 5.04 O_2/g MLVSS.h at 20% of filling rate with the removal efficiencies of 95.33, 92.13, 57.41 and

67.58% in terms of DOC, COD, PO_4-P and NH_4-N, respectively. Moreover, 19.8% increase in DOC removal was resulted from the increasing amount of biomass from 5.68 to 11.96 mg/g due to the OLR increase from 0.15 to 0.8 kg COD/m^3d, respectively. Besides, 48.19% of TN removal was achieved at the highest OLR of 0.8 kg COD/m^3d in which microbial activity was 8.53 mg O_2/g MLVSS.h. The effect of HRT on OMs and nutrients removal efficiency was also investigated and the results reveal that at all of the HRTs, more than 95% and 96% of DOC and COD removal efficiency was achieved, respectively. In addition, the experimental result show that at HRT of 4 h, the lab scale MBBR had an average TN removal efficiency of 60.58% while it was only 48.2 and 42.15% at HRT of 8 and 25 h, respectively. Variation of HRT also affected microbial growth and activity. Decreasing HRT from 25 to 8 and 4 h resulted in enhancement of microbial growth on carriers from 11.23 to 14.07 and 16.43 mg/g as well as SOUR from 8.01 to 14.66 and 22.53 mg O_2/g MLVSS.h, respectively. This means HRT of 4 h was the favourable condition for the lab scale MBBR.

In conclusion, the results indicate that MBBR with polyethylene media as biofilm carrier possessed great potential to be used for OMs removal from water and wastewater.

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CHAPTER 1

INTRODUCTION

1.1 General

The population of Australia is growing rapidly and estimated to expand by 4.5 million people by 2030 (ABS, 2006). Previously, when the population and generated waste was limited, wastes were discharged into natural water bodies to get purified naturally by natural bacterial degradation and dilution. Changing life style and urbanization on one hand and population growth on the other hand, have resulted in production of a huge amount of domestic and industrial wastewater. Increasing the amount of harmful substances in wastewater has impacted surrounding environment, human health and aquatic life. For instance, they resulted in annual death of 1.7 million people from diseases related to polluted water, lack of satisfactory sewage conditions for 4 billion people and no access to drinking water for 1.1 billion people (Ecosummit, 2012). Hence, basic wastewater treatment facilities have been introduced to decrease the level of wastewater pollution while removing harmful constituents such as organic matters and nutrients.

Organic matters (OM) can be found in wastewater either naturally or by industrial and modern life activities. The wide impacts of present organic matters in wastewater on human and aquatic environment are death of fishes and mimic natural steroid hormones, respectively (Kandarakis et al., 2009; Zheng et al., 2009; Darbre and Harvey, 2008; Fent et al., 2006). Thus, over the last two decades, scientists have been looking for efficient and cost effective treatment systems. This has resulted in the development of numerous novel technologies to improve wastewater treatment plants. For instance, high removal efficiency of organic carbon, nutrients and ammonia contents has been achieved via conventional activated sludge (CAS). Nevertheless, high energy demanding and being costly are the main drawbacks of this system. Therefore, new specific treatment systems such as moving bed biofilm reactor with a significant improvement in energy consumption and productivity have been developed to overcome these problems.

In 1988, a new design of a wastewater treatment plant was recommended by the state pollution control authority of Norway (Odegaard and Storhaug, 1990). Hence, a Norwegian company with SINTEF research organization developed moving bed biofilm reactor (MBBR). Currently, there are more than 500 large scale wastewater treatment plants based on MBBR process in operation in 50 different countries all over the world. This process has become popular in the field of wastewater treatment because it maximizes the capacity and efficiency of the treatment plant while minimizing the footprints. Moreover, it requires relatively small area compared with the conventional treatment systems. It is a highly effective biological process which has the advantages of low head loss, no requirement of back washing or sludge recycling, non-cloggable, and high specific biofilm surface area. It is also, economical and has no bulking problem compared to other technologies. MBBR systems are mostly based on aeration rate and specially designed carriers for bacteria colonization which are used inside the reactor (Rahimi et al., 2011). Therefore, even though 70% of reactor's effective volume can be loaded with carriers (Odegaard et al., 2000) due to limitation in carrier movements, MBBR performance may decrease dramatically (Weiss et al., 2005). Odegaard (2006) mentioned that fill percentages greater than 67% impede the upward rolling pattern desired by the MBBR process. In addition to limitation in carrier movements, high carrier concentration in the reactor causes higher amount of microorganism detachment from biofilm and then leads to the decrease of biomass in the reactor. However, the percentage of media required is based on wastewater characteristics and specific treatment goals. Values lower than 67% are frequently used (Odegaard, 2006). In addition to carrier filling rate and aeration rate, carrier material is another fact which affects MBBR performance (Guo et al., 2010). Different types of carriers have been used in different experiments but some of them are more popular as very thin, distributed and smooth biofilm develops on their surface such as polyethylene carriers. To transport substrates and oxygen to the biofilm surface, this type of biofilm is very actively required. Other factors reported to affect MBBR performance are flow and mixing conditions in the reactor. To have an efficient system, it is important to have adequate turbulence in the system as it cause removal of excess biomass and maintain sufficient thickness of biofilm (Odegaard et al., 2000).

Furthermore, the possible effect of different hydraulic retention times (HRT) and organic loading rates (OLR) in MBBR technology have been investigated in few studies (Li et al., 2011; Nguyen et al., 2011; Jianlong et al., 2000). Although it was reported that higher HRT and OLR increased the OM and nutrient removal efficiency, higher cost and energy consumption requirement was reported (Guo et al., 2010). Therefore, low cost and efficient treatment are the main aims of the current research on MBBR. Consequently, it is necessary to carry out a systematic study on the optimum biofilm carrier filling rate, OLR and HRT in MBBR to treat wastewater efficiently and cost effectively.

The main aim of this research is to investigate the performance of MBBR in removing the organic mattes from the synthetic domestic wastewater and to find the optimum operating conditions such as biofilm carrier's filling rate, organic loading rate and hydraulic retention time.

1.2 Objectives of the study

The specific objectives of this research are to examine:

- The effect of carrier's filling rates (FLR) on the performance of a lab-scale MBBR in terms of organic removal;
- The effect of organic loading rates (OLR) on the performance of a lab-scale MBBR in terms of organic removal; and
- The effect of hydraulic retention time (HRT) on the performance of a lab-scale MBBR in terms of organic removal.

Although this research focuses on OM removal, microbial growth and activity together with nutrient removal was also included and discussed in this study.

1.3 Scope of the study

The scope of the study is to carry out a laboratory-scale study by conducting a series of experiments using a specific MBBR to treat synthetic wastewater. The biofilm carriers used in these experiments were Anox Kaldnes polyethylene Biofilm Chip^{TM}. The reason that PE carrier was selected to be used in this experiment over other media was the advantage of thin, distributed and smooth biomass growth on their surface. The results were compared and evaluated in terms of dissolved organic carbon (DOC) and chemical oxygen demand (COD) removal efficiency to determine the optimal FLR, OLR and HRT.

1.4 Thesis Structure

Chapter 1:

This chapter provides the background, objectives and scope of the study.

Chapter 2:

This chapter provides a review of current typical wastewater treatment technologies, especially MBBR and their performance in terms of organic removal efficiency.

Chapter 3:

This chapter describes the experimental investigation which includes materials, methodologies and analytical methods.

Chapter 4:

This chapter presents all the experimental results and discusses on the organic removal efficiency associate with microbial growth and nutrients removal from MBBR at different filling rates of PE carriers, different organic loading rates and HRT.

Chapter 5:

This chapter concludes the results from the study and provides the recommendations for the future research. References are also attached at the end of the thesis.

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CHAPTER 2

LITERATURE REVIEW

In this chapter, pertinent literature, publications and reports were reviewed and presented. Search engine tools such as Scifinder Scholar, Compendex, Proquest, EBSCOhost and library services such as Interlibrary Loan, Consortium Loan and library archives were deemed extremely helpful to locate and retrieve such materials.

2.1 Introduction

Urbanization and changing life styles have resulted in an increase in the production of domestic and industrial wastewater. This increase has vastly affected human life. For example there is the death of 1.7 million people annually from diseases related to polluted water, lack of satisfactory sewage conditions for 4 billion people and no access for 1.1 billion people to drinking water. This condition is exacerbated by the increase in population (Ecosummit, 2012). Within this context, it is expected that the Australian population of the major cities will increase by 35%, by the year 2030 (ABS, 2006) which will result in the production of a larger quantity of wastewater. Wastewater contains a variety of harmful constituents such as organic matters (OM) and nutrients. The presence of OM and nutrients in the environment can adversely impacts both human and aquatic life. Hence, in order to decrease the pollution of discharged wastewater in natural water bodies, different wastewater treatment applications have been used all over the world. However, due to varying influent characteristics and stringent effluent regulations, wastewater treatment has been a challenge throughout the past few decades. One of the most important issues in this field is the huge economical cost to achieve the desired effluent water quality, particularly at medium to large wastewater treatment facilities. Therefore, further studies on finding an efficient and cost effective treatment system is necessary.

2.2 Organic matters in municipal wastewater

2.2.1 Back ground

Organic constituents in both soluble and insoluble forms exist in water and wastewater and are associated with unpleasant colour and odour, growth substrates for bacteria and can cause health problems. These compounds accidently enter the environment as a result of agriculture and urban activities, industrial runoff and sludge disposal (Ashton et al., 2004; Becker et al., 2008; Mompelat et al., 2009). Henceforward, they are affected by different processes such as biological degradation and distribution within different phases (Heberer, 2002a; Birkett and Lester, 2003; Farre et al., 2008). Since these compounds are capable of having high levels of toxicity, they have become an increasing concern for the environment (Xu et al., 2008). Physicochemical properties of organic compounds and the nature of their environment, have a direct relationship to their removal efficiency. This is mostly due to their biodegradation mechanism, the treatment system used and environmental effects.

2.2.2 Constituents of organic matter

Organic matters can be soluble, colloidal or particulate (Dignac et al., 2000). Moreover, depending on the origin, organic matters in the wastewater can be classified into two main groups namely natural organic matters and synthetic organic matters (Kazner et al., 2012).

A. Natural organic compounds

Natural organic compounds can be found in all water sources however the concentration differs (Gottschalk et al., 2010). Contaminants of this group may vary from micromolecules such as simple organic acids and sterols to macromolecules such as fulvic and humic acids (Stevens, 2006). Since humic acids are insoluble and have a complex aromatic structure, they have been reported as the most considerable fractions within humic substances. Their presence can result in a brownish colour as well as a muddy taste and an odour of water

(Hahn et al., 2002). Moreover, humic acids are in charge with the production of disinfection by products which cause adverse impacts on health such as cardiovascular and male reproductive effects and effects on foetus/litter (Baribeau et al., 2006). This is due to the reaction of humic acid with chlorine gas and hypochlorites (Selcuk et al., 2007).

One of the most considerable natural organic matters is steroid hormones. These compounds which control the endocrine and immune system (Virkutyte et al., 2010) hold higher endocrine disrupting activity in comparison to other compounds (Christiansen et al., 1998). However, since these compounds cannot be replaced, it is difficult to control them (Wilson and Knudsen, 2006). Steroid hormones can be classified into natural and synthetic hormones (Table 2.1). Steroids can adversely affect the health of fishes as well as other organisms such as amphibians and reptiles. In addition, some other adverse impacts of steroids on human health have been reported such as prostate and breast cancer as well as endometriosis (Wilson and Knudsen, 2006; Berstein and santen, 2008). Hence, due to the backer of estrone, 17-β estradiol, estriol and ethynylestradiol in estrogenicity of treated wastewater, these compounds have been considered more by scientists (Gray et al., 2000). Wastewater effluents, untreated discharges, runoff of manure, sewage sludge (Fent et al., 2006) and fish food additives (Lang et al., 2002) are the main ways that these compounds may enter the environment.

Table 2.1 Natural and synthetic steroid hormones (adapted from Virkutyte et al., 2010)

Natural hormones	Synthetic hormones
Estrogens (Estradiol, estrone, estriol)	Ethynylestradiol
Androgens (androstenedione)	Mestranol
Progestagens (Progesterone)	Dexamethasone
Corticoids (cortisol)	

B. Synthetic organic compounds

Synthetic organic compounds can be introduced to the wastewater plants either from industrial activities or modern day life. Thus, there is a variety of synthetic organic compounds in the treatment plants (Spellman and Bieber, 2012). Two important classes of these compounds are pharmaceuticals and personal care products. Pharmaceuticals have positive effects on health and their usage is expected to increase; however, their acute toxicity on the aquatic environment is a concern (Roig, 2010; Zhang et al., 2009). Although pharmaceuticals are transpired as mixtures in the environment, acute effects have been observed at much higher concentration. In the case of surfactant and personal care products, a fraction of nonylphenol ethoxylates (NPE) results in the formation of nonylphenol (NP). This product, which is more toxic than NPE, has been considered as an endocrine disruptor by scientists during the last decade (Brooke et al., 2005). These compounds can cause adverse effects on aquatic organisms such as encouraging esterogenic effects in them (Birkett and Lester, 2003; Soares et al., 2008). Moreover, the impacts of surfactants are well correlated to the species and development stage of test organisms as well as environmental characteristics (Soares et al., 2008).

2.2.3 Impacts of organic matter

Untreated wastewater contains different pathogenic micro-organisms, nutrients and toxic compounds which can affect human health and the environment. In this regard, treatment of wastewater is necessary to protect human health as well as wildlife. Some of medically active wastewater contaminants include endocrine disruptors (EDCs), pesticides, industrial chemicals, phenolic compounds, volatile organic compounds (VOCs), toxic air contaminants (TACs), disinfection by products (DBPs), odours and chlorine residuals (Metcalf and Eddy, 2004). The presence of pathogenic microorganisms such as bacteria, viruses and parasites in the wastewater (Hussain et al., 2002) can lead to human diseases such as hook worm (Feenstra et al., 2000) and ascariasis infections (Cifuentes et al., 2000) in a variety of age groups. As can be seen in Table 2.2, Endocrine Disrupting Compounds (EDCs) with highly heterogeneous group of molecules are an example of toxity variety (Kandarakis et al., 2009). They are one of the medically active contaminants present in wastewater (Tan et al., 2007) defined as an exogenous agent that interferes with the synthesis, secretion, transport, binding, action, or elimination of natural hormones in the body that are responsible for the maintenance of homeostasis, reproduction, development, and/or behavior (USEPA, 1997). This class of chemicals can widely affect human health for example by:

- Mimicking natural steroid hormones;
- Disabling natural hormones enabling EDCs to interact with steroid hormone receptors as analogs or antagonists (Kandarakis et al., 2009);
- Causing male disarray including Oligospermia, Testicular cancer (Bay et al., 2006; Sharpe, 2006) and Prostate hyperplasia (Maffini et al., 2006); and
- Causing female disarray including vaginal adenocarcinoma (Herbst et al., 1971; Li et al., 2003), disorders of ovulation, benign breast disease (McLachlan et al., 2006; Fenton, 2006), breast cancer, uterine fibroids and disturbed lactation (Fenton, 2006).

Table 2.2 EDCs classification (adapted from Kandarakis et al., 2009)

Type of EDC	Example
Industrial solvents/ lubricants	PCBs, PBBs, dioxins
Plastics	Bisphenol A
Plastisizers	Phthalates
Pesticides	Methoxychlor, chlorpyrifos, DDT
Fungicides	Vinclozolin
Pharmaceutical agents	DES

Another wastewater contaminant which has been considered widely is Volatile Organic Compounds (VOCs). They can affect human health and cause diseases such as cancer and chronic effects on the liver, kidney and nervous system (Lindeburg, 2011) as well as impact on the environment causing flammability, toxicity, odorous-ness and contributing to photochemical smog and tropospheric ozone (Metcalf and Eddy, 2004). In addition, the issue of acid rains which are caused by the greenhouse effect is due to the diffusion of VOCs into the atmosphere (Gesimondo and Postell, 2011). Chlorine residuals which can be toxic for aquatic life, have the ability to react with organics in wastewater and produce potential carcinogens named chlorinated hydrocarbons (DBPs) such as trihalomethanes (American Water Works Association, 2009).

Consequently, organic pollutants can cause toxicity as well as affecting the quality of receiving water bodies (Baun et al., 2004). In this context, acute and chronic toxicity, endocrine disruption, bioaccumulation and biomagnification have been reported as organic pollutants effect on aquatic organisms (Fent et al., 2006; Darbre and Harvey, 2008; Zheng et al., 2009). Hence, according to Moon et al. (2008); Song et al. (2006) and Seacat et al. (2002), the adverse effects of organic pollutants in summary can be on serum, the liver and kidney in animals and dermal lesions, body weight loss, hepatotoxicity, immunosuppression, hormonal changes and carcinogens in humans.

2.3 Typical biological treatment processes of organic matter

2.3.1 Background

During the early 1900s, the main objectives of biological treatment on wastewater was the conversion of dissolved constituents, suspended colloidal solids, nutrients and specific trace organic constituents into simple products and biofilm as well as the reduction of the concentration of compounds. The USEPA secondary treatment regulatory standards in 1972 also considered the removal of BOD and TSS with the removal value of 85% in addition to previous factors. Since different kinds of microorganisms are involved in this process, the removal of these compounds is performed biologically. All of the biological processes have been modelled by natural processes. In this regard, biological treatment could operate under both aerobic and anaerobic process (Metcalf and Eddy, 2004). Within aerobic conditions, microorganisms degrade organic compounds to carbon dioxide and biomass, while during anaerobic conditions carbon dioxide and methane are the bi-products.

Diverse kinds of microorganisms are involved in aerobic treatment in order to remove organic materials. The ability of aerobic heterotrophic bacteria in the production of extracellular biopolymers, results in the generation of biological flocs. This product can be separated from treated liquid. In addition, protozoa have an important role within the aerobic biological treatment processes. In comparison to heterotrophic bacteria, protozoa demand longer solid retention time, DO concentration higher than 1 mg/L and attention to toxic material. As a result, they play a crucial role due to their sensitive features. The clarification of effluent can be made by protozoa due to the consumption of free bacteria and colloidal particulates (Paul and Liu, 2012).

On the other hand, anaerobic treatment has been used effectively where liquid waste volumes are small and contain no toxic matter as well as the presence of high percentages of readily oxidized dissolved organic matter (Nemerow, 2007) and high strength organic effluent (Renou et al., 2008) such as streams from young tips (Pokhrel and Viraraghavan, 2004). Since little or no power needs to be added to anaerobic digestion (Nemerow, 2007) and few solids are produced, it is possible to save energy (Berrueta and Castrillon, 1992). Hence, in the case of anaerobic digestion, some advantages have been counted in comparison to aerobic ones, such as:

- Low operating costs (Nemerow, 2007);
- Low sludge production;
- Low nutrient need;
- In the case of compounds with high halogenate levels, anaerobic systems have dehalogenation performance (Virkutyte et al, 2010); and
- Although this system suffers from low reaction rate and long detention periods (Nemerow, 2007), at the neutral pH, it is possible to use the produced methane to warm the digester (Renou et al., 2008).

Nevertheless, high efficiency of biological processes has been reported in the field of organics and nitrogenous constituents removal from wastewater with BOD/COD ratio >0.5.

2.3.2 Conventional treatment systems

Conventional treatment systems can be categorized into two main groups named biological treatment and physical/chemical treatments. Some advantages have been reported for physical/chemical treatment in comparison to biological ones such as easy control, adaptation with a wide range of flows and loading rates and variety of application usages. However, some drawbacks such as production of high amount of sludge, presence of high concentrate of dissolved salts and high operation costs focused attention on biological treatments (Forster, 2003). Therefore, the most important biological processes are described as follows:

A. Suspended growth Process

In most aspects, suspended growth process are operated under aerobic conditions while in the cases of high organic concentration industrial and organic sludges, treatment processes may operate under anaerobic conditions (Nemerow, 2007). Different suspended growth processes are reviewed as follows:

a. Lagoon

Lagoons can be defined as artificial or natural earth basins (Nemerow, 2007). It was determined as a low cost option in order to remove pathogens from waste water. This system was especially used in developing countries due to their little need for specialised skills in order to setup the system (Maynard et al., 1999). High phenols removal efficiency by biological lagooning treatment was reported. Orupold et al. (2000) achieved up to 70% COD removal in an intermittently aerated batch while a lower COD removal of 41% in non-aerated batch was achieved. In the same experiment within a periodic aerated batch, high removal efficiency from 95 to over 99% of phenol, methylphenols and dimethylphenols was reported. In comparison to monohydric phenols, low removal efficiency was reported for resorcinol. As a result, lagooning has the advantages of low investment and maintenance cost. However, it has some drawbacks such as the danger of leakage into the soil and groundwater, the production of acetic acid smell as a result of anaerobic fermentation and the requirement of large collecting basins set up far from inhabited zones (Niaounakis and Haluadakis, 2006). In addition, in the lagooning sludge PAEs, specifically dethyl-hexyl phthalate with the concentration level of 28.67 mg/kg, was detected as a major pollutant (USEPA, 2001). Hence, this treatment system needs further controls to avoid the described problems.

b. Activated sludge

The activated sludge process was developed by Clark and Gage at the Lawrence experiment station in Massachusetts (Metcalf and Eddy, 1930) but the conception of activated sludge process was discovered by Ardern and Lockett (1914). In this type of wastewater treatment, it was illustrated that organic matter removal rate is increased as a result of municipal sewage aeration (Haandel and Lubbe, 2012). Moreover, within this process, formation of macroscopic floc particles with the size of 50 to 200 μm resulted in an increase in the organic material removal rate. This process can be applied as a treatment of domestic wastewater or as a co-treatment for leachate and sewage (Renou et al., 2008). Hoilijoki et al. (2000) pretreated municipal wastewater with activated sludge at different temperatures of 5-10°C with the addition of plastic career material. Aktas (2001) enhanced nitrification efficiency on wastewater biological treatment by the addition of PAC. Although this process may achieve high removal efficiency in the case of organic carbon, nutrients and ammonia content, disadvantages of activated sludge process led to usage of other technologies (Renou et al., 2008). The first drawback of activated sludge is the dependence of this process on gravity settling technology which controls the activated sludge system design. Gravity settling decreases the biomass concentration level as well as extends the internal recirculation of nitrogen removal (Orhon et al., 2009). Disadvantages of activated sludge treatment are listed as follows:

- Insufficient sludge settle-ability (Yeon et al., 2011);
- Need for longer aeration time (Loukidou and Zouboulis, 2001);

- Demands high levels of energy and excess production of sludge (Hoilijoki et al., 2000); and
- Occurrence of microbial restraint as a result of high ammonium nitrogen strength (Lema et al., 1988).

c. Sequencing Batch Reactor

This system is an adjusted activated sludge process which uses fill and draw mode of operation. The most significant advantage of the (SBR) system is the knowledge of biomass activity. This knowledge leads the operator to adjust the operation of SBR for optimal biomass activity, troubleshoot the SBR in order to identify problems and establish proper conditions. The SBR system can be operated in aerobic, anoxic and anaerobic conditions. The aerobic SBR system is appropriate for nitrification and denitrification processes due to the supplement operation regime as well as organic carbon oxidation and nitrification (Diamadopoulos et al., 1997). In this regard, high COD removal up to 75% and NH_4^+-N removal of 99% was reported during aerobic treatment of domestic wastewater in a SBR with a 20-40 days residence time (Lo, 1996). By comparison, anaerobic sequencing batch reactors have demonstrated good performance in the case of solid capture achievement, reduction of organics in one vessel and omission of the need for a clarifier (Renou et al., 2008). Thus, it was recommended to use aerobic-anaerobic SBRs in order to simultaneously bring down organic and nitrogen matter concentration in the effluent and increase the performance of the treatment system (Ahmed et al., 2011).

It was reported that hydraulic residence time (HRT) and temperature can affect the performance of SBR significantly (Table 2.3). In this context, Kargi and Uygur (2004) reported that at different HRTs, removal efficiency of COD, NH_4^+-N and PO_4-P varies considerably. Thus, higher removal efficiency was achieved at higher HRTs and temperatures even few limitations was reported. Consequently, advantages of SBR over activated sludge, such as the reduction of the required reactor volume, have made this system more popular (Haandel and Lubbe, 2012).

Table 2.3 AnSBR performance at different conditions (adapted from Bodik et al., 2002)

Temperature (°C)	HRT (h)	Removal efficiency		
		COD (%)	BOD_5 (%)	SS (%)
8	10	56	48	81
	20	69	78	84
	46	74	65	92
15	10	62	57	80
	20	72	73	83
	46	84	76	90
23	10	88	96	-
	20	87	86	75
	46	86	85	91

d. Up-flow Anaerobic Sludge Blanket

UASB was developed by a research group at the Wageningen Agricultural University in the Netherlands in the 1970s (Lettinga et al., 1980). The upflow anaerobic sludge blanket has become one of the most popular anaerobic waste water treatment systems. The significant feature of this system is that without any support medium, sludge granules of 1-5 mm diameter can be formed in an UASB system. Features of granules are their high density, good mechanical strength, and a high settling velocity combined with a high specific methanogenic activity (Pol and Lettinga, 1987). In this system, during the transition of influent wastewater through the sludge blanket, organic substances of wastewater are degraded by anaerobic microbes. As a result of this fact methane, carbon dioxide, hydrogen, nitrogen and hydrogen sulfide are released as biogas. In this regard, the UASB process was initially developed for the treatment of high strength industrial wastewaters through the recovery of energy in the form of methane. One of the most significant features of these systems is the high conversion rate of UASBs which is due to the presence of high biomass concentration in these systems (Fang, 2011). In comparison to other conventional treatments, UASB systems have the advantage of a lower external energy requirement as they do not need mechanical mixing and recirculation of sludge and effluent (Lettinga et al., 1997). Consequently, compared with aerobic treatments, UASB systems have some benefits such as:

- Reduction of operational costs due to no aeration;
- Significant saving in investment costs due to the need of less treatment units;
- Energy recovery by using produced methane and electricity production;
- Except for main headwork pumps and fine screens, there is no high technology equipment requirement in UASB systems;
- As the process is robust, high hydraulic and organic loading rates can be tolerated and led to higher performance in UASB reactors compared with other anaerobic reactors (Renou et al., 2008; Fang, 2011); and
- As well stabilised and dewatered sludge production in the UASB system is low, post treatment is not required (Lin et al., 2000).

In this context, UASB is a modern anaerobic treatment technology in which it is possible to achieve high treatment efficiency and a short hydraulic retention time (Lin et al., 2000). As mentioned above some factors such as temperature, HRT and OLR can significantly affect UASB removal efficiency. For instance, Kennedy and Lentz (2000) have achieved 77-91% of COD removal at low HRT (0.5-1 day) and high temperature (35°C). However, at temperature and HRT of 11-24 °C and 0.4-1.4 day, respectively, COD removal efficiency was reduced to

45-71% (Kettunen et al., 1996). The effect of HRT on UASB efficiency was investigated and reported that as the HRT deceased from 36 to 12 h, the removal efficiency reduced slightly from 99.85% to 98.40%. Moreover, as organic loading rate correlates with UASB performance, Basu and Gupta (2010) examined this correlation. In this experiment, variations of OLR from 1.5 to 3.1 $kg/m^3.d$ were studied and resulted in increase of removal efficiency of up to 99%.

Although many advantages were reported for UASB treatment technology, some difficulties have been counted for this system, including:

- To meet discharge or reuse criteria, sufficient post treatment is required in addition to anaerobic treatment although during anaerobic treatment most of the influent COD is converted to methane;
- It is not possible to prevent methane release into the atmosphere since most of the produced CH4, which is not often used for energy generation, is still dissolved in the effluent;
- Odour problems is mostly accurse as a result of gas reduction;
- High influent sulfate concentrations may cause limitation for applicability of anaerobic sewage treatment as it results in conversion of organic BOD/COD to inorganic BOD/COD (Fang, 2011); and
- This system is very sensitive to toxic substances (Sung et al., 1997).

B. Attached growth process

In attached growth process the microorganisms which convert organic materials and nutrients to gases and cell tissue are attached to an inert packing material. Packing materials, which can be non-submerged or submerged completely in liquid, include different materials such as rock, gravel, slag, sand, redwood and a wide range of plastics and synthetic materials. Hence, in this process, biofilm is responsible for biological reactions such as organic material and nutrients removal from wastewater (Metcalf and Eddy, 2004). As these systems have the ability to keep active biomass and have less of an effect on nitrification in low temperature, they were counted as high efficiency systems and high demanded ones for many years (Metcalf and Eddy, 2004). However, although the most significant feature of the attached growth process is the performance of biofilm, they could mostly be diffusion limited. Therefore, overall removal rates can be affected by diffusion rates as well as the electron donor and electron acceptor concentrations at different locations in the biofilm. This is due to the occurrence of substrate removal and electron donor utilization in the deeper parts of the attached growth biofilm (Tchobanoglous et al., 2003). This factor describes the difference of attached process with activated sludge. Diffusion limitation should be considered more whilst measuring bulk liquid dissolved oxygen (DO) concentration in the attached growth process due to its effects on the biological reaction rate. In this context, while the suspended growth aerobic process requires DO concentration of 2-3 mg/L, this low DO concentration in the case of attached growth process could be a limitation. Thus, in order to achieve a high level of nitrification in attached growth bioreactors, higher DO concentration is required when considering the ammonia concentration (Odegaard, 2006). Attached growth process can be classified as follows:

a. Trickling filter

Trickling filter is a non-submerged fixed film biological reactor that rock or plastic packing is used as a support medium for biofilm growth in it. Stone was used as a packing material. However, it was proved that plastic packing could increase treatment capacity and has the advantages of higher loading rates, less land area and lower amount of clogging (Crites and Tchobanoglous, 1998). In this system, wastewater is trickle over the surface of the filter

(Figure 2.1). Organisms that grow in a thin biofilm over the surface of the media oxidize the organic load in the wastewater. Since in trickling filters bacteria could remain in the filter for a long time, this system is potential for high hydraulic and pollutant loadings (Lekang et al., 2000). In addition, in trickling filters there is no requirement of aeration systems or external air supply. This is due to different temperatures between the ambient air and air inside the pores which creates the driving force for air flow (Tekerlekopoulou and Vayenas, 2007).

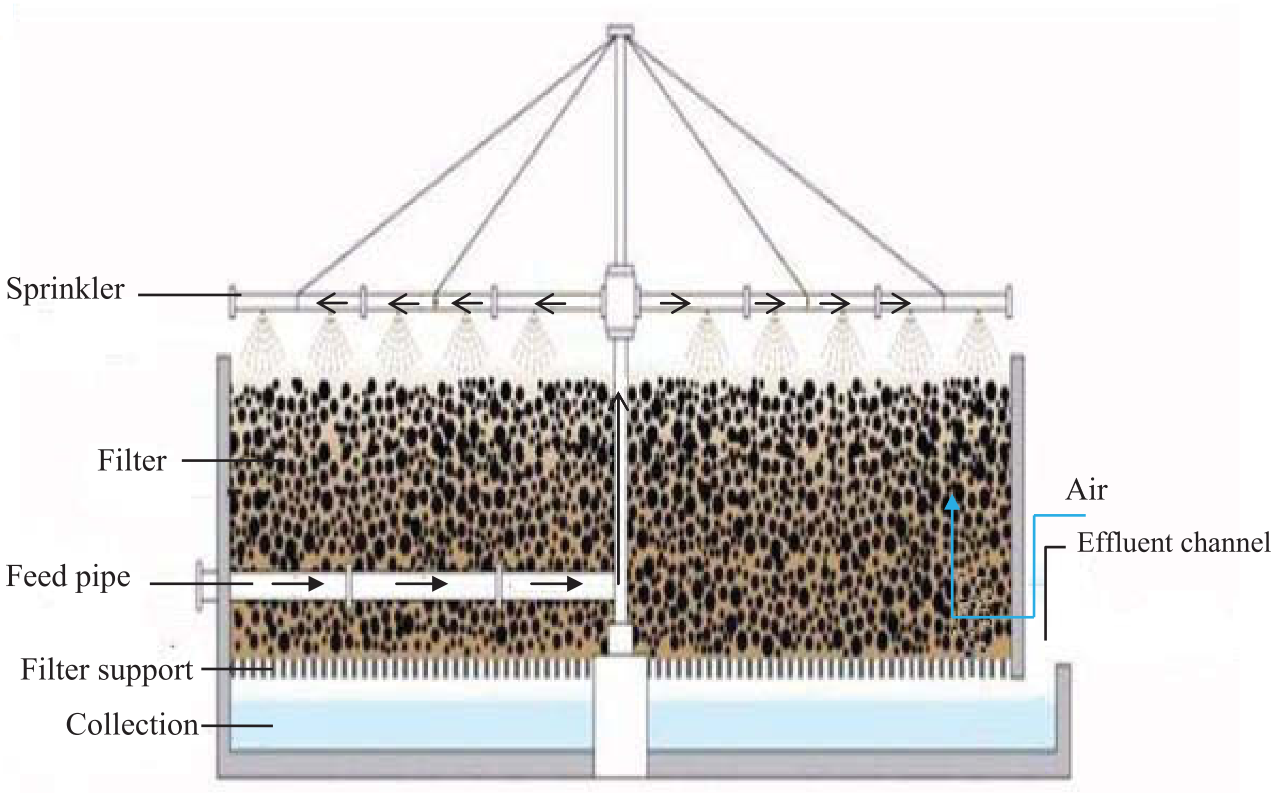


Figure 2.1 Trickling filter (adapted from Tilley et al., 2008)

Packing material and underdrain are two important factors in trickling filters for the function of biofilters. In this regard, Akker et al. (2008) noted that plastic packing trickling filter as pre-treatment for wastewater with low concentration of ammonia resulted in high removal efficiency. Moreover, high removal efficiency in the case of NH_4^+-N in a variety of temperatures was reported in aeration trickling filter (Matthews et al., 2009). Hence, compared with the activated sludge process, trickling filters as an aerobic attached growth process have some advantages, including:

- A requirement of less energy;
- Simpler operation with no problems in mixed liquor inventory control and sludge wasting;
- No issues of bulking sludge in secondary clarifiers;
- Better sludge thickening properties;
- Less equipment maintenance requirement; and
- Better recovery better from shock toxic loads (Metcalf and Eddy, 2004).

Although trickling filters have some advantages in comparison to activated sludge systems, some disadvantages have been counted for this process in contrast to activated sludge technology. These include greater sensitivity to lower temperature, poorer effluent quality in terms of BOD and TSS concentrations, production of odours, uncontrolled solids sloughing events (WEF, 2000) and lower performance in the case of some steroid hormones removal efficiency (Svenson et al., 2003). However, high removal efficiency of alkylphenol polyethoxylates (up to 77%) (Gerike, 1987) and circa (75%) (Brown et al., 1987) were achieved in a few studies. Thus, these problems make it difficult to fulfil the biological removal of nitrogen and phosphorous. This could results in higher turbidity of effluent in trickling filters.

b. Fluidized reactor

A fluidized bed bioreactor (FBBR) consists of particles like sand, stone, glass, metal mesh and plastic and activated carbon which are coated with microorganisms and are suspended in sufficiently aerated wastewater. These particles are used to keep the gas, liquid and solid particles thoroughly mixed (Vinod and Eddy, 2005). Biofilm is formed on the large surface provided by particles during fluidization and the surface characteristics such as porosity and roughness affects biofilm growth rate. Polymer particles provide a large surface area for colonization of microorganisms and have densities close to that of biofilm. This causes homogenous distribution of particles in the fluidized bed reactor. Low fluid velocity used for expansion is required for polymeric particles which have lower density and results in less power consumption (Midha et al., 2012). For instance, Midha et al. (2012) used nylon support particles in their experiment, which have a diameter and density of 2-3 mm and 1140 kg/m^3 respectively, to investigate the effects of upflow velocity, hydraulic retention time and reactor operation time on the sulfide oxidation rate in synthetic sulfide wastewater. In this experiment more than 92% of sulfide oxidation was achieved at an HRT of 75h and upflow velocity of 14 m/h (Figure 2.2).

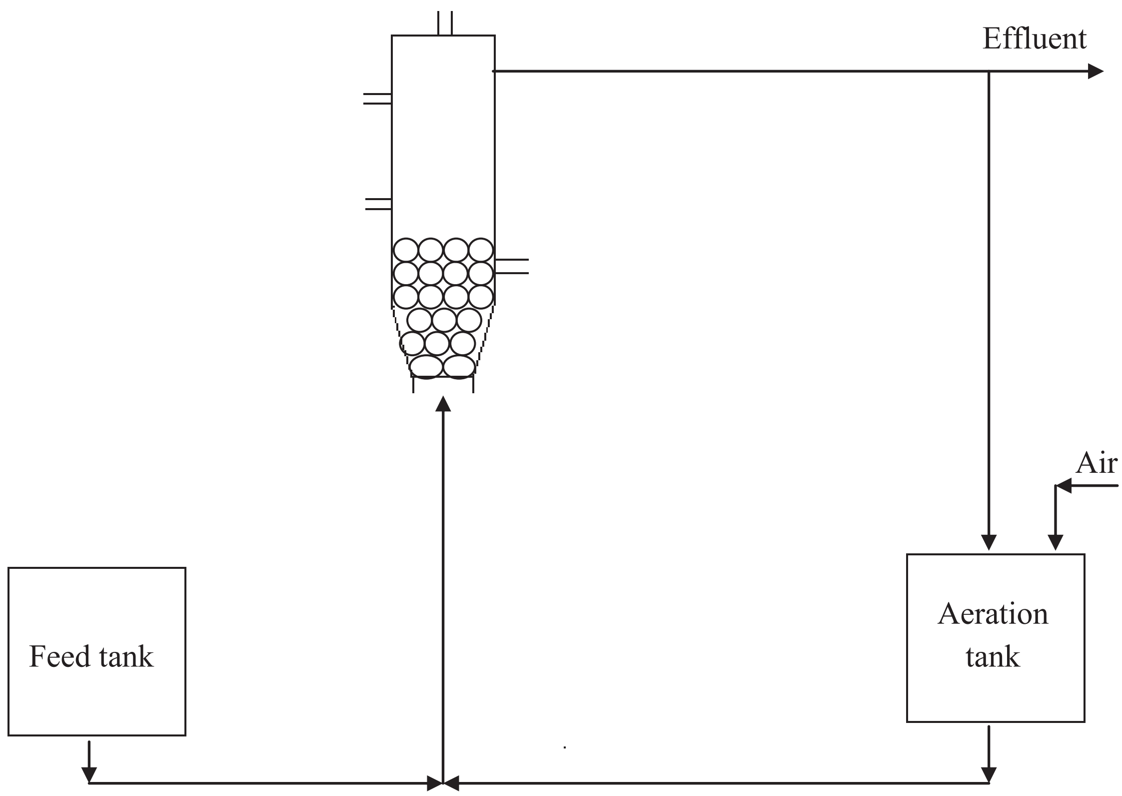


Figure 2.2 Schematic view of FBBR (adapted from Midha et al., 2012)

In fluidized reactor, the biomass grows inside the support particles. As a result, biofilm is formed and consumes the substrates entering the reactor. The level of organic matter biodegradation is reported to increase with the augmentation of the feed flow rate (Vinod and Reddy, 2005). The thickness of the biofilm layer can significantly affect fluidized bed bioreactor efficiency. In this context, excessive growth of biomass led to channelling of bioparticles in fluidized beds (Sokol, 2003). In addition, a thick layer of biofilm on support particles binds oxygen and substrate diffusion to the inner layers of the biofilm. This fact could negatively affect reactor performance (Rajasimman and Karthikeyan, 2007).

The superior performance of the fluidized-bed bioreactor is due to the attachment of significant high amount of biomass on particles. This is due to immobilization of cells onto the solid particles which reduces the time of treatment and volume of reactor (Vinod and Reddy, 2005). In addition, fluidized-bed bioreactors were found to be more efficient for phenolic wastewater treatment compared to other type of reactors. Volumetric biodegradation capacity was reported as a reason of better performance (Denac and Dunn, 1986). Hence, three basic processes occurring in the biodegradation of phenol in a fluidized-bed bioreactor were reported (Vinod and Reddy, 2005):

(a) Transport of oxygen from the gas phase into the bulk liquid;

(b) Transport of phenol, oxygen and other nutrients from the bulk liquid phase to the surface of the film; and

(c) Simultaneous diffusion, reaction and degradation of organic matter, oxygen and other nutrients within the biofilm.

Consequently, pressure drops and higher rates, no bed clogging problems, smaller reactor volume, high removal efficiency of carbon and nitrogen through large amounts of fixed biomass with a low hydraulic retention time (HRT), lower external mass transport resistance, and lower investment costs and space requirements were counted as the advantages of fluidized reactors (Mowla and Ahmadi, 2007; Wu et al., 2003).

c. *Rotating Biological Contactors*

Rotating biological contactors (RBCs), installed in West Germany in 1960, are used in industrial and domestic wastewater treatments. RBC discs are mostly submerged in wastewater and made of a corrugated light plastic material such as polystyrene and polyvinyl chloride (Najafpour et al., 2005; Metcalf and Eddy, 2004). RBCs have been successfully implemented for treatment of municipal and industrial wastewaters. It was successfully used for treatment of wastewater under medium and high organic loading rates and no limitation in the reactor elimination was reported even at high OLR values (Torkian et al., 2003). In addition, high COD removal efficiency of 88% from industrial wastewater with a COD surface loading rate of 38 g COD/m^{2}d via RBC was reported (Najafpour et al., 2005). RBC performance could be affected by different factors, such as pH and flow rate. Effect of pH on nitrification in RBC was investigated and it was reported that as the pH was increased, higher nitrification efficiency was achieved. However, neutral pH was reported as the optimum one (Flora et al., 1999). The effect of flow rate on RBC performance was considered by Najafpour et al. (2005). In this regard, it was concluded that augment of flow rate from 1.11/h to 3.61/h would results in the reduction of COD removal efficiency from 88% to 57% in high strength wastewater. In addition to pH and flow rate, there are some other factors which affect RBC performance including loading rate, rotational speed, hydraulic retention time (HRT), staging and temperature and disc submergence (Palma et al., 2003). While it is believed that by increasing the number of RBC stages COD removal efficiency is decreased, direct correlation of COD removal efficiency with rotational speed, HRT and disc submergence was reported. In addition, the effect of number of RBC stages on COD removal efficiency was investigated by Najafpour et al. (2006) using a three-stage aerobic RBC (Figure 2.3). It was illustrated that 88% of organic compounds were removed in the first stage of aerobic RBC. Consequently, single stage reactor is reported to be sufficient in practical wastewater applications.

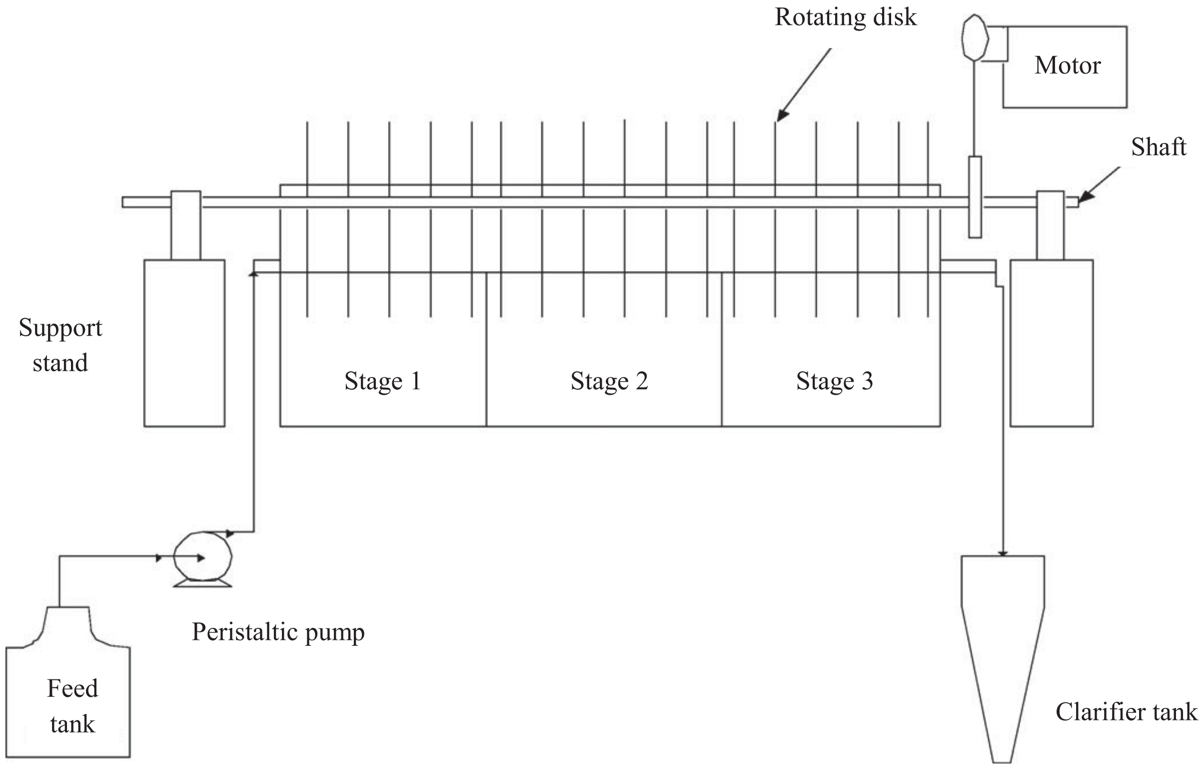


Figure 2.3 Schematic diagram of a three-stage aerobic RBC (adapted from Najafpour et al., 2006)

RBCs have the following advantages:

- Short HRT;
- High biomass concentration;
- High specific surface area;
- Requirement of low energy;

- Ease of operation;
- Less sensitivity to toxic compounds (Yamaguchi et al., 1999); and
- Effectiveness on toxic organic compound removal such as phenol, toluene and trichloroethylene (Alemzadeh et al., 2002).

On the other hand, no operational flexibility, a covering requirement in cold climates, a primary sedimentation requirement and the dryness possibility of un-submerged biofilm portion in warm climates was reported as RBC's drawbacks (Mara and Horan, 2003). This suggests the need for a more efficient system.

2.3.3 Advanced treatment systems

A. Membrane technology

In recent years, membrane technology has gained popularity in wastewater treatment particularly for decentralised and reuse applications. This is due to the advantages of these systems such as high biodegradation efficiency, ease of use, low operation costs (Wang et al., 2010), low sludge production and compactness (Le-Clech et al., 2006). All of which allow this technology to meet the standards for water and wastewater (Mohanty and Purkait, 2009). However, as they are filters, they are prone to fouling as a result of interactions between the membrane and the mixed liquor (Khan et al., 2009). Contaminants removal by membrane processes such as EDCs are strongly dependent on physicochemical properties such as molecular weight, K_{ow}, water solubility and electrostatic properties as well as membrane type (Liu et al., 2009). Based on the size of the polymer pores, membranes are categorized into four main groups as shown in Figure 2.4, namely RO, NF, UF and MF.

Microfiltration, which is commonly used for separation of suspended particulates and large colloids and bacteria, is suitable for the treatment of high turbidity and low colour or organics content wastewater. In this context, good results were achieved by MF especially for oily wastewater treatment (Song et al., 2006). Thus, Wang et al. (2009) achieved 95% of total organic carbon removal efficiency from oily wastewater by using a combination of poly-vinyl dene fluoride (PVDF) and tubular ceramic as a membrane. In addition, Abadi et al. (2011) achieved more than 95%, 85% and 98.6% removal efficiency for TOC, oil and TSS, respectively. Besides, MF removal efficiency was reported to increase through the use of pre-treatment methods (Zhang et al., 2005) or powered activated carbon (PAC) (Renou et al., 2008). In addition to high removal efficiencies, low sludge generation and decreased tank volume, were noted as the advantages of MF (Hillis, 2000).

In Ultrafiltration technology, materials used for the membrane may vary widely. Cellulose, colloidal particles, biomolecules, polymers and some sugars were used as UF membranes (Cassini et al., 2010). Due to the advantage of hydrophilicity, cellulose used to be the most common one. This feature has led to less sensitivity of membranes to membrane fouling, although the most significant limitation of this kind of membrane is pH. Hence, this type of membrane was used only in a limited range of pH (Li et al., 2008). As a result, using synthetic polymers as a UF membrane became more common. Ultrafiltration membranes made of polysulfone (Chakrabarty et al., 2010; Zhang et al., 2009; Chakrabarty et al., 2008), polyethersulfone (Celik et al., 2011; Barakat and Schmidt, 2010; Susanto and Ulricht, 2009), polyvinylidene fluoride (Yi et al., 2011; Li et al., 2006), polyamide and polyacrylonitrile (Asatekin et al., 2007) have become well demanded UF membranes in recent years. In addition to membrane material, permeate flux is another important factor in UF technology. In this regard, one of the biggest limitations of UF technology was reported to be the decrease in permeate flux (Cassini et al., 2010). Some drawbacks have been considered for UF treatments, which are summarized as follows:

- The decrease of permeate flux over time which is due to the concentration polarization and fouling phenomena and results in additional cost and energy to transport through the membrane (Cassini et al., 2010);
- Membrane fouling;
- Low dissolved organic removal efficiency (Hahn et al., 2002);
- Low removal efficiency of high concentration inorganic components such as leachate;
- Breaking up the sludge flocs of biomass which are needed for running the process (Christensen, 2011);
- Membrane cleaning and replacement costs; and
- Requirement of pre-treatment (WEF, 2008).

Nanofiltration technology (NF) is based on physical rejection such as molecular size and charge and the use of polymeric films which have the molecular cut-off between 200 and 2000 Da (Renou et al., 2008). Since the performance range of NF is classified between reverse osmosis and ultrafiltration (Figure 2.4), it can be described as RO process which permeates through some ionic solutes in feed water selectively (Cloete et al., 2010) but NF has both porous and nonporous membranes with seining and diffusion transport mechanism when compared with RO technology (Wang et al., 2010). NF is used for removal of low molecular weight organic compounds (Alley, 2006), pesticides (Chen et al., 2004), surface water treatment (Mondal and Wickramasinghe, 2008; Reiss et al., 1999), variety of effluent treatments (Balannec et al., 2005; Akbari et al., 2002; Jiraratananon et al., 2000), COD and colour retention. In this context, Lopez et al. (2005) have achieved 87% and 99% COD and colour retention respectively with DK 1073 as the nanofiltration membrane. Moreover, the effect of different temperatures and pressures on COD removal efficiency of MF pre-treated oily wastewater was investigated by Rahimpour et al. (2011) (Table 2.4). In this experiment, direct and reverse relation of COD removal efficiency with trans-membrane pressure and feed solution temperature respectively was reported. Thus, temperature of 20-30°C and pressure of 20 bars were found to be the optimum conditions for NF treatment. Fouling problems in the NF treatment system which applies extensive pre-treatment (Verberk and Dijk, 2006), difficulties of controlling the reproducibility of the membrane pore size and distribution of pore size (Wang et al., 2010) were counted as NF technology disadvantages.

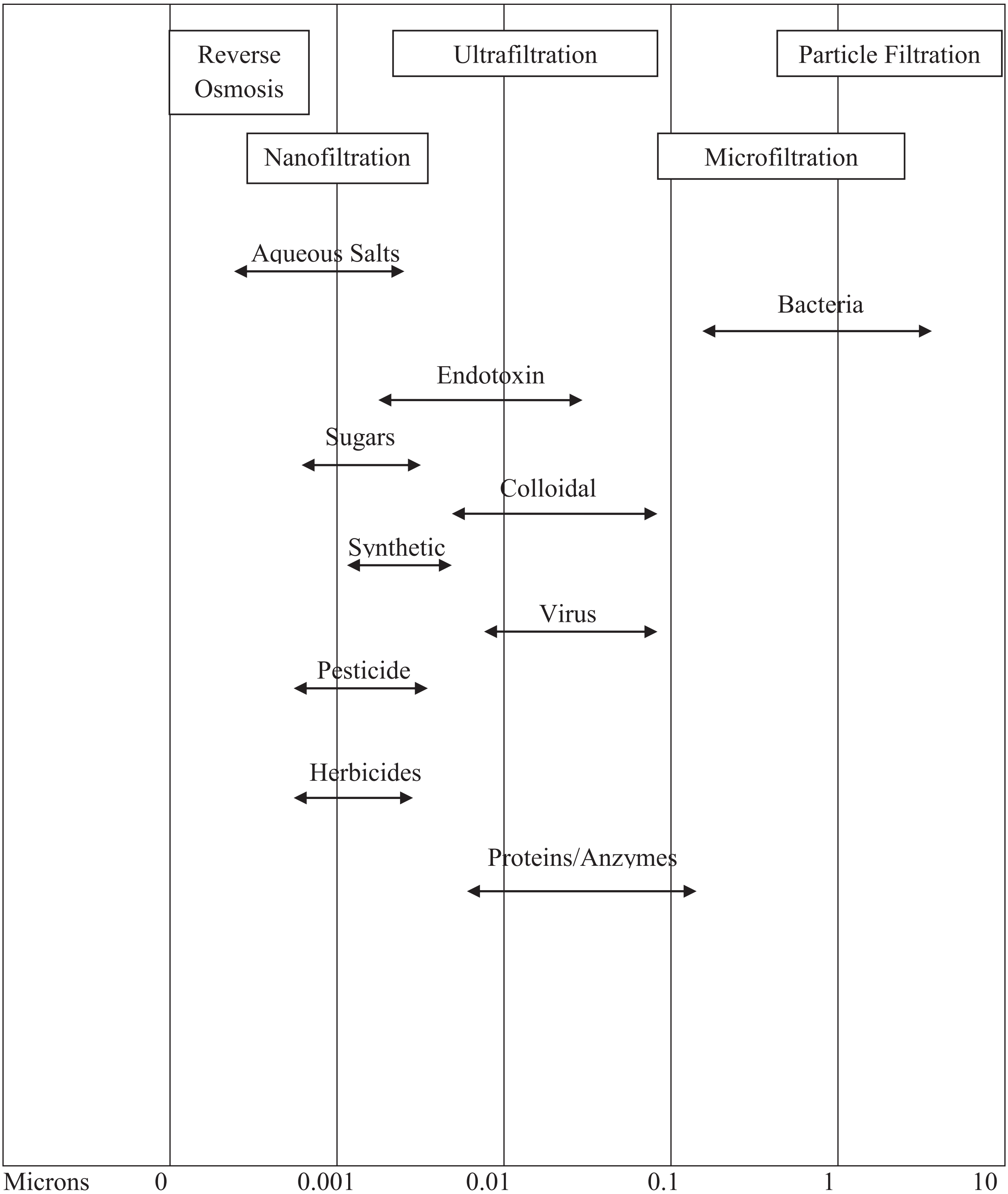


Figure 2.4 Filtration spectrums of pressure-driven membrane processes (adapted from Cloete et al., 2010; Virkutyte et al., 2010)

Table 2.4 Nanofiltration membranes characteristic (adapted from Rahimpour et al., 2011)

Nanofiltration membranes	Skin material	Support material	Membrane thickness (μm)	Surface pore size	NaCl rejection (%)	COD RE (%)
NF-1	Polyamide	Polyester and polysulfone	150	0.29	48	69
NF-2	Polyamide	Polyester and polysulfone	150	0.18	84	84
NF-3	Polyamide	Polyester and polysulfone	165	0.33	44	66
NF-5	Polyamide	Polyester and polysulfone	165	0.18	87	79

RE: removal efficiency

Reverse osmosis which is based on the demineralization technique, is more efficient for removal of ions and other dissolved contaminants from wastewater. All membrane processes are based on pressure driven processes. While MF and UF do not remove dissolved contaminants, removal of ions and other dissolved contaminants is possible with both NF and RO (American Water Works Association, 2007). RO achieved good performance in the case of water purifying, dewatering (Kucera, 2011), pharmaceuticals (Kimura et al., 2009) and EDC removal (Kimura et al., 2005). In this context, RO achieved high standards of water reuse quality and thus provided the advantages of affordability and cost effectiveness (Ranganathan and Kabadgi, 2011). Madaeni and Eslamifard (2010) achieved 98% COD, BOD, total dissolved solid (TDS) and SS removal efficiency and 45% wastewater recovery at optimum feed pressure of 15 bars. In addition, Ranganathan and Kabadgi (2011) obtained 91-99% removal efficiency in the case of TDS, sodium and chloride and 70-85% of wastewater recovery with RO treatment system for conventional pre-treated wastewater. Moreover, the linear relation between feed pressures and recovery rate in RO technology was reported (Figure 2.5).

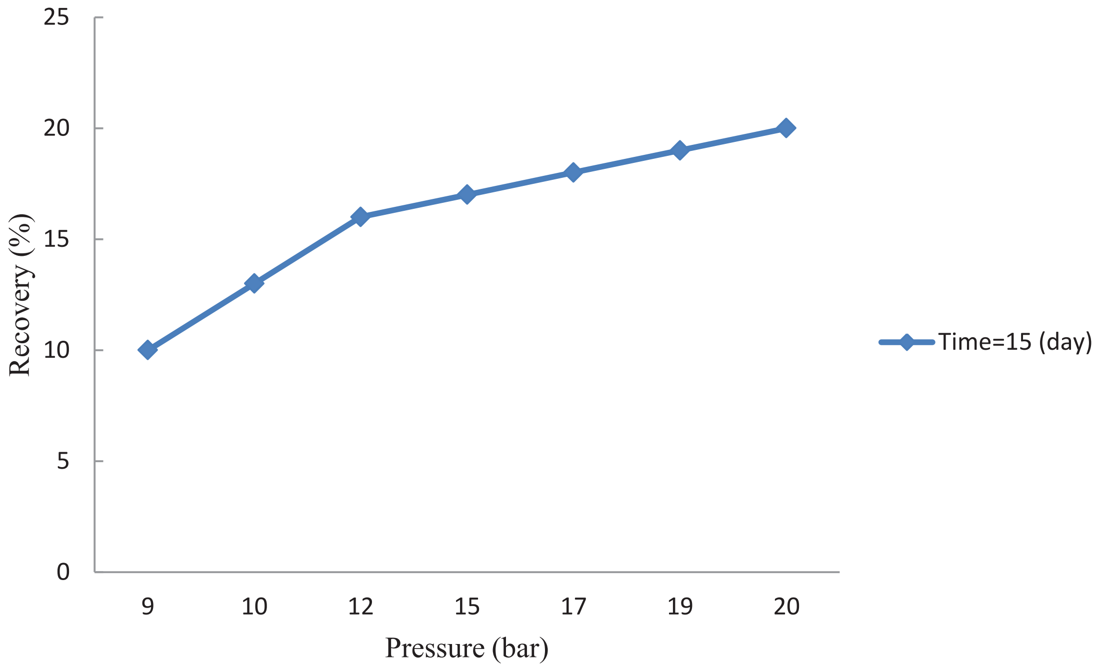


Figure 2.5: Recovery of wastewater versus feed pressure in RO (adapted from Madaeni and Eslamifard, 2010)

Drawbacks of RO technology are the requirement of pre-treatment which is due to scale formation and befouling of membranes (Ranganathan and Kabadgi, 2011), membrane extra capital costs and high pressure inlets (Bena, 2003). Despite the disadvantages reported for the RO system, this technology is considered to be one of the most efficient MBR systems due to following advantages:

- High quality treated permeate (Christensen, 2011);
- Modular nature;
- Compactness;
- Low energy consumption (Takama et al., 1980);
- Removal of more than 90% of NOM (Nghiem et al., 2002);
- Removal of nearly all dissolved salts in full flow operation and suspended materials (Bena, 2003); and

- Removal of almost all of Cr and Cu as heavy metals in wastewater (Dialynas and Diamadopoulos, 2009).

Removal efficiency of different contaminants with membrane technology may vary widely. Pharmaceutical removal efficiency via the membrane process is affected by pre-treatment. Furthermore, variations in membrane surface and the association of pharmaceuticals with organic macromolecules led to an increase in the removal efficiency of pharmaceuticals with membranes (Kimura et al., 2009). EDCs removal efficiency among all membrane types is in respect of RO (Kimura et al., 2005), NF (Agenson and Urase, 2007), UF and MF (Chang et al., 2002; Chang et al., 2003). Hence, high removal efficiencies for different contaminants in wastewater have been reported such as 95%, 88%, 97% and 90% for natural organic matters (Nghiem et al., 2002), DOC, TOC and nitrogen (Comerton et al., 2005), respectively.

B. Hybrid technology

The combination of systems is another way of increasing removal efficiency of systems. In this regard, Luostarinen et al. (2006) achieved 50-60% nitrogen and 40-70% total COD removal by using MBBR with a loading rate of 0.023–0.093 kg COD/m^3d, while the combination of pre-treating the upflow anaerobic sludge blanket (UASB) septic tank with MBBR in the same experiment resulted in higher removal rates of up to 92% COD_t and 65-70% nitrogen. In addition, combining the MBBR with the SBR system which is called SBBR, led to higher efficiency of the systems. This process combines the advantages of an SBR with the biomass retention properties of attached biofilms (Schmidt and schaechter, 2011). The hybrid UASB reactor was reported to be effective on chemical synthesis-based pharmaceutical wastewater treatment (Oktem et al., 2007). In this hybrid system, the vertical cylindrical hybrid reactor was made of PVC which had an effective internal volume (Figure

2.6). With this type of hybrid UASB, 72% COD removal at the organic loading rate of 8 kg COD/m^3d was achieved (Oktem et al., 2007).

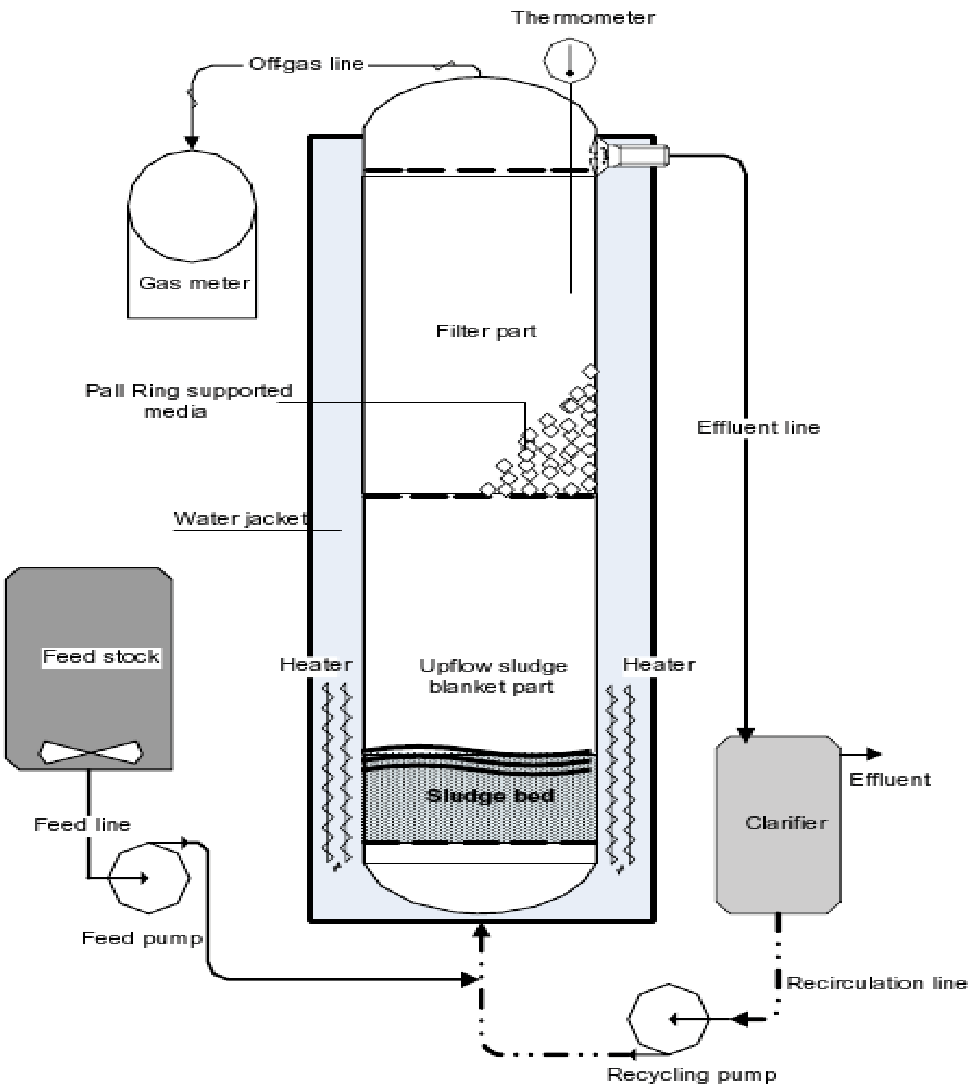


Figure 2.6 Schematic configuration of hybrid UASB (adapted from Oketm et al., 2007)

Moreover, anaerobic hybrid reactor (AHR) is another kind of hybrid reactor which is a combination of best features of both UASB reactors and anaerobic fluidized bed reactors (AFBR) showed good results in the case of low strength wastewater. Kumar et al. (2008) used a lab-scale AHR which was made of glass (Figure 2.7). In this type of AHR, in fluidized condition the up flow velocity was used to achieve better contact between biomass and contaminants. In this experiment, up to 94% COD removal efficiency was achieved at an organic loading rate of 2.08 kg COD/ m^3d with an HRT of 6.0 h. In addition, AHR showed good capability for tolerating environmental shocks which are not unusual in industrial applications (Kumar et al., 2008). The same results of 95% COD removal at OLR of 116.01 kg COD/m^3d and HRT of 24 h were achieved by Mullai et al. (2011) with AHR used for treatment of penicillin-G wastewater.

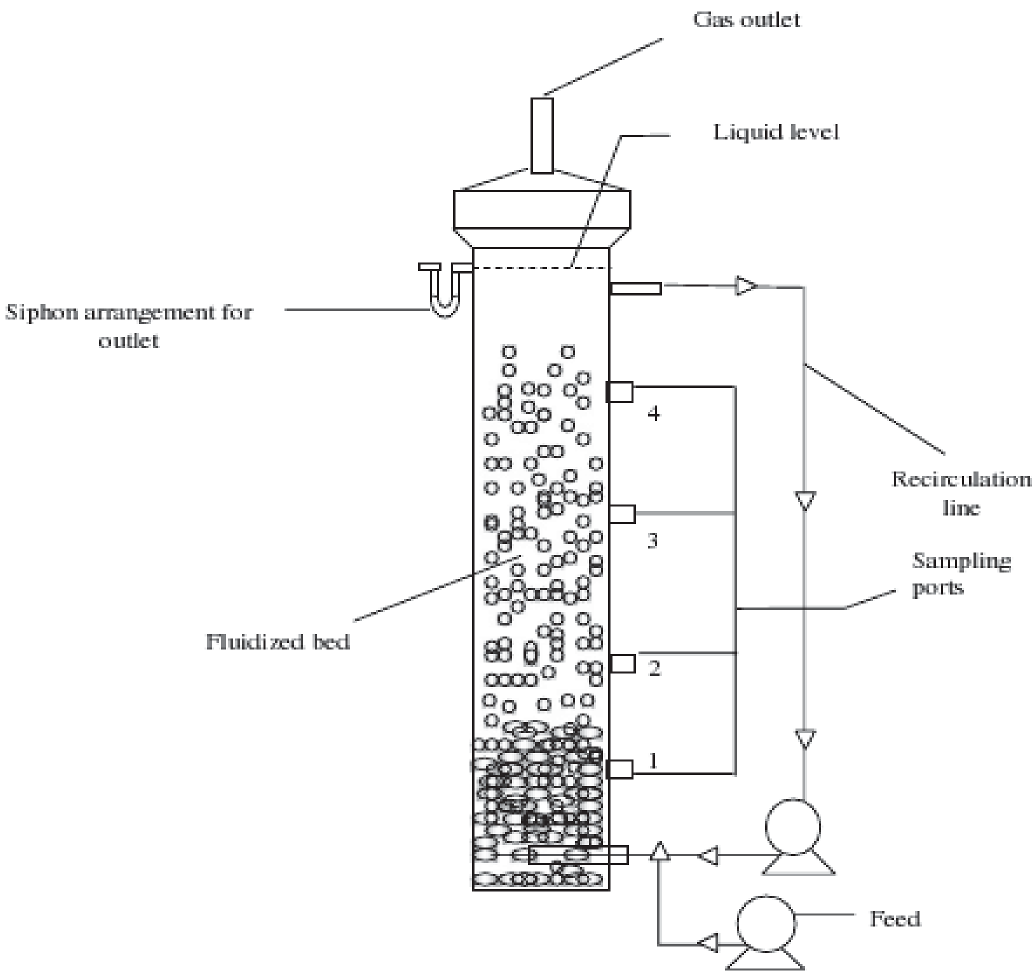


Figure 2.7 Schematic of the anaerobic hybrid reactor (adapted from Kumar et al., 2008)

Jianlong et al. (2000) demonstrated higher biomass concentration of up to 4.30-5.75 g/l in a novel hybrid biological reactor (HBR), which contained both attached growth and suspended growth biomass, by introducing porous materials into a regular activated sludge unit. Hybrid anaerobic baffled reactor (HABR) (Figure 2.8) which is proved to be suitable for treatment of polyvinyl alcohol (PVA) containing desizing wastewater, is another kind of hybrid reactor and achieved 42% and 18% removal efficiency for COD and PVA, respectively (Rongrong et al., 2011).

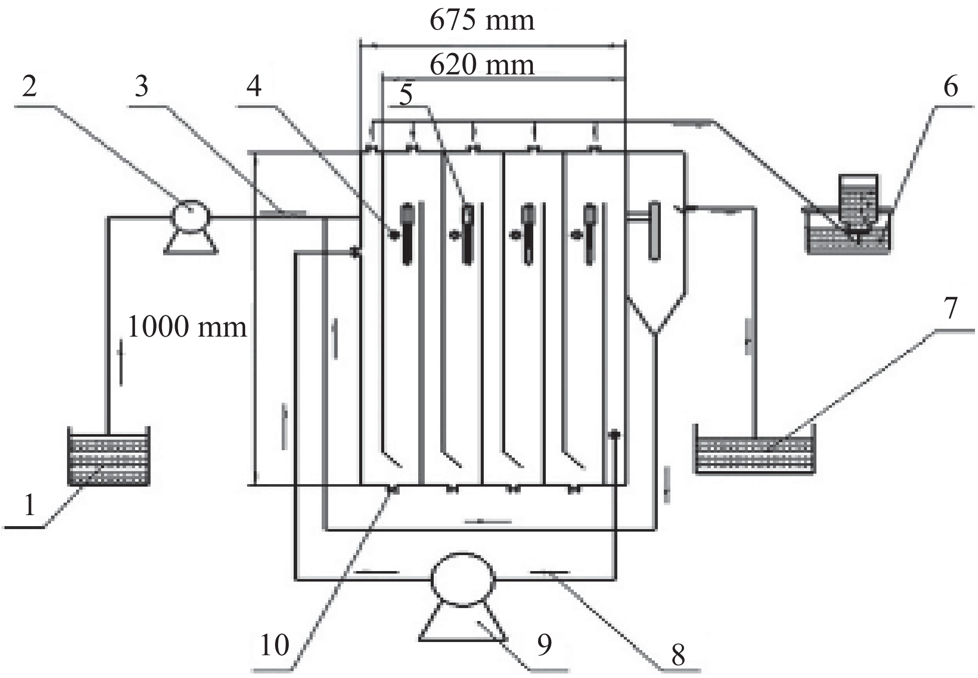


Figure 2.8 Schematic diagram of a HABR. 1. Feed tank; 2. Peristaltic pump; 3. Influent; 4. Supernatant sampling port; 5. Temperature regulator; 6. Biogas holder; 7. Effluent; 8. Wastewater recycle; 9. Industrial peristaltic pumps; 10. Sludge sampling port (adapted from Rongrong et al., 2011)

In addition to conventional treatments, the combination of advanced systems has resulted in higher performance of the systems. At the same time, combined advanced treatment systems have the possibility of COD retention. Microfiltration was combined with other technologies and led to a high performance. For instance, the combined microfiltration and ultrafiltration system led to 81% COD retention (Alonso et al. 2001). In other example, hybrid precipitation-microfiltration with mixed cellulose ester hydrophilic (MCE) membrane showed good results in the case of phosphate removal (Lu and Liu, 2010). The effect of molar ratio on the PO_4 and fluoride removal with this hybrid system was also investigated (Figure 2.9) (Lu and Liu, 2010).

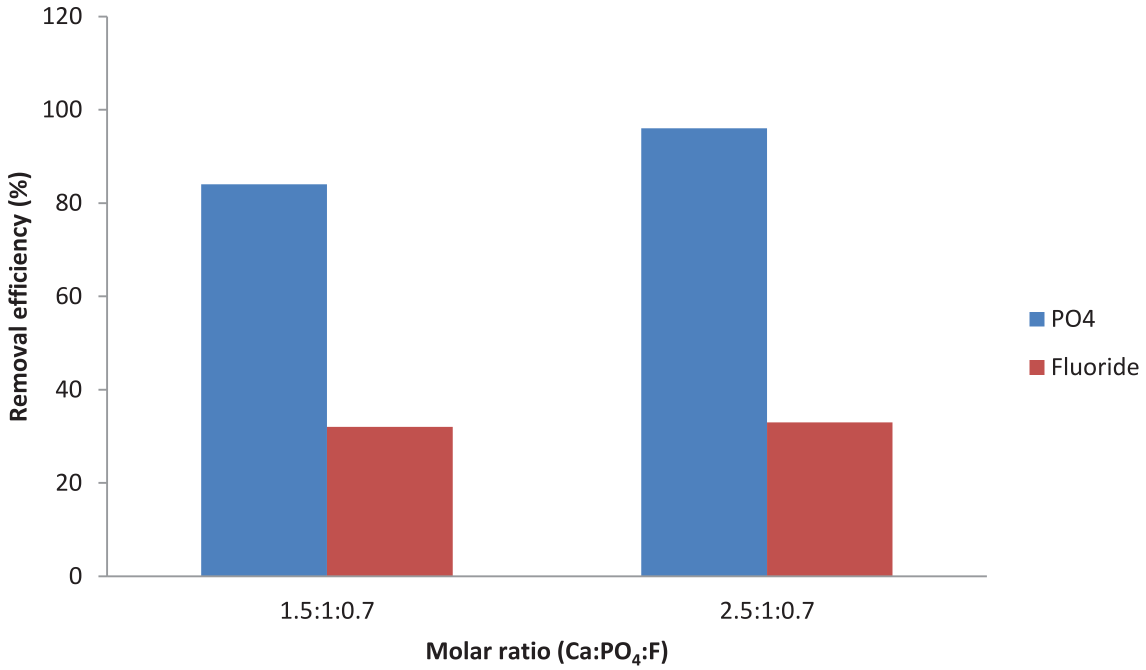


Figure 2.9 Effect of molar ratio on phosphate and fluoride removal efficiency (modified from Lu and Liu, 2010)

Moreover, Madariaga and Aguirre (2011) investigated a hybrid system of sedimentation, microfiltration and reverse osmosis. In this experiment, microfiltration improved the suspended solid recovery in the effluent and it was found that while sedimentation was useful for oxidized starch, no significant enhancement achieved for cationic starch. However, when reverse osmosis contained hydraunautics membrane was applied to the MF permeate (Figure

2.10) resulted in an increase in the system performance. In another experiment, Mohammadi and Esmaeelifar (2005) found slightly higher performance of hybrid ultrafiltration-powered activated carbon process compared to single UF treatment system (Table 2.5).

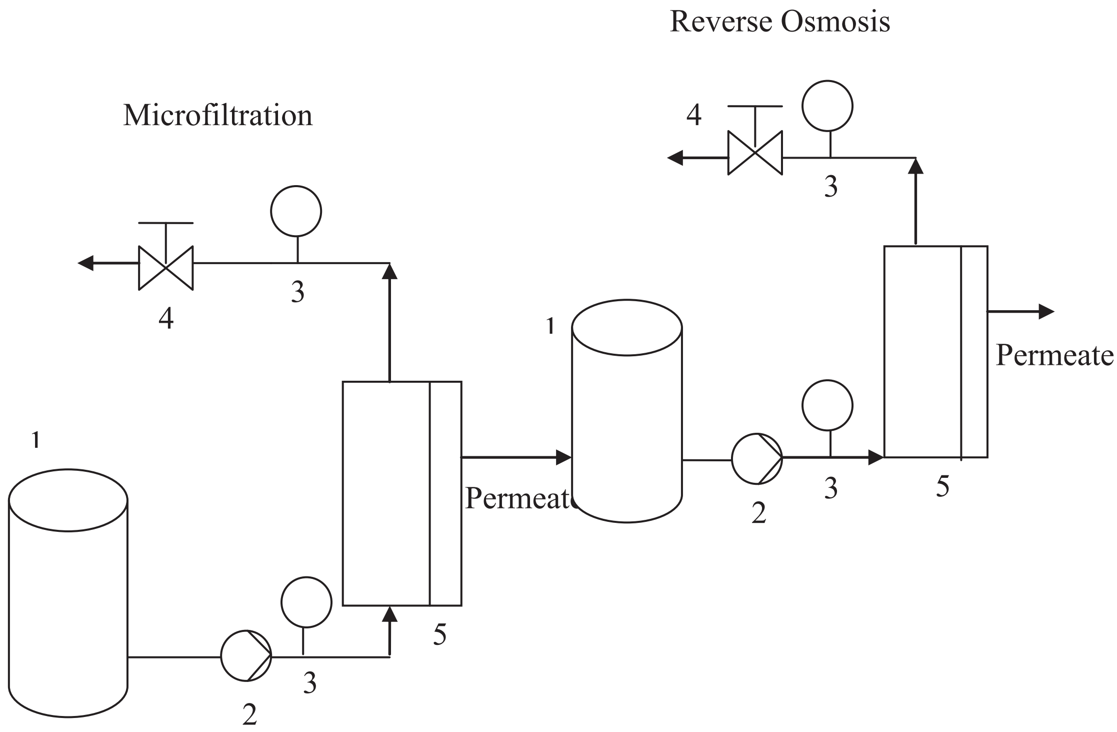


Figure 2.10 Schematic representation of the pilot and laboratory-scale experiments with RO and MF. (1) Feed tank, filled starch solution with or without prior sedimentation; (2) pump; (3) manometers; (4) valve; (5) membrane (adapted from Madariaga and Aguirre, 2011)

Table 2.5 Comparison of UF and UF-PAC process performance (source of data from Mohammadi and Esmaeelifar, 2005)

Process	**COD (%)**	**TOC (%)**	**TSS (%)**
UF	91	87	100
UF-PAC	94	93	100

Furthermore, the combination of UF and RO led to significant high removal of organic and inorganic matters (Table 2.6) while the UF process alone was impotent of such high removal efficiencies (Dialynas and Diamadopoulos, 2009).

Table 2.6 Removal efficiency of organic and inorganic matters in UF and combined UF-RO process (adapted from Dialynas and Diamadopoulos, 2009)

Parameter	UF average removal (%)	UF-RO average removal (%)
Turbidity (NTU)	99.72	84.04
DOC (mg/L)	-	52.74
TN (mg/L)	47.5	98.62
Cu (μg/L)	48.8	99.99
Cr (μg/L)	89.1	99.99

Consequently, the use of hybrid systems have further solved the difficulties of different technologies in wastewater treatment and also gained excellent results for improving system performance.

2.4 Moving bed biofilm reactor

2.4.1 Background

This type of biological treatment begins in the 1970s. The moving bed biofilm reactor (MBBR) was first developed for treatment of municipal wastewater in terms of nitrogen removal (Odegaard et. al., 1994). Afterwards, other applications of the MBBR process were developed such as treatment of industrial wastewaters, nitrification in water treatment for land based fish farming and removal of soluble organic matter in secondary treatments of municipal wastewater (Helness et. al., 2005). In moving bed biofilm process suspended porous polymeric is used as a carrier which moves continuously in the aeration tank and the active biomass grows as a biofilm on the surface of carriers (Loukidou and Zouboulis, 2001). In this context, more than 90% of biomass is attached to the media rather than suspended in the liquid (Schmidt and schaechter, 2011). The advantage of this system in comparison to a suspended growth one is the higher biomass concentration, less sensitivity to toxic compounds, lack of long sludge settling period (Loukidou and Zouboulis, 2001), less prone to the process upsets from poorly settling biomass (Schmidt and schaechter, 2011), cost effectiveness (Fang, 2011) and the achievement of both organic and ammonia removals efficiently in single stage (Horan et al., 1997). Moving bed biofilm filter within its small footprint has a positive property of the area requirement which is one fifth to one third of that needed for activated sludge treatment as well as a lower effect of temperature on the rate of biological nitrification (Salvetti et al., 2006). However, the operational costs are higher in MBBR than that of activated sludge treatment. These systems could be efficient for BOD removal and tertiary nitrification and denitrification following suspended or attached growth nitrification (Metcalf and Eddy, 2004). As the MBBR system has the important advantage of flexibility of carrier's fill fraction, these systems have become very popular for use in industrial applications and applications with high variation in the expected load in time (Haandel and Lubbe, 2012). Some factors have been reported to affect the performance of MBBR. The high specific area of the carrier media controls the system performance which is as a result of very high biofilm concentrations presence in a small reactor volume. It was reported that typical biofilm concentrations range from 3000 to 4000 g TSS /m^3, which is similar to values obtained in activated sludge processes with high sludge ages. The percentage of reactor volume comprised of media is limited to 70%, with 67% being typical (Odegaard et al.,2000). However, wastewater characteristics and specific treatment goals are the main factors determining the percentage of media required in the reactor.

2.4.2 Organic removal mechanisms in MBBR

Organic matters can cause toxicity as well as affecting the quality of receiving water bodies (Baun et al., 2004). Toxity behaviour for organic matters varies widely. Thus, different organic pollutants have shown a variety of behaviours within the removal treatment process which is related to organic matter's chemical and physical structure.

Chemical structure of OM is described as organic pollutants aromatic rings and molecular structure. Therefore, while polycyclic structures are hardly degradable, simple aliphatic and monocyclic aromatic compounds are readily degradable (Jones et al., 2005). Hence, organic compounds owning methyl group (a weak electron donor) and amid group (strong electron withdrawing) are removed poorly. On the other hand, compounds which contain amin or hydroxyl (strong electron donate) and amid group together are removed well. Comparing the performance of these compounds by Tadkaew et al. (2011) clarified that the presence of amin with amid as well as hydroxyl in a functional group made compounds more biodegradable (Tunkel et al., 2000). Molecular structure other than aromatic rings can also affect removal efficiency. For instance, the presence of chlorine in a molecular structure or complicated aromatic ring of clofibric acid, diclofenac and dichloprop led to poor removal of acidic compounds (Kimura et al., 2005).

In addition to chemical structure, the physical structure of OM, which is described as hydrophobicity and molecular weight, can affect OM removals. According to Tadkaew et al. (2011) there is a direct link between hydrophobicity of organic compounds and their removal efficiency. The removal efficiency of very hydrophobic compounds with Log D >3.2 and moderately hydrophobic compounds with Log D <3.2 was above 85% and less than 20%, respectively. Moreover, high removal efficiencies have been detected for ionisable organic compounds (sulphamethoxazole, ibuprofen, ketoprofen) at an acidic pH of 5. Under acidic pH conditions, ionisable compounds largely exist in their hydrophobic form while non-ionisable compounds (bisphenol A and carbamazepine) are pH independent. Hence, high removal efficiency was achieved under the described condition (Tadkaew et al., 2010). Furthermore, although there is not a clear correlation between molecular weight (MW) of organic compounds and their removal efficiency, a fragile relationship has been noticed. In this context, compounds with a molecular weight of >300 g/mol were removed with a high removal efficiency while for compounds with a molecular weight of < 300 g/mol there was a variation from no removal to 98% (Tadkaew et al., 2011). Therefore, the relationship between OM removal efficiency and their molecular weight is still unknown.

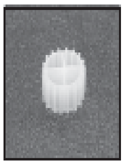
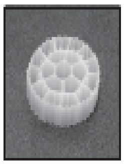
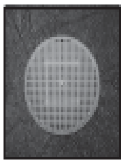
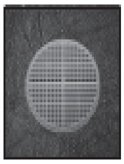
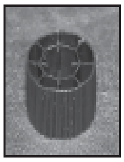
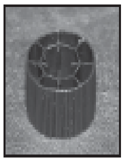
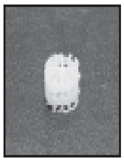
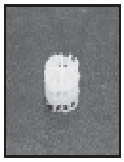
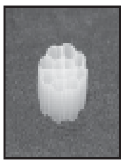
2.4.3 Materials used in MBBR

The principle of MBBR is to immobilize biomass on carrier, eliminating the need for sludge settling and return in a continuous operation system. In additions, critical to the success of any biofilm process is to maintain a high proportion of active biomass in the reactor. Therefore, carrier material plays a critical role in the removal process with MBBR. In this context, rapid and stable attachment of microorganisms to a porous media surface is an undoubted criterion. Packing materials include rock, gravel, slag, sand, redwood and a wide range of plastics and synthetic materials. AnoxKaldnes and a number of other manufacturers have developed a number of different carriers over the years using different geometries, different materials, and different manufacturing techniques (Table 2.7). Polyurethane (PU) carriers have become well demanded materials in the case of TOC and ammonium removal. This is due to the entrapment of microorganisms in the polyurethane pores which results in augmentation of the amount of nitrifiers inhabit on the carrier surface increases. On the other hand, the different character of biodegradable polymer polycaprolactones (PCL) (Table 2.8) shows good behaviour in terms of T-N removal. While T-N removal efficiency in the MBBR with PCL as a carrier was 59% which is as a result of simultaneous nitrification and denitrification, in the MBBR with PU as carrier T-N removal efficiency in different phases varies significantly. This fact was reported to be due to the changes in the amount of TOC/TN ratio in the influent (Chu and Wang, 2011). One of the advantages of MBBR system is if a treatment plant needs more capacity because of the increased loads, this can be easily provided by simply adding more biofilm carrier elements to the reactor to increase the biofilm surface area (Odegaard et al., 2000; Aspegren et al., 1998). This flexibility was proven to provide convenience especially when upgrading plants from activated sludge to the moving bed process without expansion of the existing reactor volume (Germain et al., 2007; Andreottola et al., 2003; Aspegren et al., 1998).

The effective area of the MBBR carrier medium is reported to be 70% of the total surface area due to less attachment of biofilm on the outer boundary of the media (Majeed et al., 2012). In addition, surface shape as well as the size of the media is proven to be effective in the system's removal efficiency. This results in changes on carrier biofilm thickness inside and outside of the carrier. In this context, Ngo et al. (2007) demonstrated that triangular polyurethane sponge of 70–90 cells/in^2 with a designated slope of sponge tray at 10 degrees led to good performance in terms of both organic and nutrient removal efficiency. In addition, in terms of biomass growth and pollutant removal, medium sponge size of 2×2×2 cm was reported to have the best performance in comparison to other cube sizes (Nguyen et al., 2010). Likewise, Guo et al. (2010) investigated the effect of packing material's thickness on removal efficiency of nutrient and organics. It was reported that as the thickness of packing material increased, in this experiment sponge, lower removal efficiency for organic matters and nutrients was achieved. Hence, 1 cm sponge exhibited the best T-N and T-P removal. In addition to physical properties of carriers, it is reported that ratio of packing medias also affects MBBR performance. This is due to the liner correlation between the packing media ratio in the reactor and the total biomass attachment on carrier's surface. It was proven that packing ratio significantly affected nitrogen removal efficiency, while organic removal was not considerably affected. As the media packing ratio increased from 0% to 3% and then to 6%, organic removal increased from 96.6% to 97.3% and 97.8% and nitrogen removal increased from 9.6% to 26.0% and then to 41.3%, respectively. In comparison, phosphorus removal decreased with the increase of the media packing ratio (Yeon et al., 2011).

Simultaneous removal of nitrogen and carbon was reported within a single stage of the moving-fixed bed biofilm process with polyurethane foam sponge. This was due to the separation of the oxic-anoxic zone resulted in high removal efficiency (Lin, 2008). Ngo et al. (2007) investigated an attached growth bioreactor with the usage of sponge as a media. In this experiment, high removal efficiency of 90% for ammonia and COD removal of 20-100% were achieved which was related to the media material and properties. Consequently, it can be concluded that packing material plays an undoubted role in MBBR efficiency and performance.

Table 2.7 Plastic biofilm carriers (adapted from WEF, 2011)

Manufacturer	Name	Bulk specific surface area*	Nominal carrier dimensions (depth; diameter)	Carrier photograph
Veolia, Inc.	AnoxKaldnes™ K1	500 m^2/m^3	7 mm; 9 mm	
	AnoxKaldnes™ K3	500 m^2/m^3	12 mm; 25 mm	
	AnoxKaldnes™ biofilm chip (M)	1200 m^2/m^3	2 mm; 48 mm	
	AnoxKaldnes™ biofilm chip (P)	900 m^2/m^3	2 mm; 48 mm	
Infilco Degremont, Inc.	ActiveCell™ 450	450 m^2/m^3	15 mm; 22mm	
	ActiveCell™ 515	515 m^2/m^3	15 mm; 22 mm	
Siemens Water Technologies Corp.	ABC4™	600 m^2/m^3	14 mm; 14 mm	
	ABC5™	660 m^2/m^3	12 mm; 12 mm	
Entex Technologies, Inc.	Bioportz™	589 m^2/m^3	14 mm x 18 mm	

*As reported by manufacturer

Table 2.8 Characteristics of the PCL and PU carriers (adapted from Chu and Wang, 2011)

Parameters	PCL	PU
Diameter (mm)	3.5–4	8–10
Height (mm)	3	8–10
Density (kg L^{-1})	1.08–1.12	0.3–0.5
Specific surface area	0.346 m^2 g^{-1}	900 m^2 m^{-3}
Filling ratio (%) on volume basis	16.7	20
Dry weight (g) per piece	0.0245	0.0936
Wet weight (g) per piece	0.0274	0.673

2.4.4 Operating conditions

The moving bed biofilm reactor (MBBR) can be used for aerobic and anoxic or anaerobic processes in which the performance of the system could be affected by various conditions of hydraulic retention time (HRT), organic loading rate (OLR) and carrier filling rate.

Anaerobic moving bed biofilm reactor (AMBBR) has been proved to be very reliable for treatment of different types of wastewater, especially high strength organic wastewater. This is due to the inherent advantages of AMBBR such as high volumetric loading rates, low sludge accumulation in the reactor and less energy consumption for operation (Jahren et al., 2002). In denitrification MBBRs, wall screens are generally bracket-mounted to the concrete wall that separates the pre-denitrification MBBR from the downstream treatment step (Figure 2.11). To agitate the bulk of the liquid and distribute plastic biofilm carriers uniformly the mechanical mixer is used (Figure 2.12). The majority of existing operating denitrification MBBRs makes use of submersible rail-mounted mechanical mixers (Figure 2.11). Another usage of the mechanical mixer is to control the thickness of biofilm on the carrier's surface.

However, Sheli and Moletta (2007) reported that as the OLR increased, attached biomass amount in AMBBR was augmented as well. The rate of denitrification in an MBBR is influenced by the biofilm area, type of external carbon source, bulk liquid carbon to nitrogen ratio (C:N), wastewater temperature, bulk liquid dissolved oxygen concentration, and bulk-liquid macronutrient concentrations (McQuarrie and Boltz, 2011). In the denitrification process, denitrifying organisms such as Pseudomonas, Achromobacter, Acinetobacter, Agrobacterium, Alcaligenes, Arthrobacter and Bacillus are responsible for the conversion of oxidized nitrogen compounds such as nitrite or nitrate to nitrogen gas (Wang et al., 2006). The anaerobic digestion processes produce biogas which can be used as micro-mixing of the wastewater in the digester. The composition of biogas is reported to correlate with OLR. In this context, lower CH_4 presence in biogas was described as a result of high OLR (Sheli and Moletta, 2007). In addition to denitrification, biological phosphorous removal is initiated in the anaerobic reactor where acetate is taken up by phosphorous accumulating organisms (PAO) and converted to carbon storage products. These compounds can supply energy and growth in the following anoxic and aerobic reactors (Kermani et al., 2009). Biofilm carriers in the anaerobic reactor is reported to have a brownish colour and play a major role in COD removal (92–95% at an organic loading rate of 4.1-15.7 kg COD/m^3d) due to methanogenesis (Chu and Wang, 2011). A few AMBBRs were used as pre-treatment of paper making wastewater (Jahren and Odegaard, 1999) and high strength cane vinasses (Jahren and Odegaard, 2000).

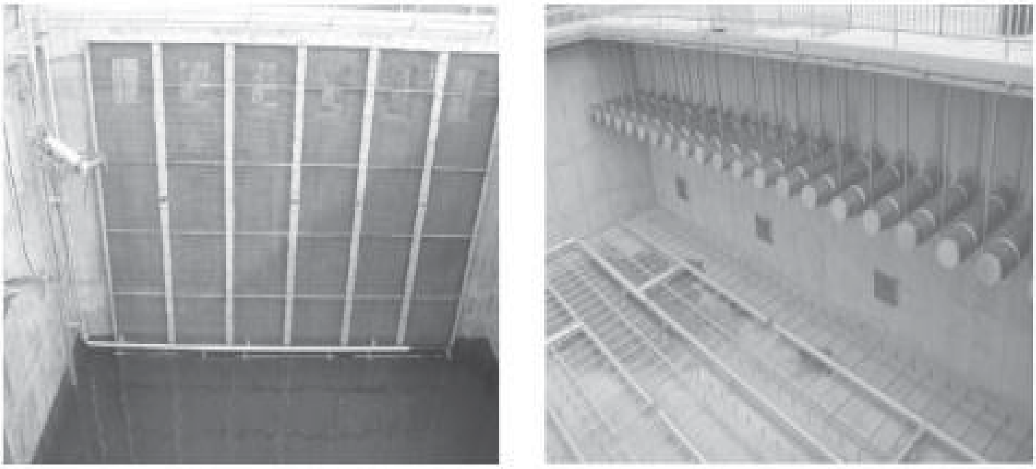


Figure 2.11 Aerobic MBBR with horizontal mounted cylindrical bar sieves (left) and anoxic MBBR with flat sieves and mixer mounted in the top left corner (right) (adapted from Haandel and Lubbe, 2012)

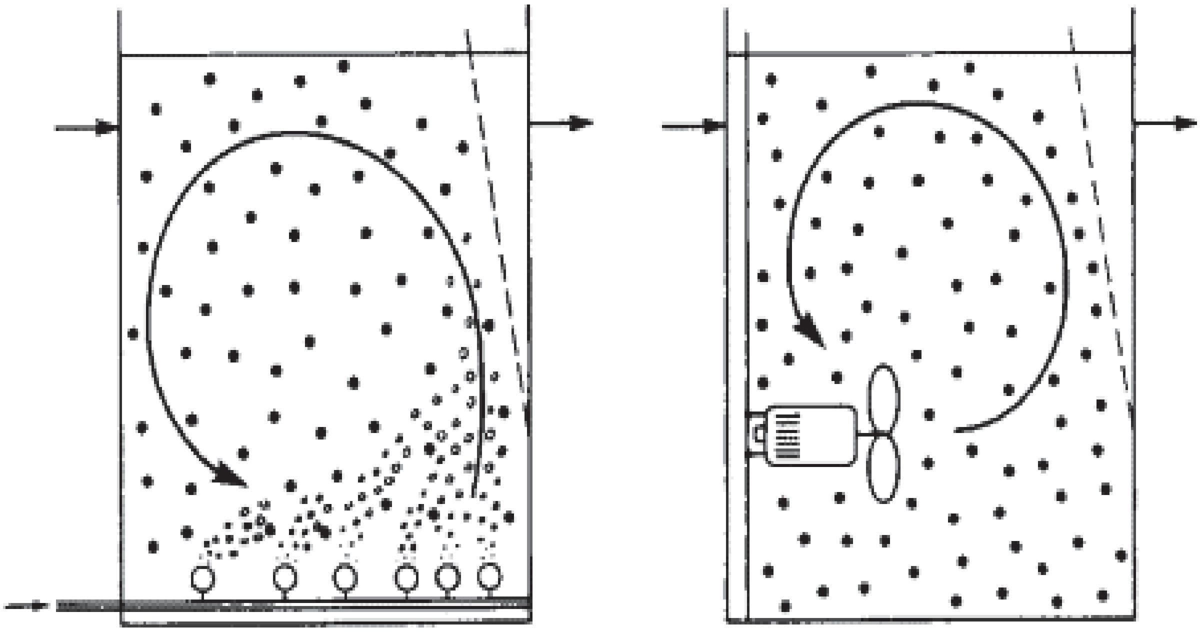


Figure 2.12 Operating principle of the MBBR process with aerobic reactors (left), anoxic and anaerobic reactor (right) (adapted from Odegaard, 1999)

Generally in aerobic MBBR, in order to retain the carriers, horizontally mounted cylindrical bar sieves are used (Figure 2.11). The movement of biofilm carriers in the aerobic MBBR initiate from the agitation introduced by means of aeration to uniformly distribute plastic biofilm carriers and provide required oxygen for process. Airflow in the aerobic MBBR, the same as the mechanical mixer in AMBBR (Figure 2.12), constrains the biofilm thickness and enters the system through a grid of diffusers that are attached to the bottom of the tank. Carrier movement plays a key role in aerobic MBBR as collision and attrition of media in the reactor causes biofilm detachment from the outer surface of media. Hence the MBBR carrier media is provided with fins on the outside to protect biofilm loss and promote biofilm growth (Odegaard et al., 2000). Adequate turbulence removes excess biomass and keeps sufficient thickness of biofilm in the reactor (Odegaard, 2000). To have enough substrate diffusion in to the biofilm, thickness of less than 100 μm is usually chosen. In addition, uniform movement of carriers inside the reactor enhances system performance by controlling the flow velocity (Odegaard et al., 2006). Water circulation pattern is controlled by flow control valves, which uniformly distributes plastic biofilm carriers (McQuarrier and Boltz, 2011). Coarse bubble diffusers have the inherent benefits of being more resistant to scaling and fouling (Stenstrom and Rosso, 2008) and less likely to require maintenance than fine bubble diffusers. Another advantage of coarse bubble diffusers is the breakdown of the bigger bubbles into smaller ones as a result of the bubble's movement through the interspace among carriers. This process cause the augmentation of the gas liquid interfacial area and favourable oxygen transfer (Jing et al., 2009). The aerobic MBBR is mostly involved in the removal of ammonium as the biofilm grown in the MBBR were reported to mainly contain the autotrophic bacteria (AOB) and Anammox (>97% at a HRT of more than 1.25 d) (Cortez et al., 2011). In addition, the aerobic MBBR achieved more than 85% COD removal efficiency at optimum carrier filling rate, HRT, OLR and dissolved oxygen (Chen et al., 2007). In another experiment also, high removal efficiency of 81, 89 and 93% for COD, phenol and NH_4^+-N, respectively was reported with aerobic MBBR used polyethylene as carrier material (Li et al., 2011).

2.4.5 Applications

Presently, there are more than 500 large scale wastewater treatment plants based on the MBBR process in 50 different countries around the world for both municipal and industrial usages. In most of the cases, MBBR is chosen because it offers a very compact treatment solution. Also, it is used as it has the lowest investment costs and total annual costs. For instance, in Australia MBBR has been used widely in advanced water treatment plants for municipal wastewater treatment in Bundamba, Darling Quarter recycled water plant in Sydney, Carlton and United Breweries in Yatala, Norco Pauls in Raleigh and Norske Skog Boyer Mill in Hobart. In mentioned applications, MBBR has been used either alone or combined with other technologies such as neosep membrane bioreactor, actiflo clarification, hydrotech discfilters, dissolved air flotation (DAF) or conventional clarifier. In this context, MBBR was used as a post treatment after the reverse osmosis concentrate (ROC) process in Bundamba with the capacity of 15.5 ml/day, to discharge in the environment. In Darling Quarter, MBBRs were used in combination with MBR and RO which produces 166 kL/day (60 ML/year) of high quality treated recycled water for reuse on site such as toilet flushing, irrigation and cooling tower make up water. In Yatala, two-stage MBBRs were used for polishing BOD after anaerobic treatment, prior to DAF and microfiltration/reverse osmosis with the capability of 140 m^3/hour and reuse water for boilers and general washing. The Raleigh application was a two-stage MBBR plant, treating 230 $m^{3/}$day of wastewater and causing a reduction of influent COD from 3,500 mg/L to COD below 100 mg/L. Finally, the Hobart application used MBBR as a pre-treatment followed by using the activated sludge process. Consequently, MBBR has been used in a variety of applications and has achieved acceptable results in the case of different contaminants removal (AnoxKaldnes, 2009).

In addition, MBBR has been used in combination with other technologies in different applications. Lei et al. (2010), for example, used the combination of hydrolysis/acidification with MBBR and then with oxidation in order to upgrade centralized wastewater treatment plant of a pharmaceutical industrial park (PIP) in China. In this treatment system, MBBR was operated at DO concentration of above 3 mg/L with the aim of good fluidization of fillers and an HRT of 10.8 h. Followed by, HRT was gradually decreased to 5.4 h and then to 3.6 h by the enhancement of inflow. In this experiment, COD and NH_4^+-N concentration of the final effluent were detected with stability below 100 and 20 mg/L, respectively which demonstrated good performance of the system.

Norway acquired six wastewater treatment plants with nitrogen removal in 2007, in which, four out of the six treatment plants were using the MBBR process. MBBR plants used the combined denitrification process for nitrogen removal and then chemical precipitation for phosphorous removal. This type of design resulted in operation flexibility and production of low effluent concentration. In this experiment, influent concentration was above 50 mg total N/L and Gardermoen WWTP measured concentrations of less than 2 mg total N/L and 1 mg total inorganic N/L in the effluent (Rusten and odegaard, 2007). The same experiment was studied in Lillehammer WWTP, Norway in 2005 and results indicated average effluent concentrations of 2.2 mg BOD5/L, 2.9 mg total N/L and 0.12 mg total P/L. Consequently, data from Lillehammer and Gardermoen WWTPs showed that these types of treatment plants have the ability to achieve more than 95% removal of total nitrogen and effluent concentrations below 1 mg NH_4^+-N and 3 mg total N/L. In addition, five WWTPs used in Sweden for the removal of nitrogen from municipal wastewater using the MBBR process verified the results of previous studies. In this experiment maximum NH_4^+-N and nitrogen removal rate in the pre-denitrification process were 91% and 49% and in the post-denitrification process were 97.7% and 75.5%, respectively (Lustig and Dahlberg, 2012).

University of Technology, Sydney

Faculty of Engineering and Information Technology

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 Introduction

The detailed of materials used, experimental set-up, methods and analytical procedures are presented in this chapter. The research investigated the effect of biofilm carriers filling rate, organic loading rate (OLR) and hydraulic retention time (HRT) on the performance of MBBR.

3.2 Materials

The characteristics of the wastewater and media are presented as follows:

3.2.1 Wastewater

The influent used in this experiment was synthetic wastewater which is similar to primary treated sewage effluent (PTSE). This was due to the need of an influent source with constant feed concentration which contains biodegradable organic pollutants. The composition of synthetic wastewater used in this study is shown in Table 3.1 (Lee et al., 2003).

Chemical oxygen demand (COD) and dissolved organic carbon (DOC) concentration of the synthetic wastewater were 330-360 mg/L and 120-130 mg/L, respectively. Synthetic wastewater contains ammonium nitrogen (NH_4-N) and orthophosphate (PO_4-P) with the concentrations of 18-19 mg/L and 3.3-3.5 mg/L, respectively. The COD:N:P ratio of the synthetic wastewater was 100:5:1.

Table 3.1 Characteristics of synthetic wastewater

Composition	Molecular weight (g/mol)	Concentration (mg/L)
Organics and nutrients		
Glucose($C_6H_{12}O_6$)	180.0	280
Ammonium sulfate (($NH_4)_3SO_4$)	132.1	72
Potassium phosphate (KH_2PO_4)	136.1	13.2
Trace nutrients		
Calcium chloride ($CaCl_2 \cdot 2H_2O$)		0.368
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	147	5.07
Manganese chloride ($MnCl_2 \cdot 4H_2O$)	246.5	0.275
Zinc sulfate ($ZnSO_4 \cdot 7H_2O$)	197.9	0.44
Ferric chloride anhydrous ($FeCl_3$)	187.5	1.45
Cupric sulfate ($CuSO_4 \cdot 5H_2O$)	162.2	0.391
Cobalt chloride ($CoCl_2 \cdot 6H_2O$)	249.7	0.42
Sodium molybdate dihydrate ($Na_2MoO_4 \cdot 2H_2O$)	237.9	1.26
Yeast extract	242	30

3.2.2 Media

The biofilm media used in this study was provided by Veolia. This type of media namely AnoxKaldnes Biofilm Chip™ is made of polyethylene with a density of about 0.95 g/cm^3. They are designed specially to provide interspaces for suspended microorganisms, offer high specific surface area of up to 1200 m^2/m^3 and circular shape (Figure 3.1) with the diameter of 4.5 cm.

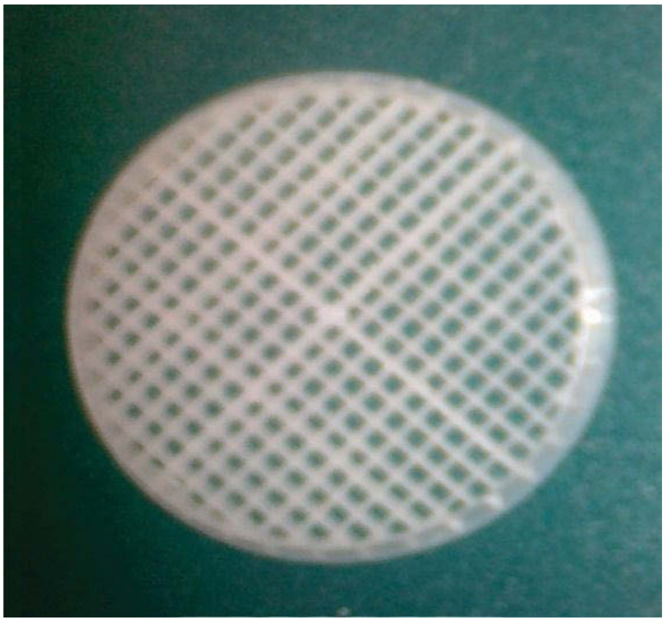


Figure 3.1: Polyethylene (PE) carrier

3.3 Methods

3.3.1 Experimental set-up

The moving bed biofilm reactor (MBBR) was set up at the Environmental Engineering Laboratory of the University of Technology, Sydney (Figure 3.2). A 12 L cylindrical shaped column built of acrylic with 60 cm height and 15 cm diameter and storage tanks were used to treat 11.52 L synthetic wastewater every day. Air diffuser and influent pipes were located at the bottom of the reactor (Figure 3.3). Air was diffused from the bottom of the reactor with a constant aeration rate of 4.5 L/min in all the stages to supply oxygen to the microbial mass for biological activity and mixing the carriers. Wastewater was pumped upward from influent storage tank through the column and downward to the effluent storage tank.

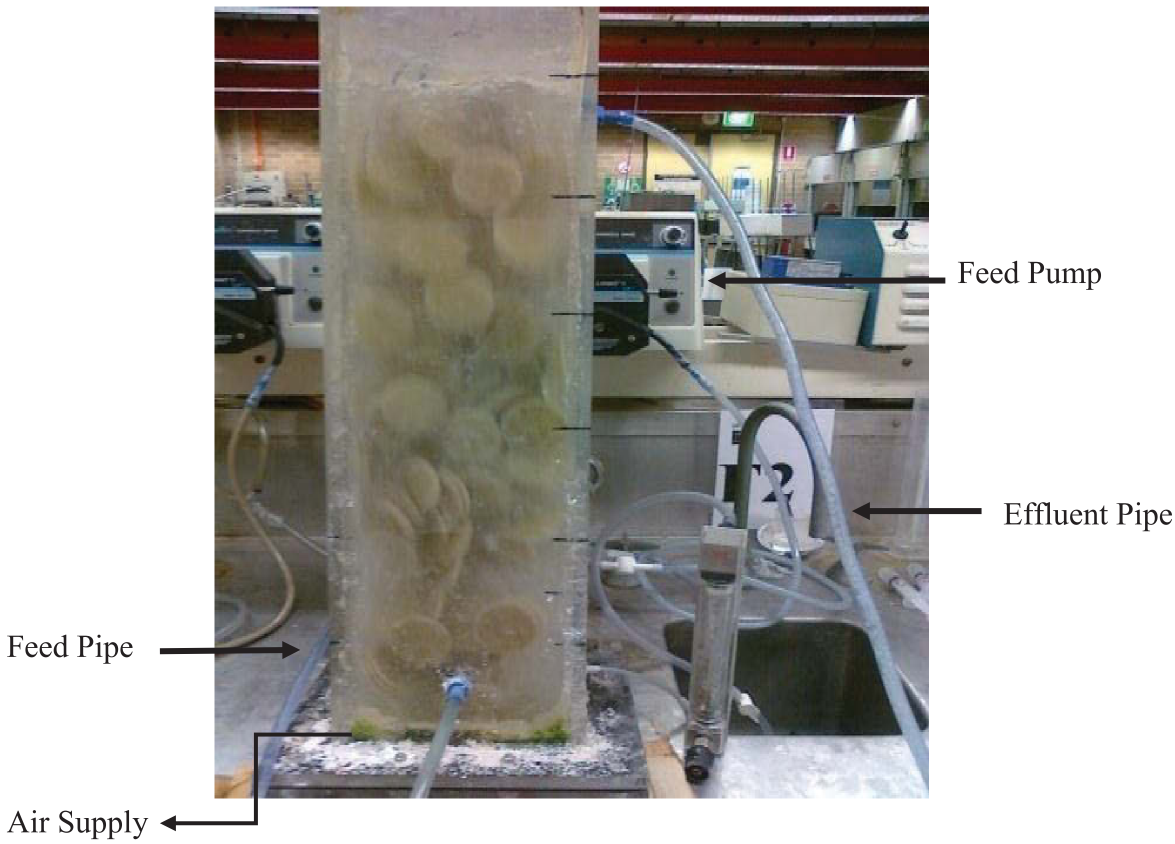


Figure 3.2 Laboratory setup of MBBR

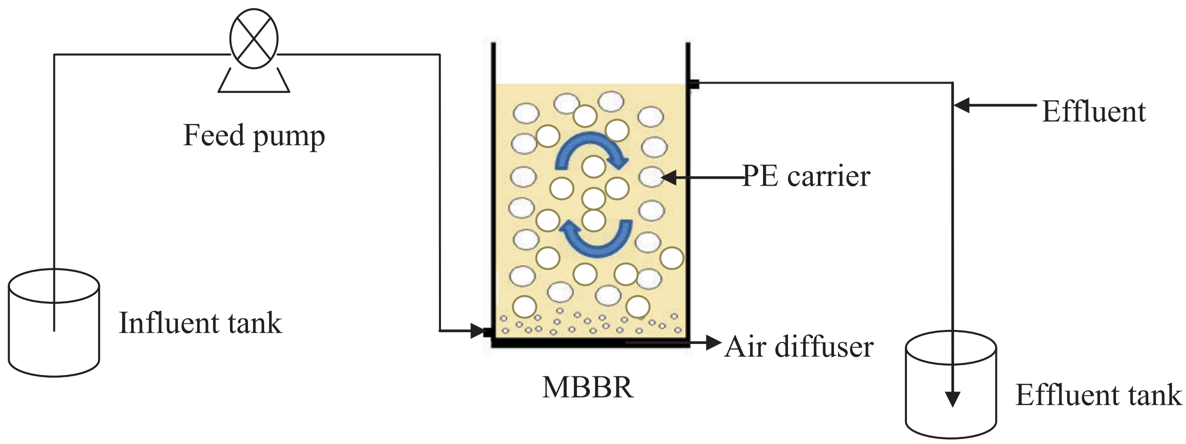


Figure 3.3 Laboratory scale MBBR

3.3.2 Experimental conditions

The experimental investigation was divided into three stages. Synthetic wastewater was prepared in the laboratory and used in all stages of the experiment with constant composition. However, the concentration of synthetic wastewater in the influent was varied depending upon the organic loading rate (OLR) conditions. In the first stage of the study, the effect of carrier filling rate on the performance of MBBR in terms of OM was examined using 10%, 20%, 30% and 40% of carriers at HRT of 25 h and OLR of 0.36 kg COD/m^3.d (Table 3.2). In the second stage, the effect of organic loading rate (OLR) on the performance of MBBR in terms of OM was examined. Four different OLRs of 0.15, 0.31, 0.47 and 0.8 kg COD/m^3.d were tested under the optimized carrier filling rate of 20% and HRT of 25 h (Table 3.3). The third stage of this study was to investigate the effect of three different hydraulic retention times (HRT) on the performance of MBBR in terms of OM removal. HRTs of 25, 8 and 4 h were examined at filling rate of 20% and OLR of 0.8 kg COD/m^3.d and the optimum HRT was achieved (Table 3.4). Subsequently, optimized operating conditions for MBBR performance were obtained within this experiment in terms of OM removal.

Table 3.2 Lab scale MBBR operated at different carrier filling rates

Carrier filling rate (%)	OLR (kg COD/m^3.d)	HRT (h)
10	0.36	25
20	0.36	25
30	0.36	25
40	0.36	25

Table 3.3 Lab scale MBBR operated at different organic loading rates

OLR (kg COD/m^3.d)	Carrier filling rate (%)	HRT (h)
0.15	20	25
0.31	20	25
0.47	20	25
0.8	20	25

Table 3.4 Lab scale MBBR operated at different hydraulic retention times

HRT (h)	OLR (kg COD/m^3.d)	Carrier filling rate (%)
25	0.8	20
8	0.8	20
4	0.8	20

Samples of influent and effluent were collected and filtered with a 0.45 μm pore size filter every day at all the stages during the experiment. Within all the stages of the experiment, same analysis on the collected samples were used including dissolved organic carbon (DOC), chemical oxygen demand (COD), oxygen uptake rate (OUR), nutrient analysis, mixed liquor suspended solid (MLSS), mixed liquor volatile suspended solid (MLVSS), dissolved oxygen (DO) and pH.

3.3.3 Experimental approach

PE carriers were acclimatized in a separate aeration tank filled with synthetic wastewater and activated sludge from a wastewater treatment plant Sydney (Figure 3.4). The acclimatization of carriers lasted for 30 days and during acclimatization period reactor was set-up and prepared for transferring carriers. The research approach consists of three different stages:

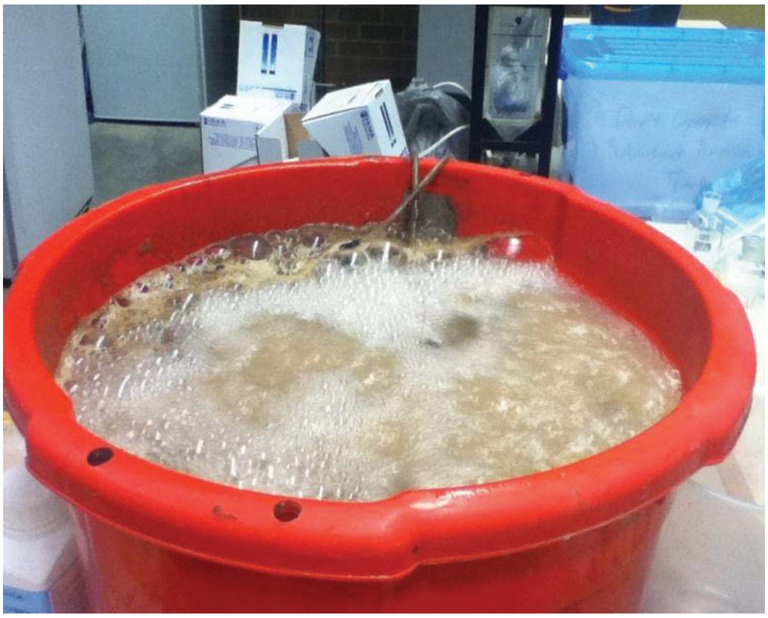


Figure 3.4 Acclimatization tank

Stage 1: Effect of carrier filling rate

To investigate the effect of carrier filling rate on MBBR performance, 60% of reactor volume (7200 mL) was filled with PE carriers. Since each carrier had a diameter of 4.5 cm and the height of ten pieces of carriers were 3 cm, the volume of 10 pieces carrier was measured at 47.71. Thus, 151 pieces of PE carriers were acclimatized in acclimatization tank and used in the experiment. Different percentages of acclimatized carriers of 10%, 20%, 30% and 40%

were added into 12L reactor in different phases. In each phase which lasted for 20 days, 151 acclimatized carriers were added to the reactor and samples were collected every day and analysed in terms of TOC, COD, nutrient, MLSS, MLVSS and OUR/SOUR. The reactor was set-up at the constant aeration rate and flow rate of 4.5 mg/L and 8mL/min, respectively. As mentioned above, COD concentration of the influent was 330-360 mg/L. By using 3.1 Formula, organic loading rate (OLR) was calculated at 0.36 kg/m^3.d. Hydraulic retention time (HRT) was calculated using 3.2 formula and was kept at 25h.

$$\mathrm{OLR} = \frac{\mathrm{ICOD} * \mathrm{F}}{\mathrm{V}} \qquad \text{(Eq. 3.1)}$$

Where: OLR is organic loading rate (kg/m^3.d)

I_{COD} is the COD concentration of synthetic wastewater influent (mg/L)

F is the flow rate of synthetic wastewater (mL/min)

V is the volume of reactor (L)

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{F}} \qquad \text{(Eq. 3.2)}$$

Where: HRT is hydraulic retention time (h)

F is the flow rate of synthetic wastewater (mL/min)

V is the volume of reactor (L)

OLR and HRT were kept constant in this phase of experiment. During this period, all of the mentioned conditions were monitored and pH of the reactor was maintained at 7.0 using sulphuric acid (H_2SO_4) or sodium carbonate anhydrous ($NaHCO_3$). The optimum carrier filling rate was utilized for the next stage of experiment.

Stage 2: Effect of organic loading rate (OLR)

To investigate the effect of influent organic concentration on microbial growth, organic matters removal efficiency at different organic loading rates (OLR) was examined in the second stage. The OLR was varied by changing the influent COD concentration. Different OLRs of 0.15, 0.31, 0.47 and 0.8 $kg/m^3.d$ were studied by changing the COD concentration of influent at an optimum carrier filling rate of 20%. Each phase of the experiment lasted for 20 days and during this period, the samples were collected and analysed in terms of TOC, COD, OUR, nutrient and microbial growth. After optimum OLR was determined, it was used in the third stage of the experiment.

Stage 3: Effect of hydraulic retention time (HRT)

With the aim of low cost system, effect of hydraulic retention time (HRT) was examined in this experiment. Optimum OLR and filling rate were used to investigate the effect of HRT on MBBR. HRTs of 25, 8 and 4 hours were examined by changing the flow rate (Eq. 3.2) from 8 to 25 and 50 mL/min. Similar to previous stages, length of each phase was 20 days and mentioned factors of collected samples were analysed and examined in each period.

3.3.4 Analysis

In this experiment the analysis of chemical oxygen demand (COD), nutrient and the measuring of mixed liquor suspended solid (MLSS) and biomass (monitored as mixed liquor volatile suspended solid, MLVSS) were accomplished according to standard methods for water and wastewater examination (APHA, 1998). To measure MLSS and biomass, three samples were taken each time and the average values were calculated. Other equipment and tools used for measurement in this study are described as follow:

A. Total organic carbon (TOC) measurement

The total organic carbon (TOC) concentration of wastewater was measured using Analytik Jena Multi N/C 3100 analyzer (Figure 3.5). As all samples were filtered with 0.45 μm filter, the TOC of the samples were dissolved organic carbon (DOC).

Figure 3.5 Analytik Jena Multi N/C 3100 analyzer

B. Oxygen uptake rate (OUR) measurement

The oxygen uptake rate (OUR) was measured using YSI 5300 Biological Oxygen Monitor (Yellow Springs Instruments Co., Yellow Springs, OH), which is a ISO2 oxygen monitor equipped with a 2 mm diameter OXELP electrode (World Precision Instruments Inc., Sarasota, FL) (Figure 3.6).

Figure 3.6 YSI 5300 Biological Oxygen Monitor

C. Other equipment

In this experiment, nutrients were analysed by photometric method using Spectroquant® Cell Test (NOVA 60, Merck) (Figure 3.7). DO and pH of the reactor were measured daily by using HORIBA ltd. Japan, model no. OM -51E and HANNA instrument, model no. HI 9025, respectively (Figure 3.8, 3.9).

All these analyses were applied for each phase of the experiment.

Figure 3.7 Spectroquant® Cell Test (NOVA 60, Merck)

Figure 3.8 HORIBA ltd. Japan, model no. OM -51E

Figure 3.9 HANNA instrument, model no. HI 9025

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CHAPTER 4

RESULTS AND DISCUSSION

This Chapter discusses the results on the effect of carrier filling rate, OLR and HRT on MBBR performance mainly in terms OM removal efficiency associate along with nutrients removal and microbial growth and activity.

4.1 Effect of carrier filling rate on the performance of moving bed biofilm reactor in terms of organic matter removal

The main principle of MBBR is to immobilize the biomass on carrier. Bacteria growth and microbial attachment on the media is due to the granular nature of media which provides a large surface area. This results in high concentration of attached biomass and small footprints (Pramanik et al., 2012). In this regard, PE carriers can provide appropriate support areas for rapid and stable attachment of microorganisms. Since collision and attrition of media in the reactor causes biofilm detachment from the outer surface of media (Majeed et al., 2012), PE carriers were used in this experiment. In PE carriers, pores are provided outside of the carrier's surface to protect biofilm loss and promote growth of biofilm. Hence, active layer is formed inside and outside of the carriers and leads to removal of OM and nutrients from wastewater.

4.1.1 Organic removal

DOC and COD removal efficiency at HRT of 25 h, OLR of 0.36 kg/m^3.d, flow rate of 8 mL/min, aeration rate of 4.5 L/min and different PE filling rates are shown in Figures 4.1 and 4.2, respectively.

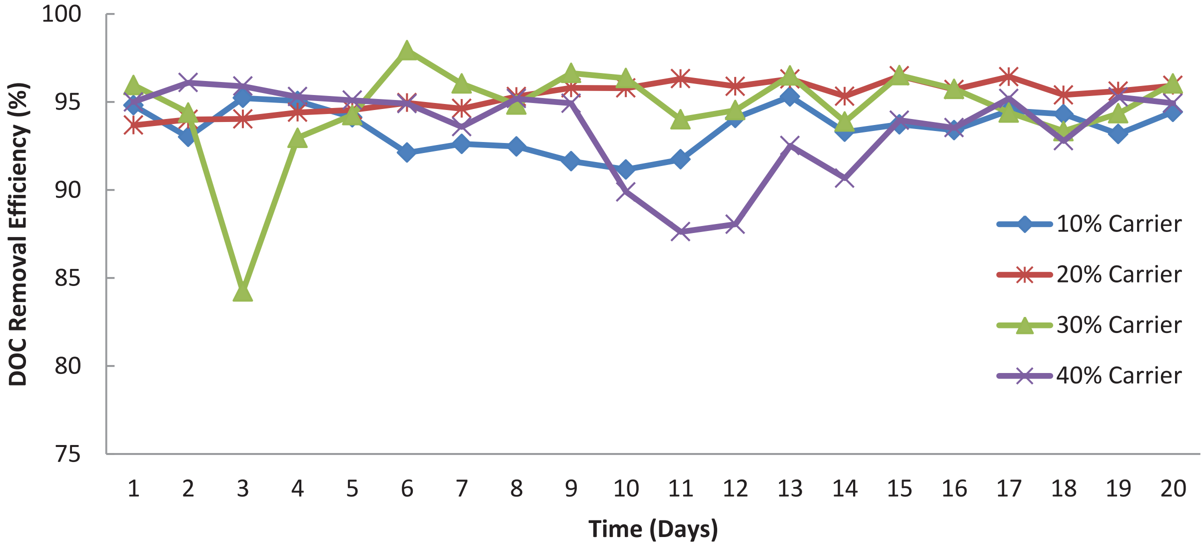

Figure 4.1 DOC removal efficiency at different PE carrier filling rates

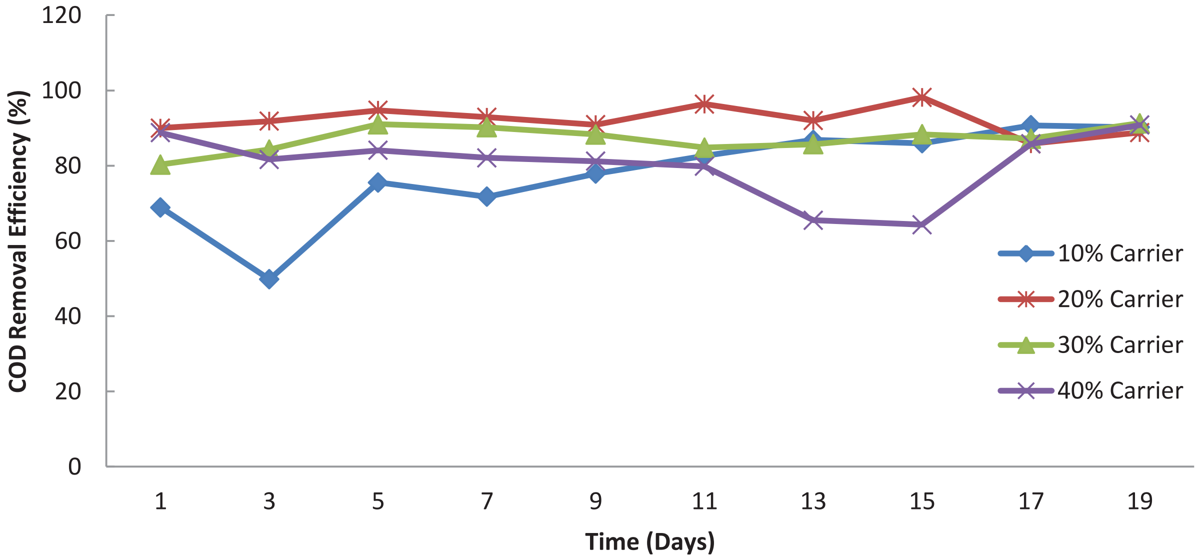

Figure 4.2 COD removal efficiency at different PE carrier filling rates

The results indicated that average DOC removal efficiency at 10, 20, 30 and 40% carrier filling rates were 93.51, 95.33, 94.65 and 93.52%, respectively. Although DOC removal efficiencies were more than 90% at all the carrier filling rates, fluctuations in the trend of DOC removal efficiency at 10, 30 and 40% carrier filling rates resulted in occurrence of an unstable condition. In comparison, average removal efficiency of 20% carrier filling rate was found to be slightly higher and steadier which may be as a result of an active biofilm layer presence on the carrier's surface.

In this study, Table 4.1 shows that the average COD removal efficiency was significantly affected by different filling rates. 78.02, 92.13, 87.14 and 80.39% COD removal efficiency were obtained at 10, 20, 30 and 40% carrier filling rates, respectively. It can be seen that COD removal efficiency increased up to 14.08% with increasing carrier filling rate from 10% to 20% (Table 4.1). However, adding higher amount of carriers (e,g. 30% and 40%) in to the reactor led to a decrease in COD removal efficiency which might be due to the accumulation of biomass on carrier's surface.

Table 4.1 Performance of MBBR in terms of COD removal efficiency

Carrier filling rate (%)	**10**	**20**	**30**	**40**
COD RE (%)	78.02	92.13	87.14	80.39
OLR (kg COD/m^3.d)	0.36	0.36	0.36	0.36
HRT (h)	25	25	25	25
Aeration rate (L/min)	4.5	4.5	4.5	4.5

RE: removal efficiency

4.1.2 Nutrients removal

PO_4-P and NH_4-N removal efficiencies at HRT of 25 h, OLR of 0.36 kg/m^3.d, flow rate of 8 mL/min, aeration rate of 4.5 L/min and different PE filling rates are shown in Figures 4.3 and 4.4 respectively.

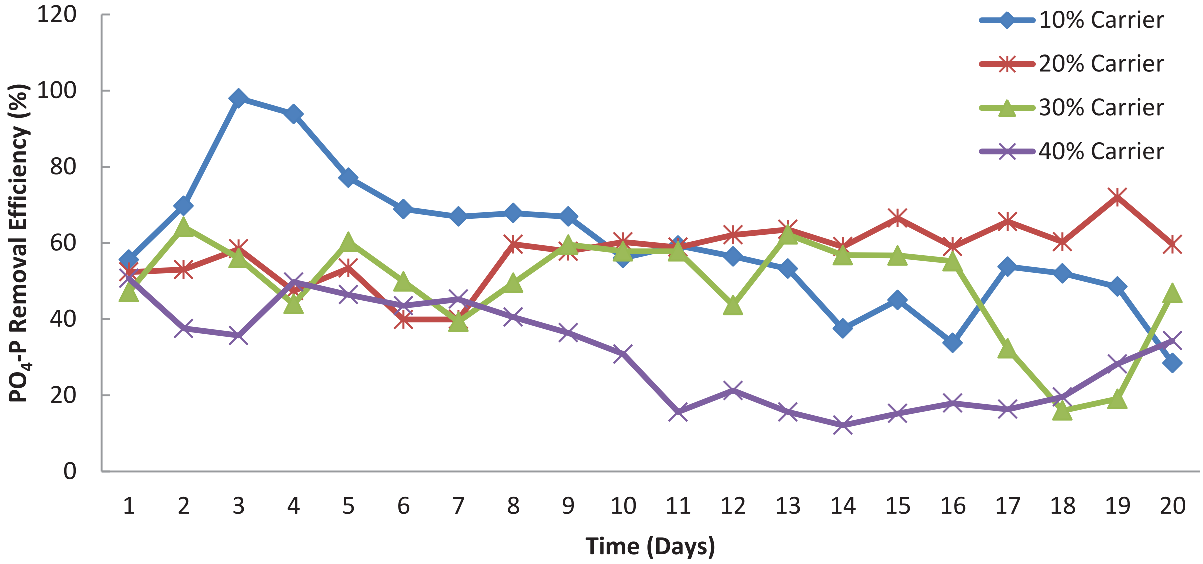

Figure 4.3 PO_4-P removal efficiency at different PE carrier filling rates

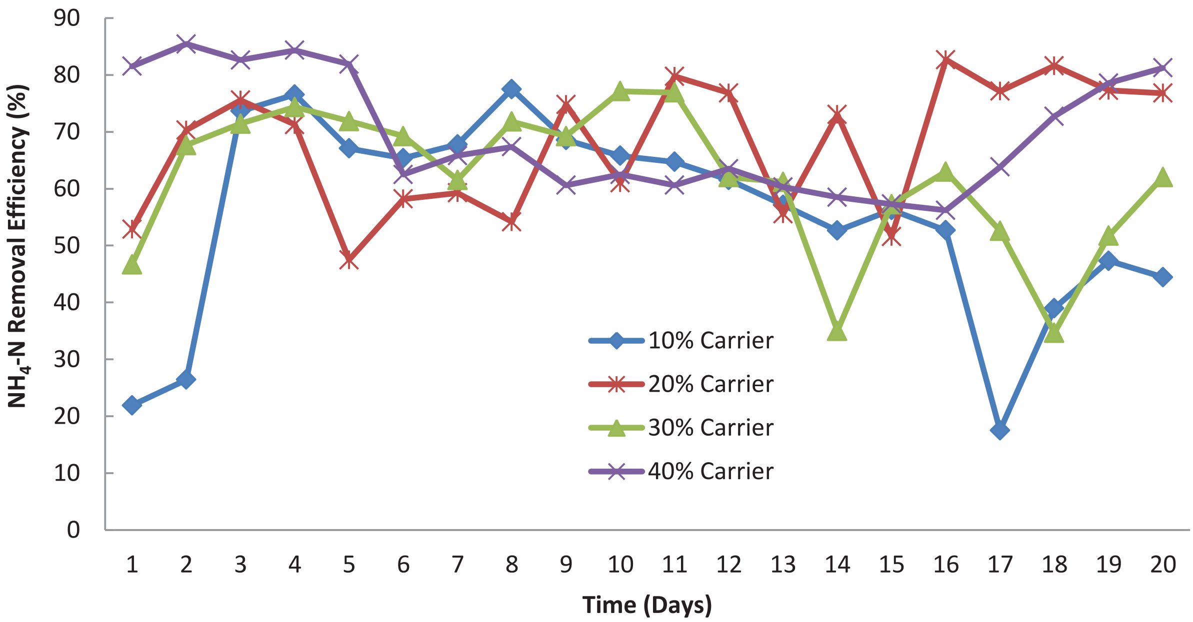

Figure 4.4 NH_4-N removal efficiency at different PE carrier filling rates

The average PO_4-P removal efficiency at four carrier filling rates of 10, 20, 30 and 40% were 59.41, 57.41, 48.68 and 30.61%, respectively (Figure 4.5). The results indicated that PO_4-P removal efficiency decreased significantly with increasing the amount of carriers in the reactor. As shown in Figure 4.3, at 10% carrier filling rate, PO_4-P removal efficiency within initial days was at the peak of 97.94% due to the microbial growth by phosphate consumption. On the other hand, there was a decrease in phosphate consumption up to 10% and 28.8% as more PE carriers were added to the reactor (e.g., 30% and 40%). This might be due to the competition for enough oxygen and space which occurs between heterotrophs and nitrifiers. Nevertheless, Figure 4.3 indicates that the MBBR system had the highest and steadiest PO_4-P removal efficiency at 20% carrier filling rate among other rates.

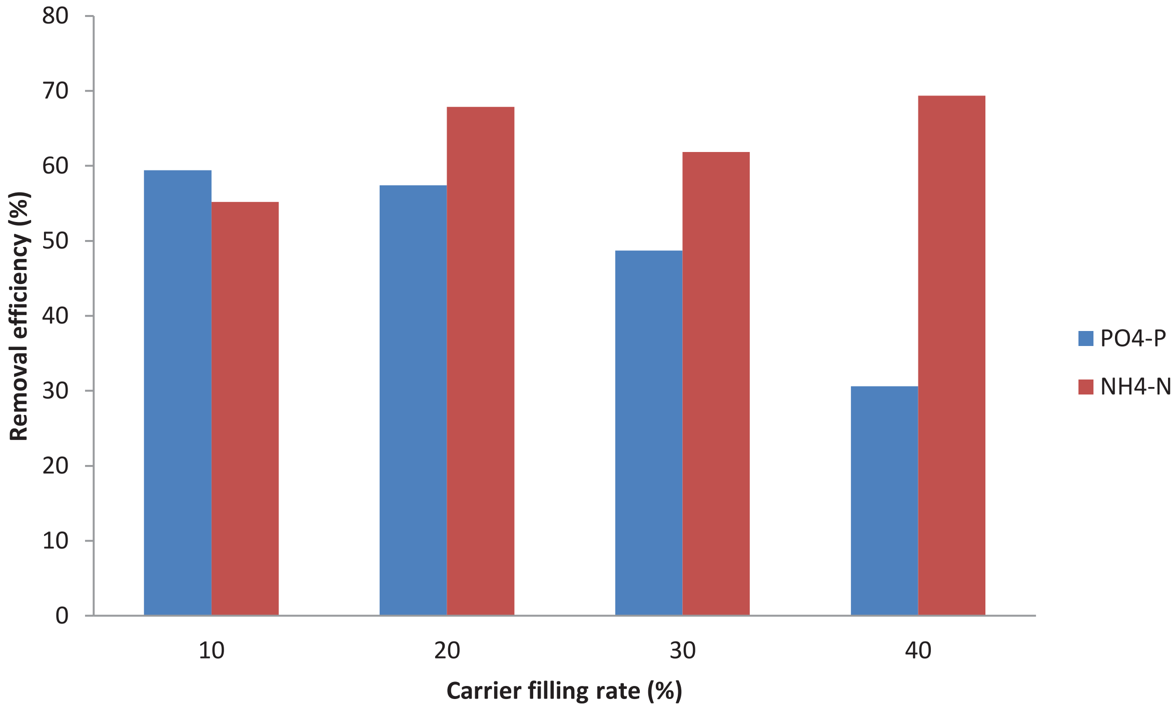

Figure 4.5 MBBR performance in terms of nutrient removal

The removal of NH_4-N in the system was also monitored during the operation of MBBR at different carrier filling rates (Figure 4.4). Basically, NH_4-N can be removed from wastewater by either assimilation into biomass or biological nitrification and denitrification process under aerobic and anaerobic conditions. NH_4-N removal efficiency was 55.19, 67.85, 61.86 and 69.36% at 10, 20, 30 and 40% carrier filling rates, respectively (Figure 4.5). The results also demonstrated that biofilm density on carriers in MBBR plays a key role in system performance and 20% filling rate can provide sufficient amount of biomass on carriers for PO_4-P and NH_4-N removals.

4.1.3 Microbial growth and activity

Biomass plays a key role in MBBR system and it is one of the major factors which controls the system performance. Thus, attachment of biomass to the carrier's surface and the activity of attached microorganisms were considered in many studies (Ahmed, 2011; Hajipour et al., 2011; Nguyen et al., 2010; Hosseiny and Borghei, 2002; Jianlong et al., 2000). MBBR is capable of retaining a considerable quantity of attached biomass which provides successful performance and achieves appreciable organic removal.

As can be seen in Figure 4.6, at 10, 20, 30 and 40% carrier filling rates and aeration rate of 4.5 mg/L, average biomass growth were 0.95, 0.82, 1.67 and 5.00 mg/g, respectively. At 10% carrier filling rate in MBBR, due to the quick movement of carriers in comparison to other filling rates, attachment of suspended microorganisms to carrier was obstructed. In addition, food consumption by attached microorganisms was hindered. This fact resulted in lower biomass growth and consequently, lower OM and nutrient removal compared to other carrier filling rates. Compared to 10%, at 20% filling rate of carriers, carriers moved uniformly and slowly which was the favourable condition for the attached microorganisms to consume food from the wastewater. Meanwhile, the suspended microorganisms had a better chance to attach to the carrier's surface and colonize when 20% of the reactor volume was filled with carriers. Accumulation of microorganisms on carrier was observed at 30 and 40% carrier filling rates due to the slow movement of carriers inside the reactor. This fact resulted in formation of a thick and insufficient biofilm layer. While swift and slow movements were the main concerns of 10, 30 and 40% carrier filling rates, uniform movement was observed at 20% filling rate.

Consequently, higher OM and nutrient removal were obtained at this condition which was due to the better food consumption, oxygen diffusion and microbial attachment on carrier. The trend of visual biomass growth at each carrier filling rate is shown in Figure 4.7. As shown in Figure 4.7, the results suggested that the increase in carrier filling rate led to increase in biomass attachment to the carrier's surface. Very thin, evenly distributed and smooth biofilm was formed on the carrier's surface at 20% carrier filling rate and seems to enable transport of substrate and oxygen to the biofilm surface.

Alves et al. (2002) reported that when the carrier concentration was very high, the fluidization of carriers was difficult and more aeration flux was needed to suspend the carriers. As a result, the operational cost of the biofilm process increased. In this regard, thick and fluffy biofilms, which formed at 30% and 40% carrier filling rates (Figure 4.7), are not desired for this system. The same results were reported by many scientists such as Chen et al. (2007). In Chen experiment, pesticide wastewater was used from a pesticide factory in Hebei Province, North of China and they found the same trend for contaminants removal and microbial growth on carriers by augmentation of carrier filling rate.

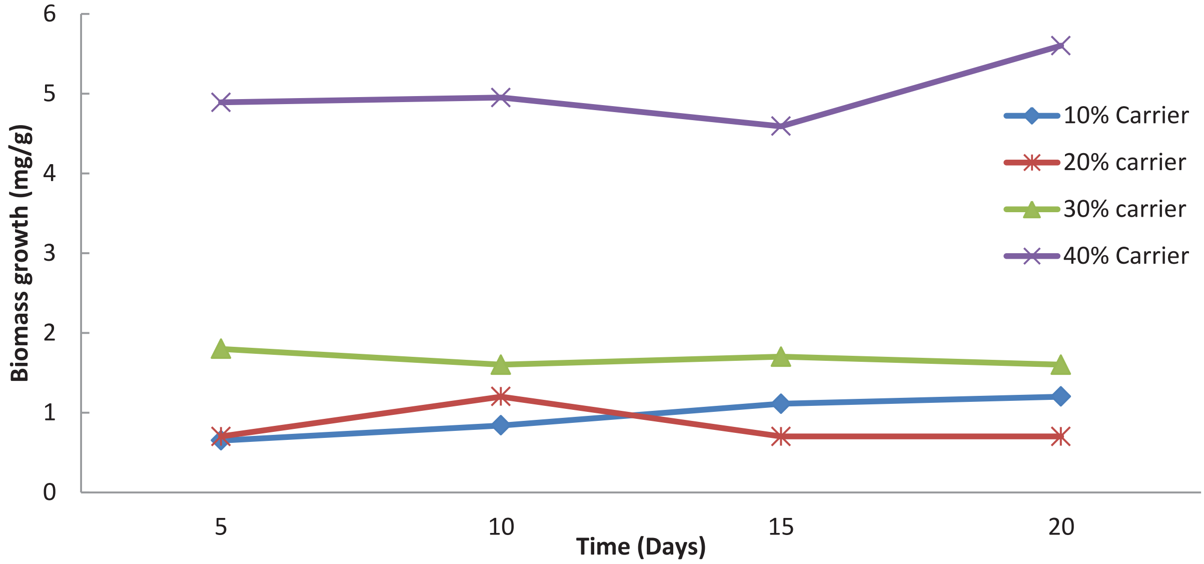

Figure 4.6 Microbial growth on PE carriers at different carrier rates

Figure 4.7 Biomass attachment on PE carriers at different filling rates

Specific oxygen uptake rate (SOUR) is often one of the most important factors that indicate microbial activity and the ongoing biochemical process. The SOUR of biofilm in the MBBR at different carrier filling rates is shown in Figure 4.8. The SOUR increased with the augmentation of carrier filling rate from 10% to 20% but it decreased when more carriers were added inside the reactor. Average SOUR at 10, 20, 30 and 40% carrier filling rates were obtained at 2.22, 5.04, 0.35 and 0.25 mg O_2/g MLVSS.h, respectively. At 10% filling rate, microorganisms grew rapidly. However, due to the swift movement of carriers and detachment of attached microorganisms, metabolic activity of microorganisms was hindered. At 20% carrier filling rate, uniform movement of carriers resulted in efficient attachment of suspended microorganisms to the PE carriers and metabolic activity of them. On the other hand, at 30 and 40% carrier filling rates, significant decrease observed in the trend of SOUR. This could be explained as a result of biomass accumulation on carriers because of slow movement. Hence, the higher the SOUR led to the better the organism activity.

When the carrier volume was low such as 10% and 20%, the biofilms formed were thinner and looser with a lower density and a relatively higher surface area, which was helpful for oxygen diffusion in the biofilms. Therefore, the bacteria could reach a higher activity expressed by SOUR. On the other hand, when the carrier volume became higher (e.g., 30% and 40%) carriers moved very slowly. In this condition, the collision and abrasion among the carrier particles became more intensive and the biofilms became thicker and denser. This fact intensified the oxygen and substrate diffusion limitation in the biofilms and thus, the activity of biofilm dropped accordingly.

Consequently, from the examination of the effect of carrier filling rate on MBBR performance, it was found that 20% carrier filling rate was the optimum rate in comparison to other carrier filling rates. Hence, 20% was used for the next stage of the experiment.

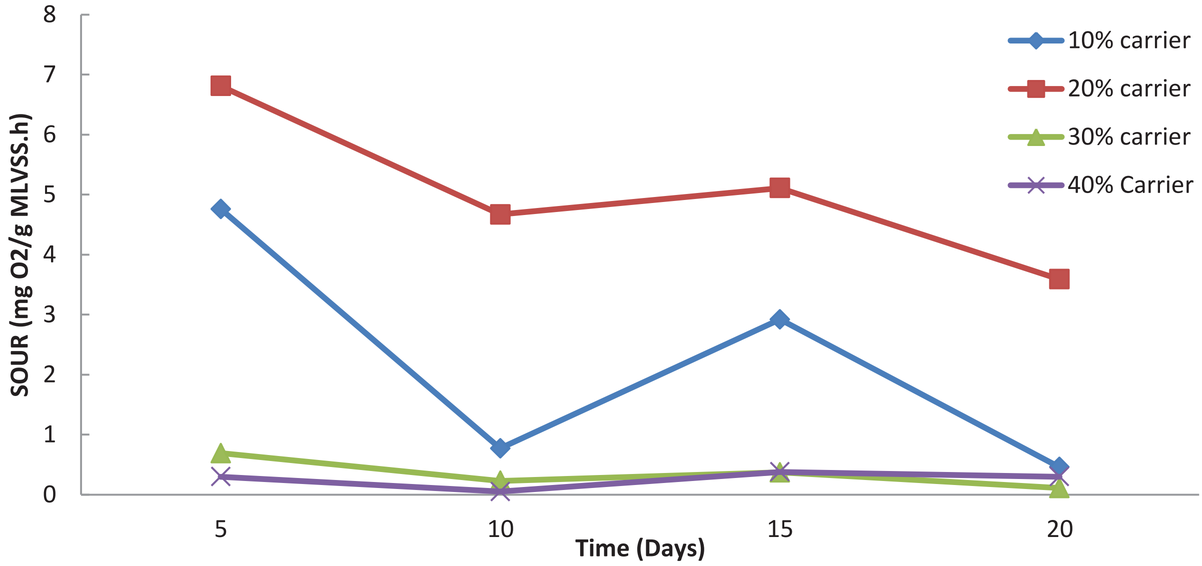

Figure 4.8 SOUR at different carrier filling rates

4.2 Effect of organic loading rate on the performance of MBBR in terms of organic matter removal

Organic loading rate can be calculated on the basis of either variation in the influent COD or reduction in the HRT. During this stage of the experiment, the initial OLR was set at 0.15 kg COD/m^3.d with influent COD concentration of 156.25 mg/L, HRT of 25h, carrier filling rate of 20%, flow rate of 8 mL/min and aeration rate of 4.5 L/min. The OLR was then increased gradually to 0.31, 0.47 and then to 0.8 kg COD/m^3.d by increasing the influent COD concentration to 322.9, 489.6 and then to 833.3 mg/L, correspondingly.

4.2.1 Organic removal

The removal efficiency of DOC and COD at different OLRs of 0.15, 0.31, 0.47 and 0.8 kg COD/m^3.d are shown in Table 4.2. The results showed that DOC removal efficiency increased proportionally with increasing OLR from 0.15 to 0.8 kg COD/m^3.d. The average DOC removal efficiency at OLR of 0.15, 0.31, 0.47 and 0.8 kg COD/m^3.d were obtained at 77.55, 86.98, 96.09 and 96.45%, respectively. Low DOC removal efficiency at OLR of 0.15

kg COD/m^3.d could be related to the lack of food existent in the influent which was caused by low influent COD concentration. It can be obviously seen from Table 4.2 that the highest DOC removal efficiencies were achieved at OLRs of higher than 0.31 kg COD/m^3.d. This could be explained as a result of enhancement of microbial growth and augmentation of their attachment on PE carriers when the OLR was increased. As organic carbon is the energy substrate for many microorganisms, microorganisms cause the degradation of carbon source and nutrient when enough oxygen is provided. As a result, increasing carbon source results in faster growth of microorganisms and enhancement of removal efficiency. This condition is an ideal condition for increasing the performance of MBBR. Hence, microbial concentration was enhanced with increasing OLR in this experiment and this resulted in high DOC and COD removal efficiency.

The results of COD removal with MBBR showed a similar trend as that of DOC removal at different OLRs. Average COD removal efficiency increased from 84.25 to 96.72% with increasing OLR from 0.15 to 0.8 kg COD/m^3.d, respectively. It was reported that higher COD removal efficiency could be achieved at higher OLR in the aerobic reactor (Li et al., 2011). This indicates that a higher OLR could enhance the activity of aerobic microorganism (Hajipour et al., 2011). Although at the beginning of each phase, where OLR was increased, there was a corresponding decrease in COD removal efficiency, the system recovered shortly and adapted to the new conditions with time as it was expected. Hajipour et al. (2011) found the same trend in COD removal efficiency at different OLRs. Aerobic thermophilic MBBR was used in their experiment and it was found that the COD removal efficiency increased primarily with increase in OLR. However, after it reached to a constant value at OLR of about 6 kg COD/m^3.d, COD removal efficiency started to decrease significantly.

In this experiment, the attachment of high biomass hold up at OLR of 0.8 kg COD/m^3.d in addition to immobilization of microorganisms on the carrier particles, contributed to such high removal efficiency. In this case, in which high concentration of biomass was attached to the PE carrier's surface, the greater part of the substrate can be consumed by the biofilm (Piirtola et al., 1999). Previous studies proved that increasing OLR results in COD removal efficiency augmentation and then COD removal efficiency reaches to a constant value (Hajipour et al., 2011; Nguyen et al., 2011). Nevertheless, more increase in OLR results in reduction of system efficiency. This point is called maximum loading capacity of a bioreactor and defined as the loading rate at which the removal rate does not increase with OLR. When the system passes maximum loading capacity, enhancement of OLR would results in reduction of removal rate. Hence, this point could vary in different systems. For instance, while Hajipour et al. (2011) achieved maximum loading capacity at constant OLR of 6 kg COD/m^3.d, Nguyen et al. (2011) reached to this point at a lower OLR of 1.2 kg COD/m^3.d. In a similar research, Chen et al. (2008) used a MBBR system with an anaerobic–aerobic arrangement. The contribution of the anaerobic MBBR to total COD removal efficiency reached 91% at an OLR of 4.08 kg COD/m^3.d at HRT of 4 days, and then gradually decreased to 86% when feed OLR increased to 15.70 kg COD/m^3.d at HRT of 0.5 days. The total COD removal efficiency of the system had a slight decrease from 94% to 92% even though the feed OLR was increased from 4.08 to 15.70 kg COD/m^3.d. This trend for COD removal efficiency at different OLRs was reported in many studies via different types of wastewater treatment systems (Ahmed, 2011; Nguyen et al., 2011; Jianlong et al., 2000).

Table 4.2 MBBR performance at different OLR in terms of DOC and COD removal efficiencies

OLR (kg COD/m^3.d)	**0.15**	**0.31**	**0.47**	**0.8**
HRT (h)	**25**	**25**	**25**	**25**
DOC RE %	77.55	86.98	96.09	96.45
COD RE %	84.25	90.8	93.52	96.72

RE: removal efficiency

4.2.2 Nutrient removal

The effect of four different OLRs on nutrient removal is shown in Figure 4.9. Biological phosphorus removal is performed by phosphate accumulating micro-organisms (PAO) that have the ability to accumulate phosphate over and above what is required for growth. Due to low influent COD at OLRs of 0.15 and 0.31 kg COD/m^3.d, less than 20% of phosphate was removed. Gradually by increasing OLR from 0.47 to 0.8 kg COD/m^3.d, phosphate removal increased up to 35.31%. Although augmentation of OLR resulted in detection of lower amount of phosphate in effluent, the highest phosphate removal efficiency was only 57.41% at the highest OLR of 0.8 kg COD/m^3.d. Previous studies also proved that attached growth systems could not achieve high removal efficiency at certain OLR (Nguyen et al., 2011; Wang et al., 2000).

Nitrogen is normally removed biologically from wastewater with nitrification of ammonia to nitrate under aerobic conditions, followed by denitrification of nitrate to nitrogen gas under anoxic conditions. Lowering organic carbon concentrations in recirculating systems enhances denitrification. This is due to the lack of space and oxygen for bacteria that consume organic carbon and bacteria consuming ammonia and nitrite. The outcomes of NH_4-N removal showed augmentation of removal efficiency rate from 46.43 to 78.92% when the OLR enhanced from 0.15 to 0.8 kg COD/m^3.d, respectively. In terms of T-N removal, the system eliminated maximum removal of 48.19% at OLR of 0.8 kg COD/m^3.d and less than 20% T-N removal efficiency at OLR of 0.15 kg COD/m^3.d. This could be described as the effect of enhanced dissolved oxygen and influent COD concentration from OLR of 0.15 to 0.8 kg COD/m^3.d which might have limited denitrification inside the carrier biomass. Dissolved oxygen at OLRs of 0.15, 0.31, 0.47 and 0.8 kg COD/m^3.d were detected at 3.58, 3.68, 4.40 and 4.8 mg/L, respectively. Hence, as expected, the ratio of I_{COD}/T-N removal was increased from 5.15 to 12.47, 18.94 and to 42.16, respectively at mentioned OLRs which is contributed to the augmentation of influent COD concentration. As a result, it was concluded that the efficiency of nitrification in MBBR was increased by enhancement of OLR from 0.15 to 0.8 kg COD/m^3.d.

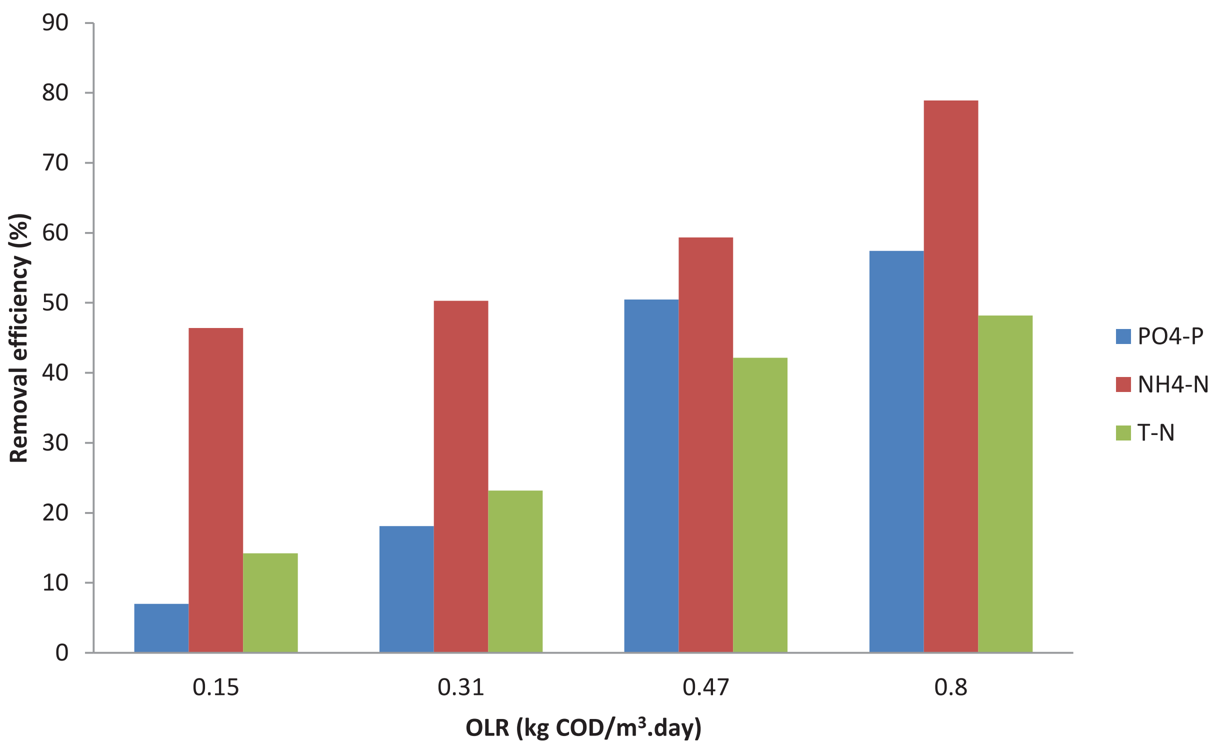

Figure 4.9 Performance of MBBR at different OLRs in terms of nutrient removal

4.2.3 Microbial growth and activity

The variation of attached biomass at different OLRs is shown in Figure 4.10. The higher organic loading rates applied in this experiment, promoted the growth of bacteria. The results showed that the amount of attached biomass developed in the MBBR increased as the organic loading rate was increased. In the MBBR reactor used in this study, biofilm reached an average concentration between 5.68 and 11.23 mg/g at different OLRs. As the OLR was increased from 0.15 to 0.31 kg COD/m^3.d, microbial growth on carriers was enhanced slightly from 5.68 to 5.87 mg/g, respectively. Similarly, average microbial growth on carrier's surface increased significantly from 6.25 to 11.23 mg/g at OLRs of 0.47 and 0.8 kg COD/m^3.d, respectively. Increasing the influent COD concentration provides more food for microorganisms to consume and increases the amount of bacteria inside the reactor. Increasing the quantity of bacteria enhances the attachment of them on carriers. This can be seen from variation in the amount of suspended solid inside the reactor (Table 4.3). Measuring the amount of the suspended solid inside the reactor revealed that biomass attachment was enhanced as a result of OLR augmentation. With increasing OLR from 0.15 to 0.31 kg COD/m^3.d, the biomass inside the reactor enhanced up to 0.19 mg/L. Nevertheless, when the OLR increased from 0.31 to 0.47 and then to 0.8 kg COD/m^3.d, the biomass inside the reactor decreased from 0.38 to 0.33 and to 0.29 mg/L, respectively. These results confirm the enhancement of biomass attachment to the carrier particles by increasing the OLR. Consequently, high concentration of active biomass inside the MBBR due to immobilization and accumulation of bacteria on the carrier's surface ensures the high treatment efficiency under high organic loading rates. The higher organic loading rates applied in this experiment, promoted the growth of bacteria. This could results in consumption of a greater part of the substrate by this biofilm and thus, attachment of larger number of microorganisms to carriers, higher growth rates, and larger fractions of organic matters would be achieved. Similar results were reported by Jianlong et al. (2000) that the attached biomass made great contribution to substrate removal.

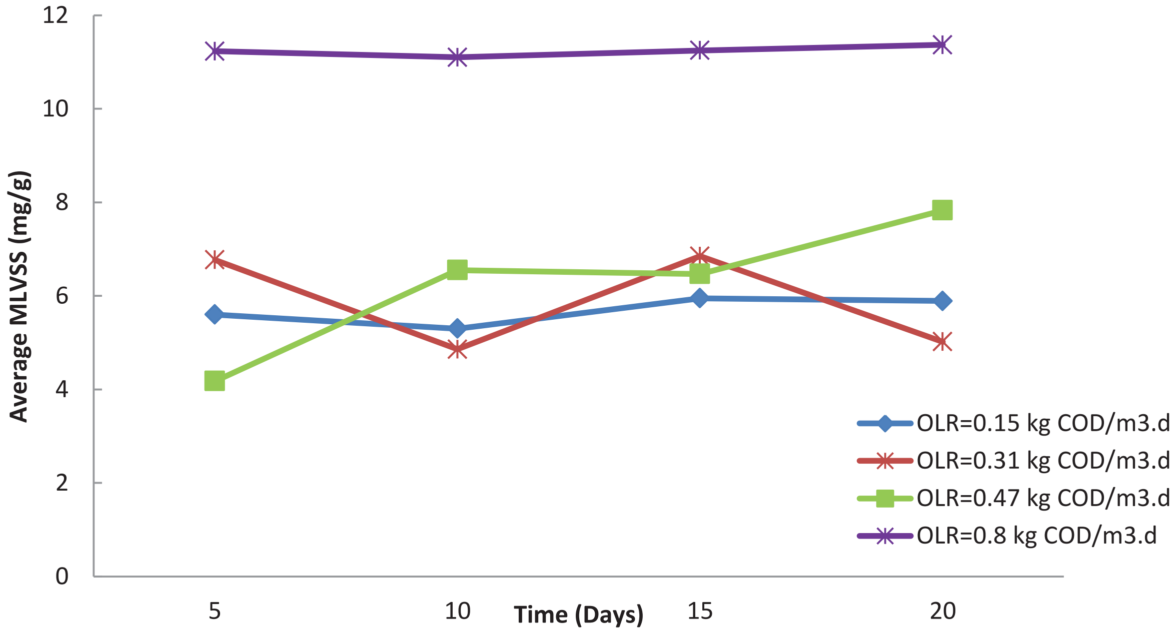

Figure 4.10 Microbial growth rates on PE carriers at different organic loading rates

The results achieved in this experiment expose the activity of microorganisms attached to the carrier's surface. Obviously, as changing OLR resulted in the increasing the amount of biomass production as well as system removal efficiency, it should have affected microbial activity which reveals in SOUR. Effect of OLR on microbial activity in the MBBR is shown in Table 4.3. Table 4.3 indicated that SOUR increased with the augmentation of OLR. The reason of this fact could be explained by variation in microbial activity and thus oxygen consumption. At OLRs of 0.15, 0.31 and 0.47 kg COD/m^3.d, dissolved oxygen was mostly consumed for attachment of microorganisms to carrier's surface. Thus, the amount of specific oxygen uptake rate used by microorganisms for food consumption was very low. This can be observed in the amount of suspended solid inside the reactor and the amount of attached biomass on carriers (Table 4.3). On the other hand, the significant increase in SOUR at OLR of 0.8 kg COD/m^3.d showed high activity of microorganisms and oxygen consumption at this phase. This could explain the reduction of suspended microorganisms in the reactor and augmentation of attached biomass. These results showed that at OLR of 0.8 kg COD/m^3.d, microorganisms used most of the present oxygen for removal of substances which led to high OM removal efficiency at OLR of 0.8 kg COD/m^3.d.

Table 4.3 Performance of MBBR at different OLRs in terms of specific oxygen uptake rate (SOUR)

OLR (kg COD/m^3.d)	**0.15**	**0.31**	**0.47**	**0.8**
SOUR (mg O_2/g MLVSS.h)	<1	1.11	2.89	8.53
VSS in the reactor (mg/L)	0.19	0.38	0.33	0.29
Biomass on the carrier (mg/g)	5.68	5.87	6.25	11.96

4.3 Effect of hydraulic retention time (HRT) on the performance of MBBR in terms of organic matter removal

Hydraulic retention time (HRT) is an important operational variable which can be easily controlled (Elefsiniotis and Oldham, 2006). It is average length of time a molecule of liquid remains in the reactor and can be defined as the volume of the reactor divided by the average influent flow rate.

4.3.1 Organic removal

To understand the effect of hydraulic retention time (HRT) on MBBR performance, the HRT was changed by varying the flow rate in this phase of the experiment. In this regard, this stage of the experiment was conducted at the optimal conditions and maintained a constant OLR of 0.8 kg COD/m^3.d (Table 4.4). In order to decrease the HRT while the OLR is constant, the influent COD concentration decreased from 833.3 to 266.6 and then to 133.3

mg/L by changing the HRT from 25 to 8 and then to 4h, respectively (Table 4.4). The results for DOC and COD removal efficiency at different HRTs are discussed as follows.

Table 4.4 Moving bed biofilm reactor operating condition at the third stage of the experiment

HRT (h)	**25**	**8**	**4**
OLR (kg COD/m^3.d)	0.8	0.8	0.8
Influent COD concentration (mg/L)	833.3	266.6	133.3
Flow rate (mL/min)	8	25	50

At the initial stage of this phase, the HRT of 25h was selected, which required a flow of 8 mL/min. At this stage, long contact time between carriers and influent were provided. This was to enhance the rate of microbial attachment and growth on PE carriers. As soon as completing this period of the cycle, the HRT variation was started with the aim of understanding the effect of HRT on MBBR performance in this study. Table 4.5 shows DOC removal efficiency at different HRTs. The results showed that the system could achieve more than 96 % of DOC removal efficiency at the highest HRT of 25h, while it was slightly lower at HRTs of 8 and 4h. Normally, higher HRT provides enough contact time for the biodegradation of OM in the reactor and hence, a longer contact time between support media and wastewater enhances the pollutant removal efficiency (Najafpour et al., 2006). This may be as a result of enough time for attachment of microorganisms on carrier's surface and hence, developing a very active biomass layer on carrier's surface.

Table 4.5 Performance of MBBR at different HRT in terms of DOC and COD removal efficiency

HRT (h)	**25**	**8**	**4**
OLR (kg COD/m^3.d)	**0.8**	**0.8**	**0.8**
DOC RE (%)	96.45	95.34	95.03
COD RE (%)	96.64	96.92	97.24
MLSS (mg/g)	11.96	14.76	16.82

RE: removal efficiency

In terms of COD removal, although the HRT was decreased, MBBR conditions were became stabilized shortly within the first few days of each cycle and high removal efficiency was achieved after the stabilization days. Variation of the HRT between 25, 8 and 4h indicated that HRT did not have a significant effect on COD removal efficiency. Table 4.5 shows COD removal efficiency at different HRTs. Although more than 96% of COD removal efficiency was achieved at all the HRTs, COD removal increased slightly with augmentation of HRT and the highest removal efficiency was obtained at the HRT of 4h. This high COD removal was attributed to the MBBR advantage that can completely retain biomass presents in the mixed liquor to produce a high quality effluent. In addition, Table 4.5 indicates that the removal of organic pollutants was a co-function of microbial metabolism (Ren et al., 2005). In this regard, when the HRT decreased from 25 to 8 and to 4h, the average COD removal efficiency increased from 96.64 to 96.92 and then to 97.24% with the augmentation of average MLSS from 10.96 to 15.21 and to 45.8 mg/g, respectively. In other experiments, the optimal HRT was different due to the difference in operating condition. For example, Hajipour et al. (2011) found the appropriate HRT in the range of 12 to 16.5 h and lower performance was achieved when the HRT decreased to 9h. However, the same trend for the effect of HRT on COD removal efficiency was achieved in this study.

4.3.2 Nutrient removal

Figures 4.11, 4.12 and 4.13 show the effect of HRT on PO_4-P, NH_4-N and T-N removal, respectively. Figure 4.11 shows the remarkable increase of PO_4-P removal efficiency by decreasing the HRT. The average PO_4-P removal increased significantly from 39.96 to 63.72% by decreasing HRT from 25 to 8h. Moreover, as HRT decreased to 4h, phosphate removal efficiency reached to the peak of 75.85%. Within the longest contact time of 25 h between mixed liquor and biomass, phosphate was consumed by microorganisms for microbial growth. In addition, Figure 4.11 shows that as the HRT decreased to 8 and 4 h, respectively, larger amount of phosphate were consumed by microorganisms.

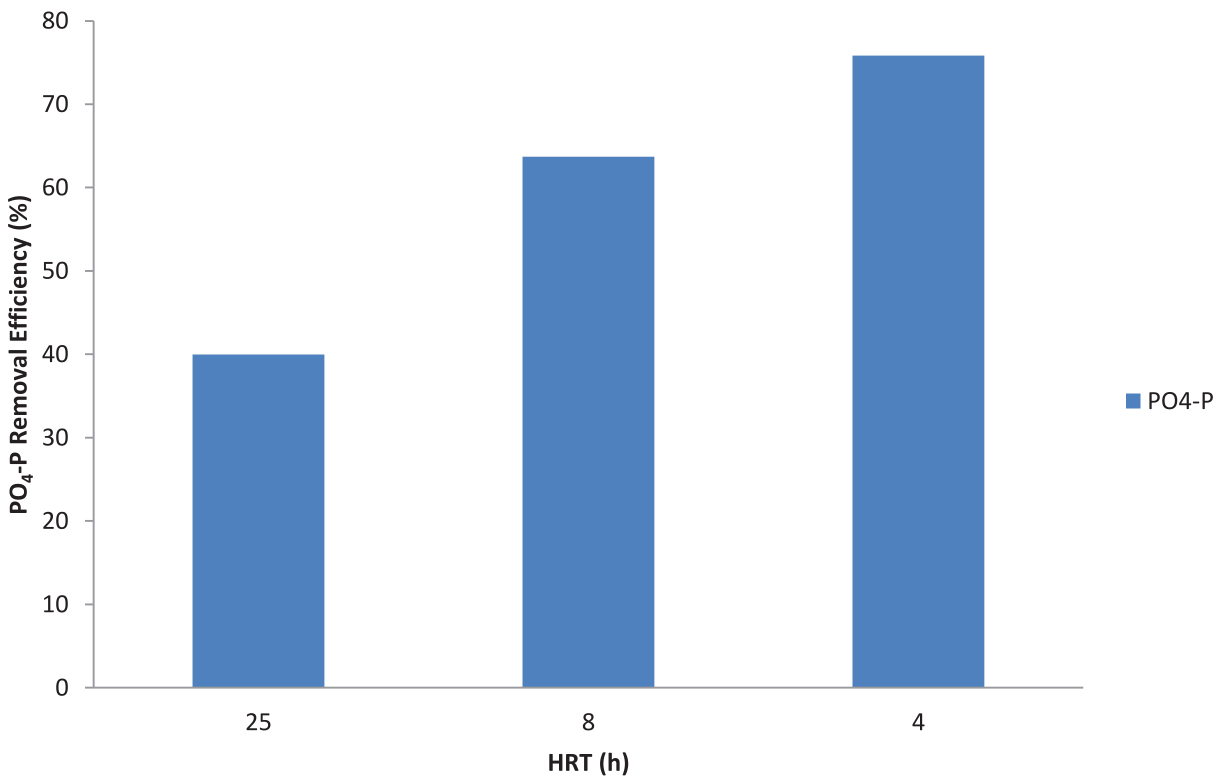

Figure 4.11 MBBR performance in terms of phosphate removal at different HRTs

NH_4-N removal in variety of HRT during the operational of MBBR is shown in Figure 4.12. Figure 4.12 demonstrates that the NH_4-N removal efficiency was higher at shorter HRT. In this regards, the average NH_4-N removal efficiency obtained were 46.43, 50.3 and 62.89 % at HRT of 25, 8 and 4h, respectively. This significant increase in the trend of NH_4-N removal from HRT of 8 to 4h could be attributed to the active biofilm layer presented on carrier's surface at the lowest HRT which resulted in augmentation of the nitrification rate. The same trend for NH_4-N removal was reported by Chen et al, (2008).

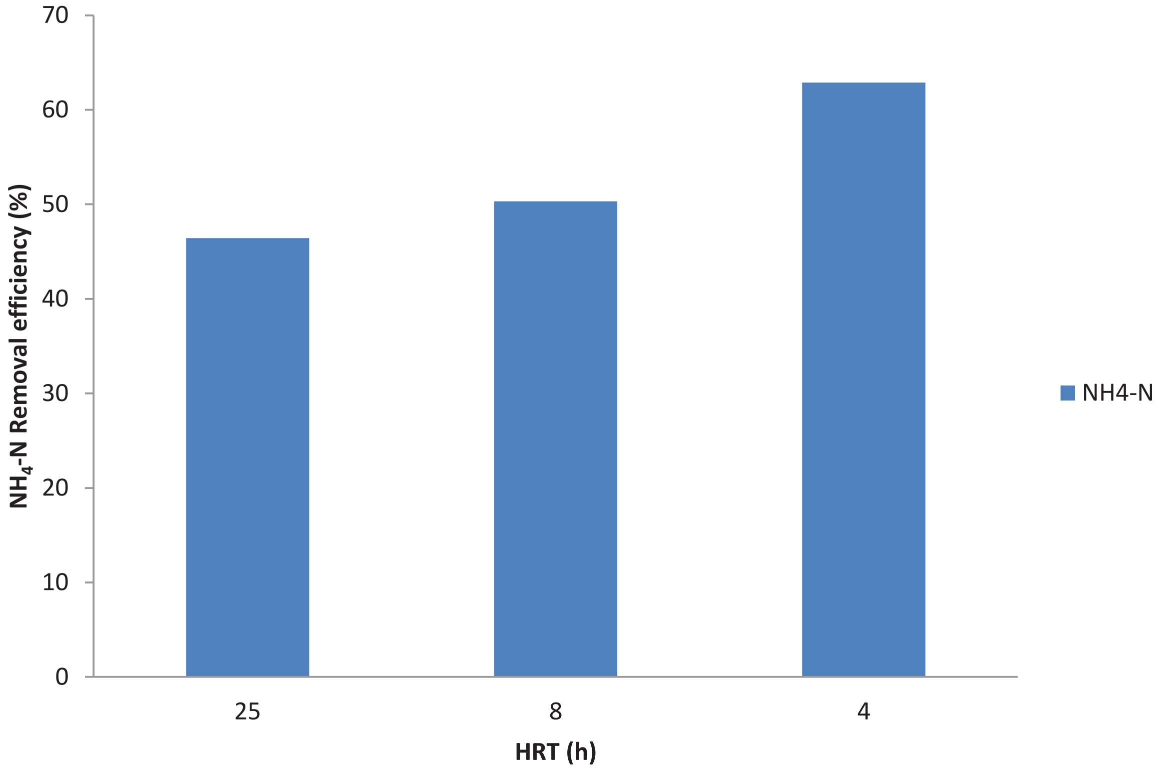

Figure 4.12 MBBR performance in terms of ammonium removal at different HRTs

In this experiment, the effect of HRT on T-N removal was also investigated (Figure 4.13). The same trend as NH_4-N was monitored for T-N removal. The results revealed that when the HRT of the MBBR decreased from 25 to 8 and then to 4 h, T-N removal increased from 42.15 to 48.2 and then to 60.58%, respectively. The results suggested the enhancement of nitrification by reduction of HRT.

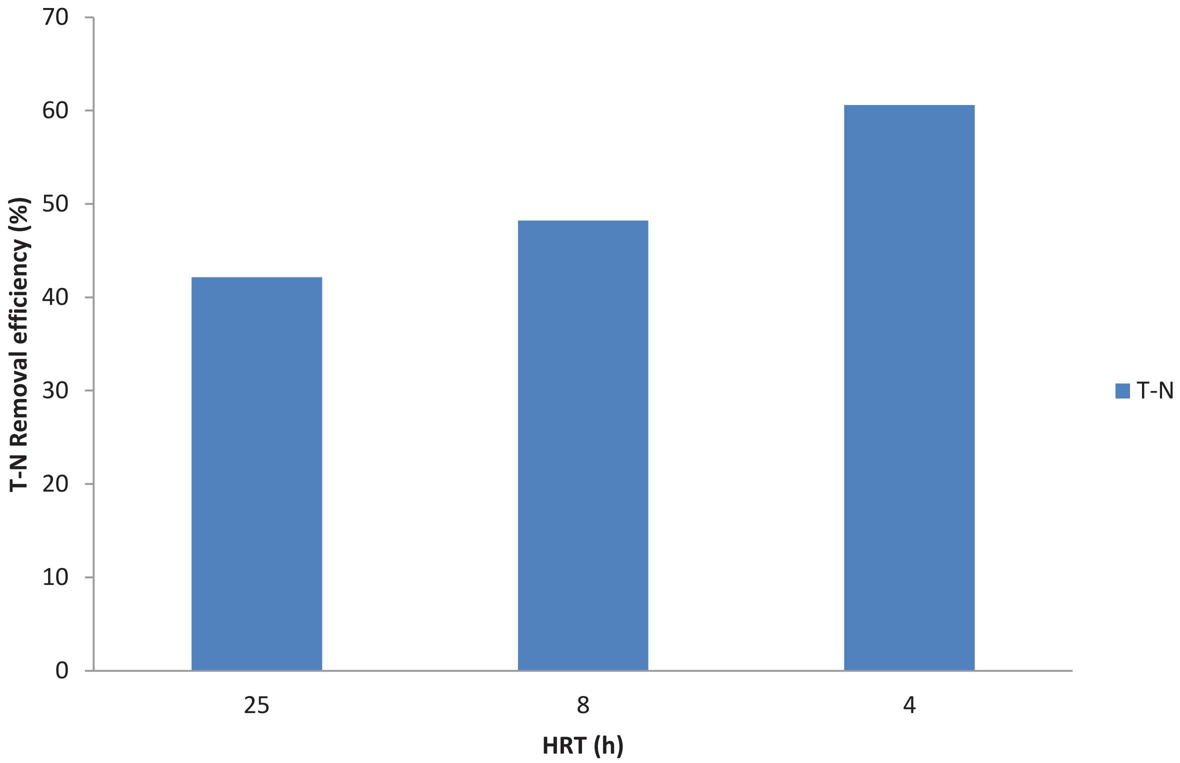

Figure 4.13 MBBR performance in terms of total nitrogen removal at different HRTs

4.3.3 Microbial growth and activity

These experiments also indicated the effect of different HRTs on the metabolic activity of the mixed microbial community within the MBBR reactor. The results of the 20 day experiment of the effect of HRT on PE carrier's microbial growth (MLSS and MLVSS) and SOUR in MBBR is shown in Figures 4.14, 4.15 and 4.16, respectively. Figure 4.14 and 4.15 show that higher MLSS and MLVSS were observed when HRT reduced successively from 25 to 8 and 4. In this regard, with the reduction of HRT from 25 to 8 and 4 h, MLSS increased from 11.96 to 14.76 and 16.82 mg/g and with a same trend MLVSS increased from 11.23 to 14.07 and 16.43 mg/g, respectively. These results also indicate that HRT reduction enhanced the growth of biomass and accumulation of the soluble microbial products. This could be explained as a result of the biomass multiplication and more carbon conversion from organic compounds to methane gas.

HRT affects the metabolic activity of the mixed microbial community within the bioreactor as reflected by the measurement of SOUR. Figure 4.16 shows that SOUR was measured at 8.01 mg O_2/g MLVSS.h at the highest HRT of 25 h, while it was significantly increased to 14.66 O_2/g MLVSS.h and finally reached at the peak of 22.53 O_2/g MLVSS.h at HRTs of 8 and 4 h, respectively. As the HRT was increased, less carbonaceous substrate was provided to the bacteria, leading to a decrease in the SOUR values. Hence, shorter HRTs led to a significant increase in SOUR which shows satisfactory level of microbial activity in the system (Barr et al., 1996).

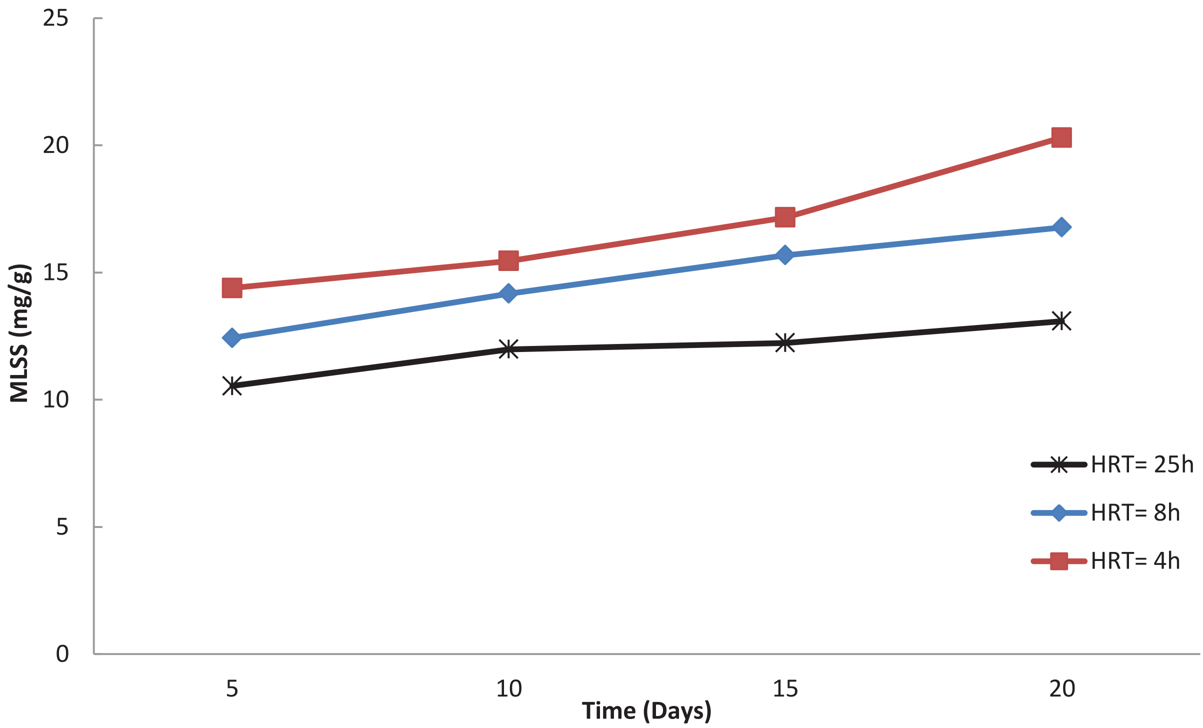

Figure 4.14 Average MLSS on PE carriers at different hydraulic retention times

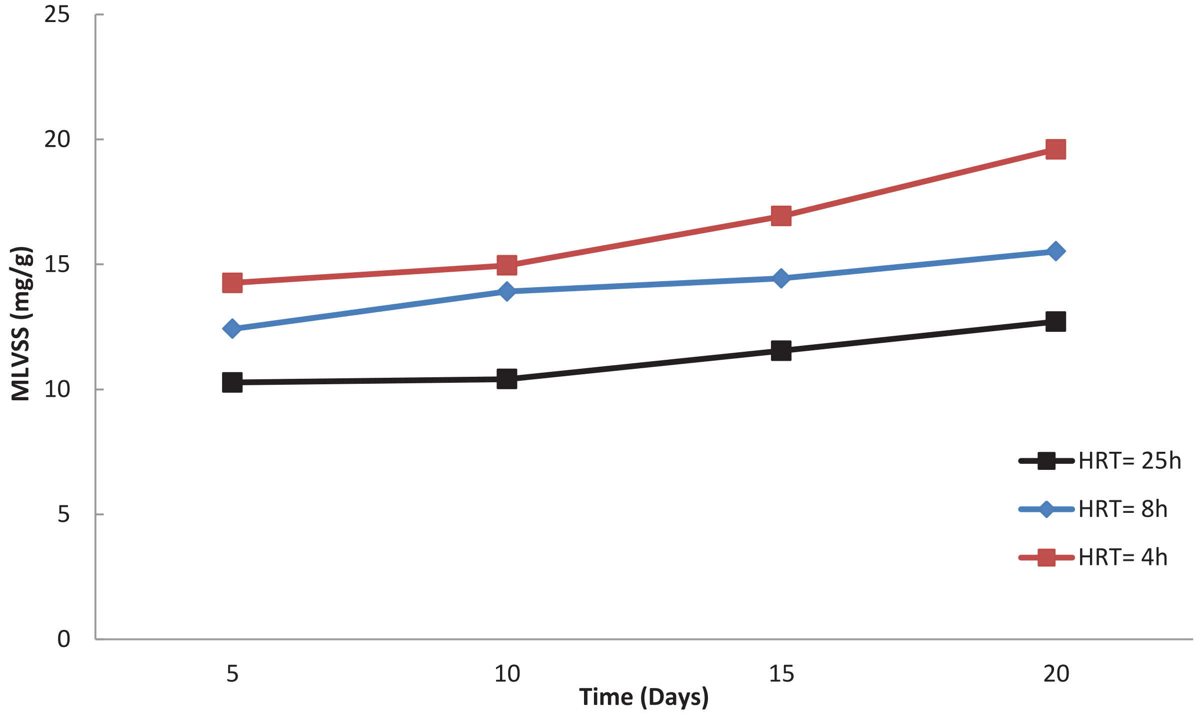

Figure 4.15 Average MLVSS on PE carriers at different hydraulic retention times

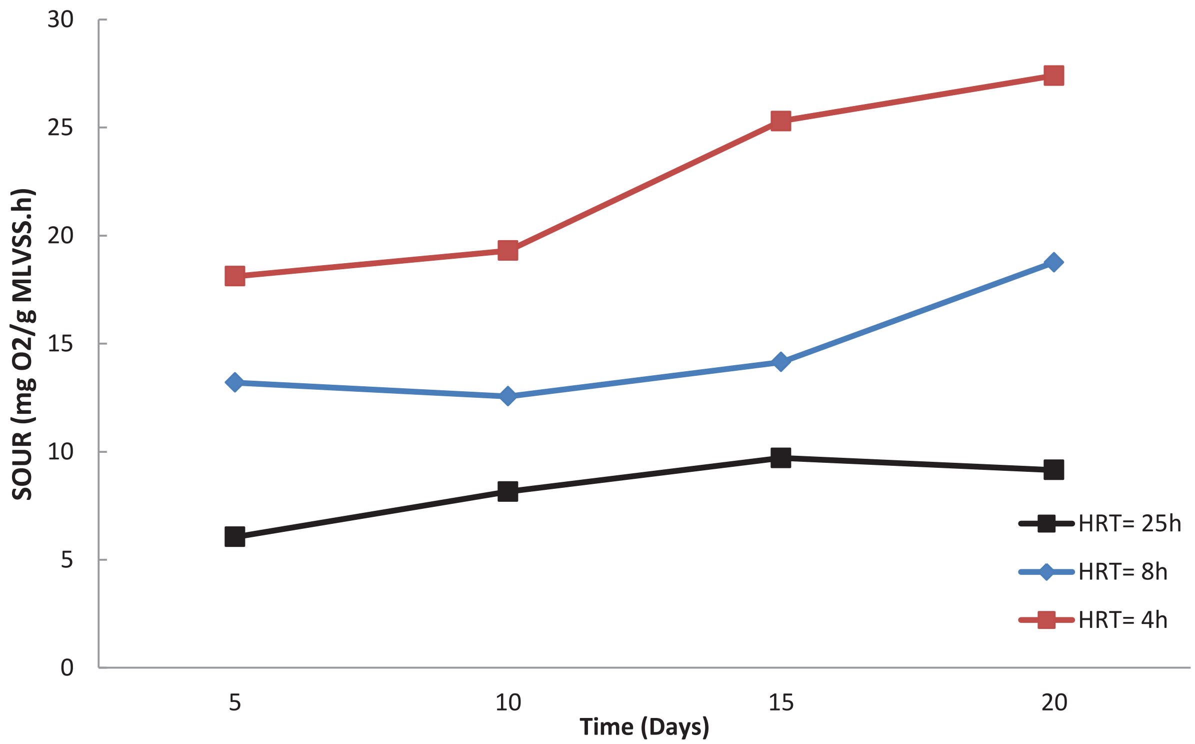

Figure 4.16 Average SOUR at different hydraulic retention times

Consequently, this experimental results show that HRT of 4 h was the favourable condition for continuous lab-scale MBBR in which, reactor were operated under 20% carrier filling rate, OLR of 0.8 kg COD/m^3.d and aeration rate of 4.5 L/min.

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CHAPTER 5

CONCLUSION AND RECCOMENDATIONS

5.1 Conclusion

Moving bed biofilm reactor (MBBR) is a very cost effective and eco-friendly option for the removal of organic matters (OM) from wastewater. This particular research work analysed the removal of OM from the synthetic domestic wastewater using MBBR. In this study, the effects of vital factors such as carrier filling rate, organic loading rate (OLR) and hydraulic retention time (HRT) affecting the MBBR performance in terms of OM removal were investigated. In general, this research ascertained that MBBR with polyethylene media (PE) as biofilm support carrier could be efficient for OM removal from wastewater. Some specific findings of this study can be drawn as follows:

- At 20% of carrier filling rate, carriers could move uniformly in 12 L reactor and give favourable surface area for microbial growth. As a result, higher DOC and COD removal efficiency were achieved at 20% filling rate compared to that of 10% and 30% carrier filling rates.
- MBBR was capable of retaining a considerable quantity of attached biomass which would provide successful performance and achieve appreciable organic removal. Thus, the higher the OLR led to the greater the amount of attached biomass on support material that resulted in consumption of a greater part of the substrate by this biofilm.
- The highest DOC, COD, phosphate and total nitrogen removal efficiency were achieved at the OLR of 0.8 kg COD/m^3.d.
- Although in the MBBR longer contact time between carrier and mixed liquor results in the higher amount of OM biodegradation, HRT variation in this experiment did not significantly affect the MBBR performance in terms of COD and DOC removal as an active biofilm layer was formed on biofilm carriers' surface in all different HRTs.
- HRT variation from 25 to 4 h resulted in augmentation of PO_4-P and T-N removal efficiency from 39.96 and 42.15% to 75.85 and 60.58%, respectively.

- High accumulations of biomass in the biofilm process when coupled with good oxygen transfer capability of the system ensure the high treatment capacity and operational stability. This can make the MBBR process attractive and promising to apply for organic matter removal from wastewater.

5.2 Recommendations

Based on the findings obtained in this research, the following recommendations can be made for the future study:

- Comparison study using different types of biofilm carriers at different filling rates to determine the best biofilm carrier type for highest OM removal efficiency;
- Further study on the investigation using real municipal wastewater to verify the effectiveness of the MBBR and implement this type of system in practical field;
- Further detailed investigation on the MBBR to determine the optimal aeration rate; and
- Further investigations on the performance of MBBR to remove trace organics in wastewater.

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