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Investigation of Pre-treatment used for Organic Foulant Removal from Wastewater Effluent on Fouling of Membranes used for Wastewater Treatment and Reuse

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

The volume of global water is very large. However, the source of water on the globe is finite and also distributed in quite uneven manner. In addition to this, freshwater source is dwindling and becoming scarce from human intervention including anthropogenic input, reduced rainfall due to climate change and increased water demand for drinking, hydropower, irrigation and industrial use combine with increasing pollution load from urban, industrial and agricultural discharges. This results many part of the world with only limited or no fresh water source to meet the increasing water demand. So, development of alternative water resource such as wastewater recycling is highly essential to face the degradation of and shortage of water. In this context, the use of membranes in wastewater reuse process is likely to play an important role to combat the potential degradation and shortage of the water resources as well as to meet increasingly stringent standards in terms of potable and industrial use. It has been used for the treatment of wastewater effluent at Beenyup and Kwinana wastewater treatment plant by Water Corporation. While Beenyup will recycle water to recharge the aquifer for future use, Kwinana plant recycles it for industrial use. Despite various promises of membrane, the wide application is still limited as both plants experienced membrane fouling particularly organic and biofouling leading to increase in operation cost. Organic foulants could cause both reversible and irreversible fouling. While reversible fouling can be overcome by backwashing, irreversible fouling tenders expensive membranes useless. So, this research aimed to investigate the in-depth assessment of organic matter removal particularly focusing on pre-treatment side to reduce the fouling rate by minimizing the organic material prior to the membrane filtration. Two fundamental mechanism particularly physicochemical and biological processes were investigated both separately and in combination in this research. They were analysed in terms of organic matter removal (DOC, UV254, SUVA, Turbidity,… etc) during the study of these process. Enhanced coagulation by Ferric Chloride and MIEX® were studied as physico chemical process while BAC was studied as biological treatment process for various experimental configurations. The laboratory results showed that physio chemical process can achieve around 60 percent removal of organic carbon present in the wastewater. Similarly, biological process was also found to be effective and achieved up to 45 percent removal of organic carbon. The combined performance of pre-treatment particularly BAC followed by the

coagulation was also investigated and found to be more effective as BAC converted non-sorbable organic carbon to sorbable organic carbon by increasing the efficiency of coagulant significantly. This combination achieved the removal of organic carbon even up to 90 percent. This means, fouling of membrane can be reduced significantly by applying fore mentioned treatment individually or in combination. However, to understand the fouling mechanism further, more detail laboratory works need to be done. So, various pre-treated secondary wastewater needs to be brought into membrane fouling experiments in the next stage of research in order to understand the insight of membrane fouling and its minimization to make the membrane technology economical for the reuse of wastewater.

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CHAPTER 1

INTRODUCTION

1.1 Membrane Fouling

The use of membranes in water treatment process is likely to play an important role in combating the potential degradation and shortage of the water resources as well as meeting increasingly stringent standards in terms of potable and industrial use. However, wide application is still limited as it encounters fouling and leads to expensive operational cost. The term membrane fouling generally refers to decline in flux because of clogging of membrane pores by the layers of undesirable deposits of both organic and inorganic matters present in the water on and inside the membrane pores. The fouling caused by suspended solids and inorganic colloids generally makes the cake layer on the membrane surface and it is reversible in nature. It can be cleaned by backwashing, although it halts the continuous operation of membrane. However, the fouling caused by organic material particularly organic carbon and nitrogen leads to organic and bio fouling and consequently increases the operation cost. Organic foulants could cause both reversible and irreversible fouling. While reversible fouling can be overcome by backwashing, irreversible fouling tenders expensive membranes useless.

The classification of organic fouling overlaps those of colloidal fouling and bio fouling. In addition to macro molecules, organic foulants can include organic colloids. Moreover, bio fouling can be considered as a biotic form of organic fouling while organic matter derived from microbiologically-derived cellular debris can be considered as an abiotic form of bio fouling (Amy, 2008). The control of bio fouling during membrane filtration is extraordinarily complex as it is associated with enormous range and properties of bio foulants such as humic acids, polysaccharides, lipids and glycoproteins as well as variety of micro organisms particularly bacteria. In addition, the interaction between the suspended colloids with those deposited cake in a mix species environment has the potential to change the nature of the foulant layer significantly in terms of resistance and reversibility (Pierre et al., 2006). So, the challenge lies in identifying foulants or conditions leading to irreversible fouling and extending the life span of membrane and hence to get the economical cost of wastewater recycling.

1.2 Advantages of Pre-treatment

The long life span of membrane with low operation cost is possible only if the organic matter responsible for fouling particularly organic carbon and nitrogen can be removed beforehand. Therefore, pre-treatment of wastewater will be highly effective to take them away prior to sending them through the membrane. These organic carbon and nitrogen act as precursors of disinfection by products (DBPs). Hence, their prior removal is highly effective in reducing the carcinogenic DBPs. For example, DBPs such as Nitroso Di Methyl Amine (NDMA) is a potential carcinogen which can be formed when organic nitrogen reacts with disinfectants such as chloramine. As it is highly soluble in water, even Reverse Osmosis (RO) membrane filtration can not effectively remove them. In this context, pre-treatment of wastewater could be an effective measure to reduce both membrane fouling and DBPs.

Despite several researches, the most appropriate pre-treatment method remains still not investigated. Each method has its own beneficial and detrimental sides. For instance, physico chemical treatment produces a lot of sludge but takes shorter time; biological process takes longer time but gives relatively economic operational cost and so on. In this context, optimising the pre-treatment either by improving the conventional understanding on various pre-treatment methods or achieving synergic effect in combination to achieve the economically viable desired removal efficiency of organic matter is a great deal of concern at present.

Thus, this research investigates the in-depth assessment of organic matter removal particularly focused on pre-treatment side to reduce the fouling rate by minimizing organic material prior to the membrane filtration. Various treatment methods were studied both individually and in combination in terms of removal of organic material in secondary wastewater effluent (SWWE) treatment by providing economical way of water treatment to address the increasing water deficit. In order to further understand the synergic effect of combination of various pre-treatment methods for different kind of wastewater to be treated, a detailed literature review was conducted. The details are explained in second chapter.

1.3 The Objectives of the Research and Scope of the Study

As mentioned earlier, organic matters are particularly responsible for the fouling of membrane regardless of organic or bio fouling. This research therefore focuses on removing them

particularly dissolve organic carbon (DOC) and dissolve organic nitrogen (DON) using various pre-treatment methods in laboratory scale experiments.

The main objective of this research is to identify best pre-treatment method or combination that can significantly reduce the organic matter in secondary wastewater and hence reduce the irreversible fouling on the membrane for the reuse. As dissolved organic nitrogen is responsible for the formation of NDMA, another objective of this research is to reduce it by reducing its precursor during pre-treatment. So, to fulfil the major objective of finding a suitable pre-treatment method, the research investigates the following aspects.

• Initial investigation of various existing pre-treatment options

• Pre-treatment options which can reduce organic and bio fouling

• Pre-treatment options that can reduce the DON and hence, reduce the carcinogenic DBP formation like NDMA

1.4 Research Significance

The volume of global water is very large; even, the distribution of annual precipitation on earth seems sufficient for the whole population. However, it is distributed in quite an uneven manner. In addition, as a result of the increasing pressure from human intervention including domestic, agricultural and industrial use, some parts of the world are facing limited water access and even no fresh water sources. Furthermore, water supply related problems have been caused by wasteful exploitation of fresh water, reckless release of deleterious and dangerous water borne wastes in to water bodies such as river, lake ocean, as well as careless management and mismanagement of watersheds, recharge areas and aquifers. So, the demand is increasing while the fresh water resource is continuously decreasing. As a result, the rift of demand and supply required for the population is widening.

Development of sustainable alternative water resource is highly essential to prevent the degradation and shortage of water in both dry and densely populated areas of the world. Domestic wastewater contains more than 99 percent of water and less than 1 percent of solid (Shon et al., 2004). So, recycle and reuse of the wastewater could be a promising solution to overcome the potential water demand as water sources available at present are under duress from human intervention including anthropogenic input, reduced rainfall due to climate change, increased water extraction for domestic, agricultural and industrial use.

In this context, to overcome the potential degradation and shortage of water resources and to meet increasingly stringent standards in terms of drinking water, public health and environmental protection, membrane filtration processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis are being applied in wastewater treatment and reuse. However, the biggest problem associated with them is the fouling caused by organic compounds and micro organisms found in wastewater that tenders expensive membrane useless. This means that an appropriate measure to control membrane fouling can provide economical way for wastewater treatment as well as reuse in order to minimize the potential water deficit.

1.5 Composition of the Thesis

This research was carried out with the aim of recycling the secondary wastewater to address the potential water deficit.

Chapter 1 begins with a discussion on fouling of membrane and advantages of pre-treatment prior to membrane filtration. In addition to this, the significance of research is also highlighted in this chapter.

Chapter 2 provides a detailed literature review in order to understand the membrane fouling and the effects of various pre-treatment methods alone or in combination for different kinds of wastewater to be treated. Finally, critical points from previous researches have been reinforced.

Chapter 3 provide details on sample sources and general methodology of pre-treatment and analysis of organic material involved in all experiments carried out in this research.

Chapter 4 presents the result and discussion for various types of pre-treatment ranging from physicochemical to biological process. In some of the cases, the results are also compared with the result from drinking water to establish the comparative efficiency of particular pre-treatment.

Chapter 5 summarizes the achievements of the research along with some suggestions for the future work.

This thesis ends with a list of references.

CHAPTER 2

LITERATURE REVIEW

2.1 Membrane Fouling and Evaluation of Pre-treatment Method

2.1.1 Membrane fouling

The flux reduction due to the accumulation of material on or in the membrane is generally referred as membrane fouling. Fouling is partially reversible when it regains most of its permeability after applying a counter pressure coupled with counter flow, commonly called backwash. However, over the long periods of operation, membrane fouling is generally not totally reversible by the hydraulic backwash procedure. As the number of filtration cycle increases the irreversible fraction of membrane fouling also increases. In order to obtain the desired production flow rates, or flux, an increase in transmembrane pressure is required resulting in reduction of the overall plant capacity limiting wider application of membrane filtration. (Crozes et al., 1997)

In the operation of a membrane system, membrane fouling is dependent on many parameters such as membrane characteristics, source or feed water characteristics, and hydraulic condition of the system. Among them, organic constituents contained in waste water effluent, designated as effluent organic matter (EfOM) such as refractory natural organic matter (NOM), synthetic organic compounds (SOC) and DBP, and soluble microbial product (SMP), are found to play an important role as membrane foulants. (Jarusutthirak et al., 2002)

Regarding membrane characteristics, Cuperus and Smolders (1991) suggested that surface porosity can have a severe impact on flux decline during the actual filtration process as low surface porosity can aggravate the effect of adsorption and fouling. This is due to a large build up of solute near membrane pores. Upon increasing surface porosity, the solute accumulation will be spread more evenly, which also decreases the effect of fouling.

Cuperus and Smolders (1991) further suggested that depending on the molecular structure, membrane surface can contain different types of charged sites. However, even without such special entities, membrane pore surfaces carry a definite charge. Several species that have to be separated by UF, like proteins, are charged too. In such case the performance of the

membrane will be strongly influenced by the interaction between membrane and solute as well. In one study, Jarusutthirak and Amy (2007) also found that EfOM rejection, flux decline, and fouling mechanism depended on the membrane surface charge. Both surface charge and hydrophobicity of the membrane play a significant role in the adsorption of EfOM. Similarly, in one experiment, Yoon et al., (2005) found higher than expected NOM rejection for negatively charged UF membranes although they had larger pore size than the NOM molecular size. The results obtained from this study clearly indicated that NOM and rejection by the UF membranes was controlled by both electrostatic exclusion and hydrophobic interaction.

Nilson and DiGiano (1996) found that hydrophobic NOM caused severe decline in permeate flux compared to the hydrophilic compounds. Crozes et al., (1993) also investigated the effect of membrane hydrophilicity and similarly concluded that hydrophobic compounds appeared as principal foulants. Jucker and Clark (1994) carried out direct adsorption measurements of humic substance on hydrophobic ultrafiltration membranes. They also found a decrease in adsorption with an increase in hydrophilicity. Yoon et al., (2005) found more flux decline with hydrophobic NOM feed water than hydrophilic when using hydrophobic membrane due to hydrophobic adsorption. Shon et al., (2006) found that the flux decline with the hydrophobic was very high compared to the Transphilic and Hydrophilic. The flux decline with the hydrophilic fraction was found to be minimum. However, they suggested extensive experiments. The summary of some studies in terms of hydrophobicity and hydrophilicity is presented in Table 2.1. These studies depict that hydrophobic compounds are mostly responsible for membrane fouling.

Table 2.1: Summary of Membrane performance in terms of hydrophobicity

SN	Membrane Type	Membrane Polymer	Organics Source	Major Foulant	Membrane most affected	Reference
1	Asynetruc UF membranes (Hydrophobic and hydrophilic)	Various	Suwanne River reference humic and fulvic acid	Humic acid>fulvic acid	Hydrophobic, greater porosity and less negatively charged	Jucker and Clark, 1994
2	hydrophobic and hydrophilic	Various	Horsetooth Reservoir and Orange country ground water	Not mentioned	Hydrophobic	Yoon et al, 2005

S N	Membrane Type	Membrane Polymer	Organics Source	Major Foulant	Membrane most affected	Reference
3	UF-Hydrophobic	Polyethersulphone	Horsetooth Reservoir and Orange country ground water	negatively charged carboxylic and phenolic group	Only one tested	Lee et al, 2001
4	hydrophobic and hydrophilic	Acryclic derivativeand cellulose polymer	Strongly and Poorly adsorbable compound respectively Tannic acid and T10 dextran(Pharmica, Uppasala, Swden)	Aromatic compounds	Hydrophobic	Crozes et al, 1993
5	Low pressure MF and UF (hydrophobic and hydrophilic)	Various	Four surface water	polysaccharides, proteins and peptidoglycans enriched in amino sugars	roughness more influential than hydrophobicity	Amy, 2008
6	UF-Hydrophobic and hydrophilic	Polyvinylidene fluoride	Three Australian surface water	High molecular weight neutral	Hydrophobic	Fan et al, 2001

Amy (2008) reported that polysaccharide and protein like NOM represent the most problematical foulants, occurring in both macromolecular and colloidal forms. Protein-like NOM also is manifested in higher DON level while polysaccharide-like NOM is also captured by a higher hydrophilic DOC level. While these foulants are partially amenable to hydraulic reversibility, they adversely affect the feed-water filterability, length of filtration cycle and associated loss of permeability during a cycle.

Rapid membrane fouling occurs at high permeation rates, even under chemical conditions not favourable for fouling such as low ionic strength, low level of divalent cations, and high pH. Moreover, for given chemical conditions, a critical permeate flux exists below which the fouling rate is very low. These observations along with the theoretical analysis, suggest that the extent of NOM membrane fouling is controlled by interplay between permeation drag and

electrostatic double layer repulsion. So, control of permeate flux or transmembrane pressure can be an important strategy for coping with membrane fouling (Hong and Elimelech, 1997).

The improvement of fouling performance in membrane filtration is possible if the organic compound mainly responsible for fouling can be removed prior to the filtration. Different types of pre-treatment methods alone or in combination might reduce the complexity of organic material present in the waste water. There are different ways to remove DOC. In this report, three different pre-treatment methods are analysed in terms of DOC removal as they are the principal foulants of the membrane. The literature review for each analysis is conducted and presented separately in following sections.

2.1.2 Coagulation by Ferric Chloride as Pre-treatment

The coagulation process is usually presented as one dealing with the destabilization of colloidal particles usually of very small size often encountered in water and wastewater treatment (Johnson and Amirtharajah, 1983). Those colloidal particles in wastewater are known to carry an electrical charge in aqueous solution. Most of them carry negative charge. However, the primary charges on the particle are counter balanced by charge in aqueous phase resulting in an electric double layer at every interface between solid and water. The forces of diffusion and electrostatic attraction spread the charge in the water around each particle in diffusion layer (O'Melia, 1972). During this process colloids keep on changing chemically and become able to overcome the forces maintaining the stable suspension, promoting aggregation and the formation of larger particles called floc. Such removal achieved through series of destabilization and precipitation particularly (1) compression of diffusion layer, (2) adsorption to produce charge neutralization, (3) enmeshment in precipitate and (4) adsorption to permit inter particle bridging (Duan and Gregory, 2003; Gregor et al., 1997; Johnson and Amirtharajah, 1983). These mechanisms apply mainly to the removal of colloidal NOM, particularly for larger molecular weight humic acids.

Based on the literature discussed in section 2.1, most of the study found that hydrophobic portion such as proteins, polysaccharides, humic acids are mostly responsible for Membrane fouling. Therefore, coagulation can be used to reduce fouling on membrane as it preferentially removes hydrophobic organic matter present in the water (Liang and Singer, 2003).

According to Slujinski et al., (2000), the majority of NOM exists in its dissolved form and DOC concentration offers a bulk measure of the organic matter present in the water and is commonly used as an accurate estimation of the amount of NOM. These NOM present in the water can be divided in to three fractions mainly humic acid, non polar and non sorbable fractions based on the investigation carried out by Kastl et al., (2004). These three fractions represent three different fraction of DOC. The removal of non polar fraction can be achieved over a wide range of pH while humic acid fraction removal depends upon pH of the water. However, the non sorbable fraction can not be touched by coagulant regardless of pH and increased coagulant dose. The schematic representation of this concept is presented in Figure 2.1 and also described mathematically in equation 1 below. This model is also applied in this research and described in detail in section 4.1.1.7.

$$\frac{DOCsorbable - DOCeq}{D} = \frac{a \times b \times DOCeq}{1 + b \times DOCeq} \tag{1}$$

Where 'DOCeq' is the final concentration of sorbable DOC (mg/L) in water, 'DOC$sorbable$' is the sorbable DOC in water before coagulant addition (mg/L), 'D' is the dose of ferric coagulant (meq/L), 'a' is the maximum DOC sorption capacity (mg/DOC/meq metal) and 'b' is the sorption coefficient (L/mg).

The maximum sorption capacity of floc, a, was assumed to be a function of pH, and the following empirical relationship between them was proposed. (Tseng and Edwards., 1999)

a = $x_3 \times pH^3 + x_2 \times pH^2 + x_1 \times pH^1$ (2)

For the purpose of the model, DOC present in water is assumed to comprise three major groups of compounds (Figures 2.1 and 2.2). The first group is the non-sorbable compounds (DOC$_{nonsorb}$), which are not removed by metal coagulants. The second group comprises humic acid compounds (DOC$_{ha}$) that are adsorbed depending on the concentration of their neutral (associated) form and thus the prevailing pH. The third group comprises the nonpolar compounds (DOC $_{nonpolar}$) that are adsorbed at any pH within range of 4-9 for ferric coagulants and 5-9 for alum. To distinguish between chemically defined compounds and the fractions used in this article, the following convention is used. HAGs, NPGs and NSGs refer to three model compounds: humic acid groups, nonpolar groups and nonsorbable groups. If initial DOC is described as DOC$_0$ then:

$$DOC_{ha,0} + DOC_{nonpolar,0} + DOC_{nonsorb} = DOC_0 \tag{3}$$

Here, the subscript 0 refers to initial conditions.

Figure 2.1: The Conceptual Representation of DOC Fraction in Raw Water (Kastl et al., 2004)
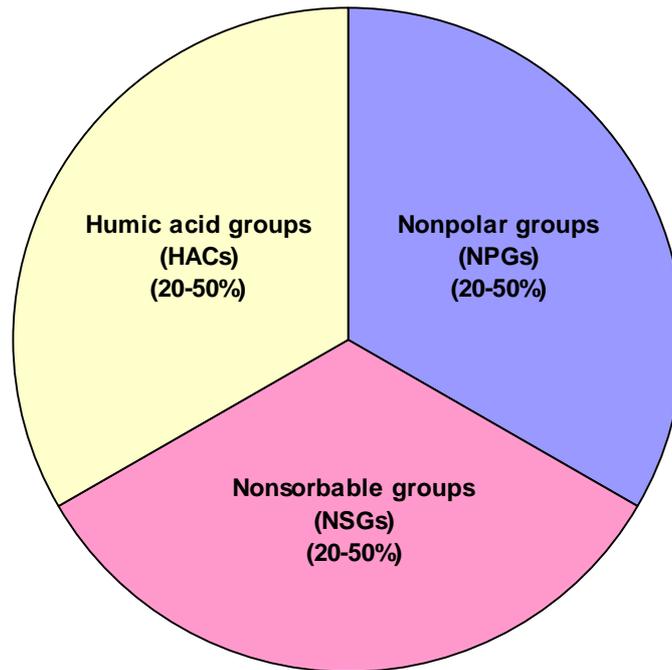
Because only HAG and NPG compounds can be adsorbed, the initial sorbable DOC ($DOC_{sorbable,0}$) can be defined as:

$$DOC_{sorbable,0} = DOC_{nonpolar,0} + DOC_{ha,0} \tag{4}$$

The initial fractions of NPG ($f_{nonpolar}$), HAG (f_{ha}), and NSG ($f_{nonsorb}$) can be defined as follows:

$$DOC_{nonsorb} = f_{nonsorb} \times DOC_0 \tag{5}$$

$$DOC_{ha,0} = f_{ha} \times DOC_0 \tag{6}$$

$$DOC_{nonpolar,0} = f_{nonpolar} \times DOC_0 \tag{7}$$

Figure 2.2: The Conceptualization of Model Fractions (Kastl et al., 2004)
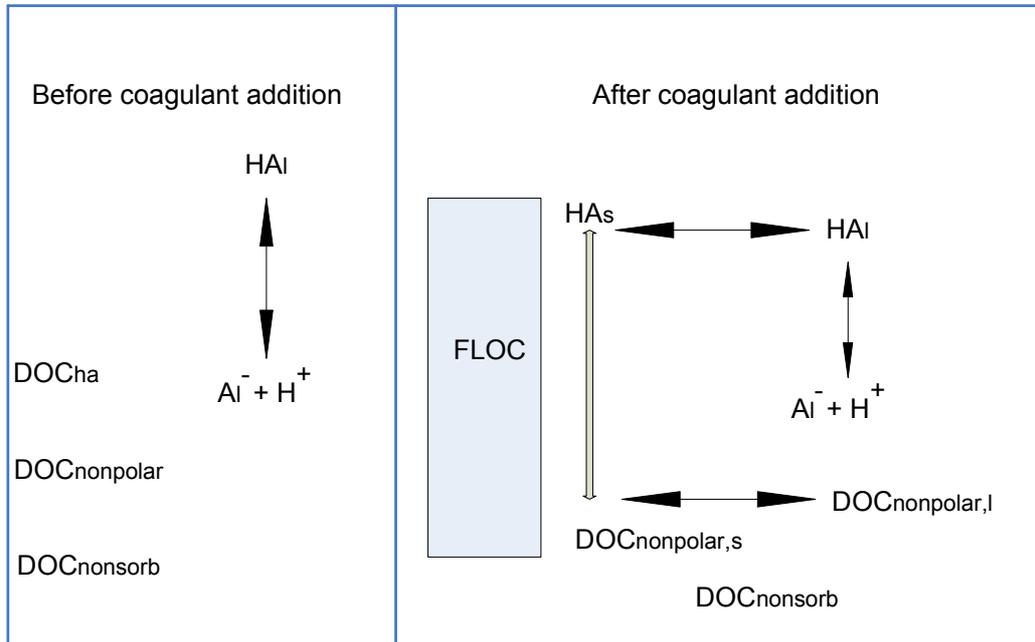
A⁻ ionized form of humic acid (HA) groups (DOCha) that can not be adsorbed, DOC-dissolved organic carbon, DOCnonpolar-DOC in suitable form for removal at any pH, DOCnonsorb-DOC that cannot be removed at any pH, H⁺-hydrogen ion, HA-nonionized (associated) form of DOCha that can be absorbed (subscript 'l' indicates the substance is in water and 's' indicates it is attached to the solid [hydroxide])

Following the study by Tseng and Edwards (1999), variation of DOC in a given source water is assumed to be because of dilution or concentration of these fractions in the same proportion. This implies that even if the DOC of the source water is changed, the fractions $f_{nonsorb}$, f_{ha}, and $f_{nonpolar}$, would be constant for a given source water. This assumption proved satisfactory, and no contraction was encountered in any experimental data. However, if a given source water considerabley changes its characteristics, then a modified set of coefficients may need to be derived from a new set of jar tests. For example, such circumstances could be a major algal bloom, a mix of significantly different water sources, or switching to a significantly different water source, SUVA may provide some guidance on the resulting change of DOC characteristics, but it would be better to relate such variability to local conditions.

The equilibrium between the associated (HA) and dissociated (A⁻) forms of HAGs in water is described by the equation 8;

$$Ka = \frac{[A^-]_l \times [H^+]_l}{[HA]_l} \qquad (8)$$

Here, Ka is the apparent dissociation constant of HAGs and subscript *l* refers to concentration in water.

If [HA]$_s$ and DOC$_{nonpolar,s}$ are the amounts of HAG and NPG compounds adsorbed on to the metal hydroxide floc and DOC$_{nonpolar,l}$ is the equilibrium concentration in water after the addition of metal coagulant, then equations 9, 10 and 11 hold.

$$[HA]_s + [HA]_l + [A^-]_l = DOC_{ha,0} \qquad (9)$$

$$\frac{[HA]_s}{D} = \frac{a \times b \times [HA]_l}{1 + ([HA]_l + k \times DOCnonpolar, l)} \qquad (10)$$

$$\frac{DOCnonpolar,0 - DOCnonpolar,l}{D} = \frac{a \times b \times k \times DOCnonpolar,l}{1 + b \times ([HA]_l + k \times DOCnonpolar,l)} \qquad (11)$$

Here, k is the relative adsorption constant for the nonpolar fraction.

Equation 10 and 11 are similar in form to equation 1, which describes adsorption of a single compound with a Langmuir isotherm. In addition, it has been assumed in equation 10 and 11 that adsorption of HA and DOC$_{nonpolar}$ is competitive.

Further, the maximum sorption capacity is assumed to remain constant across the pH range over which the model was tested (5-9 for alum and 4-9 for ferric coagulants). A minimum of pH of 5 and 4 for alum and ferric coagulants, respectively, was chosen to avoid the issue of floc solubility. The additional complexity required to include floc solubility was not considered worthwhile, as practical enhanced coagulation is well within the range over which the model is valid in terms of its final DOC prediction.

The predicted remaining DOC (denoted as DOC$_{mod}$) can be determined from equation 12:

$$DOC_{mod} = DOC_{nonsorb} + [HA]_l + [A^-]_l + DOC_{nonpolar,l} \qquad (12)$$

Coagulation by ferric salt has been widely and extensively investigated for the removal of natural organic matter (NOM) in water treatment (Shin et al., 2008). The removal of organic matter has become increasingly important in light of its potential to form carcinogenic DBPs (Hu et al., 2006) and to reduce in membrane fouling (Shon et al., 2006). As these primary organic compounds influencing coagulation, humic substances and their removal by coagulation has attracted extensive interest (Kazpard et al., 2006).

The US Environmental Protection Agency (USEPA) Disinfectants/DBP (D/DBP) Rule of 1998 mandates that utilities remove pre-determined concentrations of total organic carbon (TOC) as a means to reduce DBP precursors (USEPA, 1998) and identifies enhanced coagulation as the best available technology for drinking water treatment.

In one study Shon et al., (2004); it has been found that pre-treatment with flocculation followed by adsorption resulted in the highest flux improvement and total organic carbon (TOC) removal of more than 90 percent. With the same combination Habercamp et al., (2007) found largely enhanced removal of biopolymers from the secondary effluents. Hence simultaneous coagulation and adsorption yields the superposition of the individual elimination rates in terms of biopolymer removal.

Vilg-Ritter et al., (1999) in one experiment found that all floc formed with ferric chloride were enriched in polyhydroxy aromatics. They also found selectivity of ferric salt toward polyhydroxy aromatics in the clarified water and removed them preferentially. Similarly, Vrijenhock et al., (1998) found that percent reduction in UV254 is higher than the corresponding reduction in TOC which is consistent with the previous findings suggesting that humic substances are removed more effectively by chemical coagulation (Edzwald et al., 1985).

Similarly, White et al., (1997) also tested the effect of hydrophobic-hydrophilic content on coagulation of NOM. They found that waters with relatively high amounts of hydrophobic organic material exhibit higher degrees of organics removal than those with low hydrophobic content. In addition to this, they also found DOC removal tended to be slightly higher than the hydrophobic DOC content of the water indicating some hydrophilic portion was also removed by coagulation. However, the majority removed DOC was hydrophobic DOC.

SWWE contains wide range of compounds measured in terms of DOC of both high and low molecular weight (MW), such as humic acids and fulvic acids, polysaccharides, proteins, nucleic acids, organic acids, enzymes and structural components of cells (Barker et al., 2000). This means it contains high concentration of aromatic and hydrophobic fractions. On this ground, coagulation as pre-treatment can greatly enhance the membrane performance by taking hydrophobic portion away from wastewater before sending it through the membrane.

2.1.3 Biologically Activated Carbon as Pre-treatment

The Biological Activated Carbon (BAC) process, which has been developed in the 1970s, has been extensively used for the removal of dissolve organics from water and wastewater. It is generally believed that bacteria, which proliferate in BAC filters, may be responsible for fraction of the net removal of organics in the filter. In this process, beds and pores of carbon are utilized as a habitat for bacteria by providing organic matter in water and wastewater as a source of nutrient for them. Initially, most of the removal occurs through physical adsorption while the bacteria colonize the BAC surface. This phase is considered as first stage. Then during the second stage biological activity increases and physical adsorption process gradually decreases and reaches a steady stage 3. During this stage major removal of organic matter occurs by biological oxidation because of already acclimatized bacteria in the BAC bed. It means adsorption and biodegradation of organic matter occurs in the BAC bed at the same time with significant amount of biomass growth; giving long operating life for the carbon. (Dusset and Stone, 2009; Xiaojian et al., 1990). The long operating life is achieved mainly due to the following mechanisms that occur in BAC process.

1. Micro organism can be utilized to regenerate the activated carbon while the carbon bed is in operation (Perrotti and Rodman, 1974; Rodman et al., 1978; Rice and Robson, 1982)
2. Adsorption of less biodegradable organics on the carbon and degradation of micro organism can occur simultaneously (Weber and Ying, 1977; Rice and Robson, 1982)
3. Biological reaction rates become higher on activated carbon due to an enrichment of organics by carbon adsorption (Weber and Ying, 1977; Ying and Weber, 1979)

The major advantage of BAC process is low capital cost, with lower energy requirements and operating cost. It minimizes the waste load applied to subsequent physiochemical treatment

process (Ying et al., 1979). This is mainly achieved due to the regeneration of activated carbon by bacterial bio film (Walker and Weatherley, 1999).

Bio-regeneration is defined as an increase in adsorptive capacity resulting from bacterial removal of material adsorbed on carbon. Biodegradation of compounds in bioactive BAC columns may occur even through the compounds have not been adsorbed and this may increase the useful life of the column (Chudyk and Snoeyink, 1984). Similarly, Saito et al., (1996) suggested that, granular activated carbon (GAC) can supply adsorbed substances to the attached bacteria without releasing them to bulk liquid. They also suggested the possibility of enhancing the attached bacterial activity.

The empty bed contact time (EBCT) is one of the major governing parameter for the removal of organic matter in BAC process. This time should be selected based on the treatment objectives, required effluent quality, temperature and so on. EBCT can be varied by manipulating bed depth and flow by making one parameter constant while varying the other. This is discussed in detail in result and discussion in third section of chapter 4.

EBCT is obtained by dividing bed volume by the superficial flow rate of the fluid stream through the adsorber. Adsorber volume depends on bed volume and volume of freeboard or excess vessel capacity over bed volume. Freeboard may range up to about 50 percent for fixed bed and expanded bed system. If bed expansion is not required, even with backwashing to remove collected solids, a freeboard of 20-30 percent may be adequate. Virtually no freeboard is required for upflow pulsed beds. With the given EBCT, the required volume of carbon can be calculated as follows. (Boonathanon, 2000)

$$V = (Q \times EBCT)$$

Where,

V is volume of activated carbon required (m^3)

Q is rate of water flow (m^3/s)

EBCT is empty bed contact time (s)

The success of biological filtration requires that the amount of bio mass be carefully managed during the filtration cycle and that bio mass losses during backwashing be controlled. Because bio filters accumulate both biological and non-biological particles, the difference in the

detachment of these groups of particles during backwashing will influence the optimization of backwash strategies for bio filters (Urfer et al., 1997). BAC process removes some of the suspended solids and large debris that may have been entrapped on the top layer of the bed. In addition to this, it can be useful to lift the media if compaction has occurred and to remove unwanted protozoa that prohibit the bacterial growth while using wastewater in this process. However, Hoang et al., (2008) in one experiment did not find any significant effect on the organic removal efficiency of the filter even with daily backwash to avoid the physical clogging of the bio filter.

Urfer et al., (1997) considered temperature also as an important parameter in BAC process. Biodegradable organic matter in bio filters is expected to increase at higher temperature as both microbial kinetics and mass transfer are more rapid at higher favourable temperature.

In one experiment, Ying et al., (1979) found that removal of biologically resistant compounds that may be carcinogenic by adsorption and biological removal of low-molecular weight oxygenated compounds that would otherwise be partially removed by activated carbon alone. They also found extended carbon service cycles and reduced carbon exhaustion rates resulted in reductions in associated regeneration costs and energy utilization. Similarly, Tsuno et al., (2006) found that the organic compounds like phenol and tetrachloroethylene are strong in adsorption on activated carbon and removed well and stably at a removal efficiency of more than 99.9 percent. In addition, the compounds, which are weak in adsorption such as chloroacetaldehyde are also removed very efficiently at around 98 percent. This shows that BAC process is also useful for the treatment of wastewater containing hazardous chemicals as well as readily degradable organic substrate.

Kim and Kang (2008), showed that 99 percent removal of halo acetic acid (HAA_5) was achieved even after 6 months of operation, which is mainly due to biodegradation on the surface of activated carbon. They found BAC process efficient in terms of turbidity as well.

Kelvens et al., (1996) studied the Ozone/BAC filtration process and found that effective in reducing specific NOM fractions which contributed to significant reductions in the formation of DBP's, chlorine demand, UV254, and biodegradable dissolve organic carbon (BDOC). NOM fractions, amenable to the removal by bio filtration, were smaller (3k amu), hydrophilic compounds. Biodegradable substrate was increased by ozonation but significantly reduced

through 5 and 10 min contact BAC filters, such that most readily available substrate was removed. Remaining BDOC in filter effluent was comprised of more slowly biodegradable compounds compared to the raw water influent. Direct GAC filtration of raw water performed similarly as BAC filtration of ozonated water in the removal of TOC, UV254 and BDOC. However, chlorine demand and DBP formation were unchanged by GAC. Most readily biodegradable organics in ozonated water were consumed within first 5 min contact in BAC filters.

Similarly, many authors reported that powdered activated carbon (PAC) addition to a membrane bioreactor (MBR) system improved the organic removal efficiency. Pirabazari et al., (1996) coupled the MBR with PAC and found improvement in organic removal efficiency by the adsorption of the less-biodegradable organic compounds. The effect of PAC on the performance of aerobic MBR was investigated under cross flow and submerged condition by Kim and Lee (2003). They found the permeability in membrane was enhanced by more than 35 percent in cross flow bio reactor. It was more pronounced for submerged system resulting significant decrease in transmembrane pressure.

BAC process was also found to be highly effective to remove carcinogenic DBPs. Asami et al., (2009) found a significant reduction in nitrosodimethylamine (NDMA) by BAC treatment. Despite the hydrophilic nature of NDMA, they found more than 90 percent removal during this process. This indicates that biological degradation plays more role than adsorption to reduce NDMA. Hence, use of as BAC as pre-treatment can possibly work effectively to reduce both organic and bio fouling in the membrane and at the same time reduce NDMA.

So, these multidimensional features ranging from adsorption of aromatic compounds to biodegradation of hydrophilic compounds suggest, effective use of them might be highly useful to achieve optimum flux condition when used with membrane filtration system as pre-treatment. Some literatures also suggests the reduction on flux decline when BAC is used as pre-treatment. In one study Tsujimoto et al., (1998) found GAC treatment as an effective measure to prevent irreversible fouling and continuous stable operation with minimum frequency of chemical cleaning. Similarly, Chinu et al., (2009) found GAC bio filter as an effective pre-treatment to reduce fouling on RO membrane by reducing significant amount of organic matter. Similarly, Shon et al., (2004) investigated various pre-treatment methods alone or in combination. On doing so, GAC as bio filter resulted in improving the flux decline.

Similarly, Shon et al., (2005) used GAC filtration in combination with Floc-Ads and found to be effective in removing the hydrophobic fraction with reduction of membrane fouling.

2.1.4 MIEX® as Pre-treatment

The MIEX® resin is micro sized, macro porous, strong base, magnetic ion exchange resin, developed for the reversible removal of negatively charged organic ions. Those negatively charged DOC is removed from water by exchanging it with a chloride ion on the active sites on the resin surface (Hammann et al., 2004). Anion exchange effectively removes DOM from solution. It employs a different separation mechanism from other physicochemical techniques that rely on hydrophobic interactions, such as carbon adsorption, hydrophobic resin adsorption and coagulation (Tan et al., 2005).

The MIEX® resin was specifically designed and developed for the removal of DOC from drinking water supplies. In addition to the strong base reactivity, this resin has a macro porous structure made from a moderately cross-linked acrylic skeleton, which contains quarternary amine functional groups that provide the charged sites (Budd et al., 2001). As the name suggests, MIEX® resin particles include a magnetic component incorporated into its polymeric structure. This allows weak individual resin beads to rapidly agglomerate into larger, fast-settling particles when mixing is stopped (Hammann et al. 2004). Superior drainage system of treated water and regenerantion can be achieved (Nguyen et al. 1997).

Figure 2.3: Chemistry of DOC Exchange
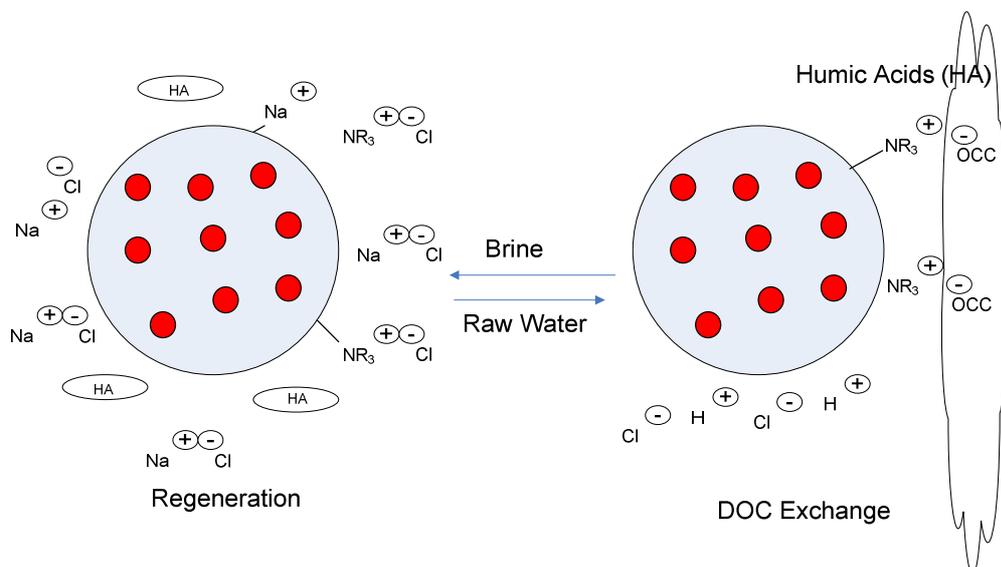
Slunjski et al., (2000) stated that, DOC removal by ion exchange resins is based on the character of humic substances weak organic acid and the process is reversible and considered as its main advantage over other DOC sorption process as shown in Figure 2.3. Further, DOC sorption part of the exchange cycle is based on the high affinity of anionic resins for DOC. This allows DOC to be removed from raw waters containing low levels of DOC and other naturally occurring anions.

Similarly, Hamm and Bourke (2002) explained that the MIEX® DOC resin beads are much smaller than conventional resin beads, at around 180 microns, which provides much greater surface area. These characteristics provide a high DOC exchange capacity and rapid exchange kinetics, resulting in very low resin concentrations (0.4-2.0 percent vol/vol) being required to achieve the desired DOC removal during a 10 to 30 minute contact time.

MIEX® is very effective pre-treatment to get rid of organic carbon up to some extent as it can take both hydrophilic and hydrophobic organic matters from the water (Son et al., 2005). In one experiment Moran et al., (2004) investigated MIEX® in combination with coagulation and found more DOC removal than enhanced coagulation removed. In addition to this, they also found that MIEX® treatment resulted in significant decrease in coagulant dose up to 75 percent. Similar results were obtained when same combination was investigated by Fearing et al., (2004).

Fabris et al., (2007) investigated the combination of MIEX® and coagulation using alum salt as pre-treatment before sending water through MF membrane. They found that reduced the majority of bulk water DOC of all molecular weight ranges; including colloidal (Very high MW) material, which successfully prevented short term fouling of micro filtration. MIEX® is highly effective in removing UV absorbing substances and DOC in raw waters with a high SUVA. The removal of these compounds was much higher when compared with alum coagulation (Boyer et al., 2005). From the literature review in previous section, UV absorbing hydrophobic part is highly responsible for membrane fouling with some share to hydrophilic part as well. In this context the pre-treatment combination of MIEX® with coagulation might be highly effective to reduce the fouling in membrane.

The improvement of fouling performance in membrane filtration is possible if the organic compound potential for fouling can be removed prior to the filtration. Different types of pre-

treatment method alone or in combination with proper investigation might reduce the complexity of organic material present in the wastewater. Some literature reviews provided clues and concepts regarding the fundamentals of fouling and effective pre-treatment method as listed below.

1. Dissolved Organic Carbon mainly hydrophobic portion of them is highly responsible for membrane fouling.

2. Polysaccharide and protein like compounds present in the wastewater appears as problematical foulants occurring in both macro molecular and colloidal forms.

3. Sequential removal of organic compound from the wastewater prior to the membrane filtration can improve the performance of membrane.

4. BAC process can effectively be used to adsorb high molecular weight hydrophobic organic compounds and also can be used to convert some hydrophilic portion by biodegradation.

5. Combination of pre-treatments like BAC process and coagulation can remove both hydrophilic as well as hydrophobic portion and the efficiency of coagulant can be increased significantly when used in combination.

6. Activated carbon might be partially regenerated biologically and bacteria can be utilized as to take organic carbon as the source of nutrient for them.

7. BAC process might be helpful to reduce organic fouling and hence reducing the overall wastewater treatment cost. In addition, it removes BDOC making it a strong candidate to reduce bio fouling on membranes.

8. Pre-treatment like coagulation can be used in combination with BAC to get higher efficiency in terms of DOC removal and membrane fouling

CHAPTER 3

SAMPLE MANAGEMENT AND METHODOLOGY OF ANALYSIS

3.1 Sample Sources, Collection and Preservation

3.1.1 Description of the studied system

The secondary wastewater effluent from Beenyup wastewater treatment plant (BWTP) was used in the course of the study period. In addition to this, wastewater from Woodman Point Wastewater Treatment Plant (WPWTP) was also used for the investigation to find the consistency in the experiment results. The BWTP serves Perth's rapidly developing northern suburbs from Quinns Beach through to Scarborough and inland through Dianella and Bayswater to the foothills east of Midland. It is an advanced secondary treatment plant with current capacity of 120 million litres per day with a target to treat 200 million litres per day which can serve a population of 1.1 million people. The wastewater is predominantly coming from household kitchens, bathrooms toilets and laundries. Wastewater entering the plant contains more than 99 percent of water.

The BWTP uses an advanced secondary treatment process incorporating a conventional activated sludge process with biological nutrient removal (Figure 3.1). The primary treated wastewater is blended with the microbiological biomass, to form mixed liquor in reinforced concrete aeration tank. The diffused air is applied to provide oxygen for the microbiological process that breaks down the organic compounds in the primary treated wastewater. Then, biologically active sludge that settles in these tanks is continually removed and returned to the aeration tanks to sustain microbiological population there and the overflow from the sedimentation tanks is the final treated secondary wastewater. While at Woodman Point, it is first aerated before being settled. The settling allows the purifying micro organisms to settle to the bottom of tank and clean, treated wastewater is then decanted from the top (Figure 3.2).

Membrane filtration has been used for further treatment of wastewater effluent at both Beenyup and Woodman Point wastewater treatment plant by Water Corporation. While BWTP will recycle water to recharge the aquifer for future use, WPWTP recycles it for industrial use.

Figure 3.1: Flow Chart for Beenyup Wastewater Treatment Plant

Odour
Control

North Whitford
Branch Sewer

Ocean
Disposal

Hammersley
Main Sewer

Secondary
Wastewater

Step
Screen

Grit Tanks

Primary Sedimentation
Tanks

Aeration
Tanks

Ground Water
Replenishment

Burns Beach
Main Sewer

Liquor

Liquor

Grit

Returned
Activated
Sludge

Secondary
Sedimentation
Tanks

Screening
Wash
Presses

Grit
Washer

Raw Sludge

Screenings

DAFT Effluent

Dissolve Air
Flotation Thickness
(DAFT)

Screenings to
Landfill

Grit to
Landfill

Thickened Excess
Activated Sludge

Centrate

Centrifuges

Anaerobic
Digester

Biosolids
Benificial Use

Figure 3.2: Flow Chart for Woodman Point Wastewater Treatment Plant
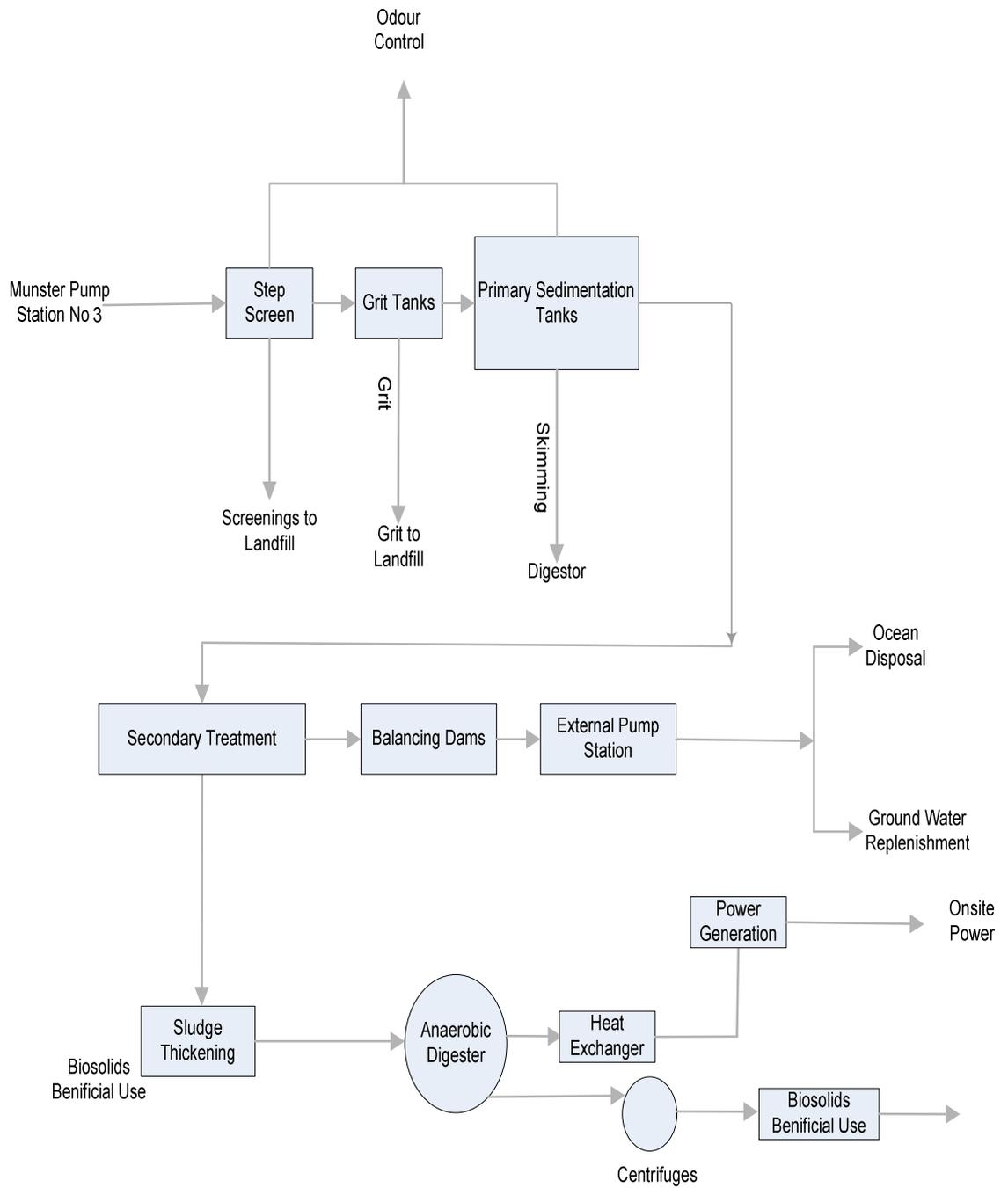
However, both plants have experienced membrane fouling particularly organic and bio fouling leading to increase in operation cost. Organic foulants could cause both reversible and irreversible fouling. Although reversible fouling can be backwashed, increased frequency of backwashing does increase operation cost and decrease production while irreversible fouling deteriorates expensive membrane and makes them useless. So, there lies a challenge to identify and reduce foulants or condition causing irreversible fouling.

3.1.2 Sample Collection, Storage and Preservation

Most of the samples used for the investigation in the laboratory were secondary wastewater obtained from BWTP prior to membrane filtration. Similarly, wastewater sample of WPWTP was collected for the verification of few conclusions made in BWTP. The samples were collected in 20 litre black plastic containers with air tight plastic cover. Collected samples were immediately transported to the laboratory and preserved in refrigerator at 4°celsius and kept intact except for sampling and analysis. Samples were used both by acclimatizing to room temperature by leaving for 24 hr at room temperature of around 25°celsius or used straight away for the analysis based on the nature of experiment. The samples were collected on a regular basis from the wastewater treatment plant based on the requirement for the reactor and other experiment to avoid the storage for long time.

3.1.3 Virgin MIEX® Sampling

The MIEX® resin was delivered in slurry form in a plastic container. The plastic container contained approximately 90% resin and 10% carrier water by volume. MIEX® doses were manipulated firstly by vigorously shaking the plastic container and then filling 10ml glass graduated cylinders with the slurry. The slurry was given sufficient time to settle, afterwards a specific dose was executed by withdrawing resin from the graduated cylinder with a plastic syringe and ejecting into bulk water.

3.2 Methodology of Pre-treatment

3.2.1 Jar Test

Jar test was particularly carried out to investigate the effect of coagulation and MIEX® pre-treatment. Lovibond® jar tester with six stirrers was used to mix the sample. The experiment was conducted on two-litre glass beaker.

Coagulation and Flocculation

The coagulation flocculation was carried out using Ferric Chloride ($FeCl_3.6H_2O$) salt at seven different predetermined doses. The dose of Ferric Chloride varied from 1.25mg/L to 160mg/L. The pH was adjusted using Sodium Hydroxide and Sulphuric Acid. Afterwards, samples were put on Jar Tester and stirred at 200 RPM for first two minutes followed by 20 RPM for another 20 minutes. The pH was also recorded just before mixing and during the mixing. Then, these samples were allowed to settle for 30 minute before filtration and measurements.

MIEX® Resin Pre-conditioning and Wastewater Treatment

The virgin MIEX® resin was first preconditioned with secondary wastewater from BWTP in order to remove any contaminants present in the virgin resin from the manufacturer and also to ensure its similar 'contact age' to resin being repeatedly used in real batch process. To simulate the treatment conditions of the MIEX® treatment process of the Beenyup wastewater, Jar Test protocol developed by Orica Advanced Water Technology was performed (Hamilton, 2007). The summary of the preconditioning process is described in detail below. Based on that, resin contact time was considered 15 minutes with 42 ml of MIEX® used to treat 1litre of water. The regeneration rate was assumed 5 percent. This means

42 ml of MIEX® used to treat 1litre water

Therefore, Bed Volume (BV) = $\dfrac{1*1000ml}{42}$ = 23.8

Regeneration rate = 5%

Using this regeneration rate, the number of BV can be treated by the same MIEX® resin before regeneration required can be calculated as follows

Number of Bed Volume = $\dfrac{23.8}{0.05}$ = 476 BV

Therefore 476 BV of raw water can be treated by the same 42 ml of MIEX® resin until regeneration is required.

Figure 3.3: Flow Chart of the Pre-treatment Investigation
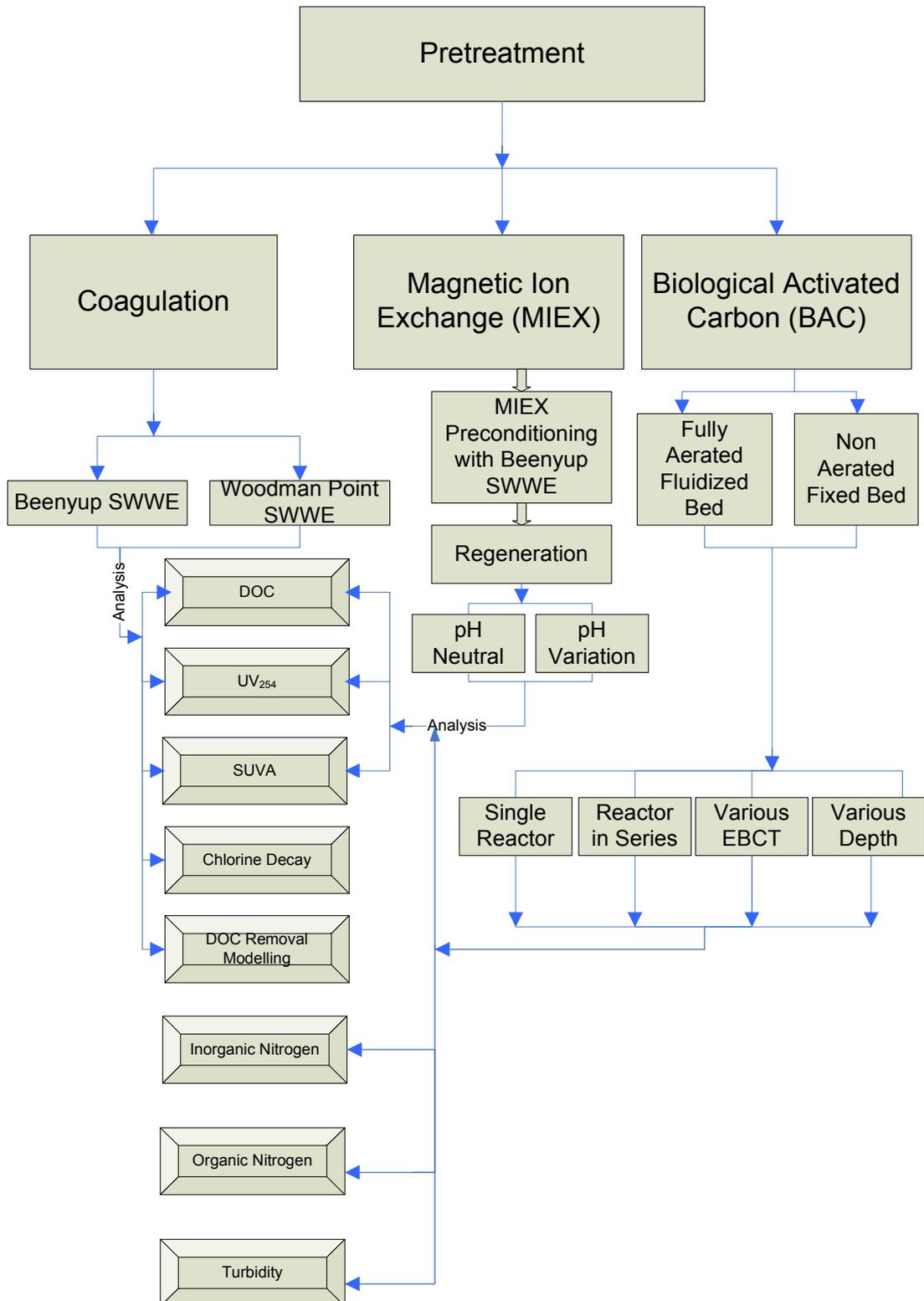
The total BV can be converted to volume of water

Volume required for preconditioning = Number of Bed Volume/ Bed Volume

$$= \frac{476}{23.8}$$

$$= 20 \text{ L}$$

This means 42 ml of MIEX® needs 20L water for preconditioning

$$100\text{mL of MIEX}^{®} \text{ needs } \frac{20}{42} *100 \text{ L}$$

$$= 47.62$$

$$\sim 50 \text{ litre of water}$$

6 Jars were employed for preconditioning. This means,

$$\text{MIEX}^{®} \text{ in each Jar} = \frac{100}{6} = 16.7\text{ml}$$

$$\text{Water Required for each Jar} = \frac{50}{6} = \sim 8 \text{ L}$$

So, wastewater from BWTP was stirred in a 2L beaker with Virgin MIEX® resin (16.7ml) for four times (2*4 =8 for one jar) for preconditioning. Water was decanted after mixing for 30min. Then this process was repeated 3 more times. The same procedure was applied to five MIEX samples of 16.7ml, before regenerating all of these with NaCl. In this way, roughly same contact time was managed as 42ml of MIEX® when mixed with 1L of water for 20 times as per orica protocol. Then the all MIEX® from the six jars was collected in one jar to add 600ml of 10 percent aqueous Sodium Chloride solution. Then again it was mixed for 30 minutes and allowed resin to settle after mixing. Then the Sodium Chloride solution was decanted again and 600ml deionised water was added to MIEX® and stirred it for 10 min. After this, DI water was decanted and settled resin was collected to use for the experiment.

During all the process of preconditioning and wastewater treatment the mixing was done at 150 RPM. The MIEX® dose was investigated for five different doses ranging from 2 ml/L to 32 ml/L. In addition to this, pH was also varied and tested within the pH range from 4 to 9. The pH was also recorded during the time of mixing. After mixing for 20min resins were allowed to settle and filtered before testing.

3.2.2 Biological Treatment Process using Continuous Reactor

Biologically Activated Carbon filter column was used as continuous reactor in different mode. The reactors were designed with three ports; for feeding wastewater, feeding air (in fully aerated reactor) and outlet for collection of BAC effluent. Columns of diameter 3.9 cm were taken for all reactors. The GAC used in the experiments was washed with DI water for several times and dried in an oven at 105 degree centigrade for 24 hour to ensure all the GAC is free from ashes and other impurities by making it benign before use. Then the temperature was adjusted to room temperature before packing in to columns. Two different configurations of reactors basically fully aerated and non aerated columns were used for the study. Only single column was designed for fully aerated reactor while more than one columns were used in series for non aerated reactors which are discussed in the following section.

3.2.2.1 Fully Aerated (Reactor Set 1)

This column was packed using 120cubic cm activated carbon with 10 cm depth. The flow was maintained accordingly to achieve 20 min EBCT using peristaltic pump with variable speeds. Both air and water were fed from the bottom of the reactor to ensure the sufficient amount of oxygen in the feed water. Upward flow mode was used and treated water was collected from the upper outlet of the reactor. Secondary wastewater effluent from BWTP was used throughout the process and operated in continuous mode. The summary of this reactor is also presented in table 3.1.

Figure 3.4: Fully Aerated (Reactor Set 1)
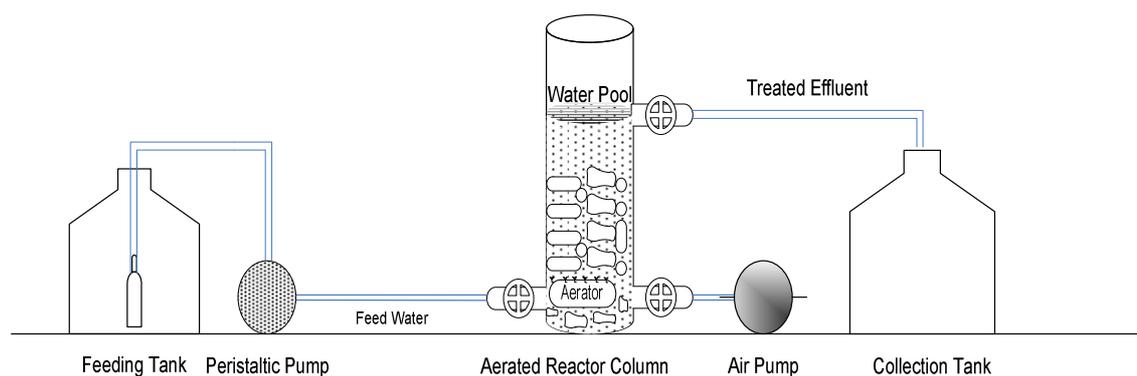
3.2.2.2 Reactor in Series (No air feeding)

This set of experiment was designed by connecting two or three reactor columns in series. Three different bed depths were investigated for same bed contact time. All the reactors were operated in continuous mode. The bed depth of all columns was kept equal for an individual

reactor set to maintain the same bed contact time throughout the series with same amount of flow. The peristaltic pumps with variable speeds were used to feed secondary wastewater from feeding tank to the first column. Then gravity flow was designed to carry the water from one column to another until reached the final BAC effluent collection tank. The water from one column to another was fed drop by drop from a sufficient height to allow water drops in contact with sufficient amount of oxygen as shown in Figures 3.3, 3.4 and 3.5. For all non aerated reactor columns secondary wastewater was fed from the top and treated water was collected from lower port placed at the bottom of the column. To ensure the full contact of water molecules with the bed of activated carbon effluent was extracted from the height of 1 cm above the upper BAC level of the column using plastic pipes connected to the bottom outlet port of the column. In this way equal bed contact time was constantly maintained in all columns throughout the series. Altogether, three sets of reactor were operated in series which are explained in detail below.

Low Depth (Reactor Set 2)

In this set, two BAC columns referred as Rc and Rd were connected in series. Each column was packed up to 5cm depth with 60 cubic cm of activated carbon. The EBCT for this series was maintained 20 minute throughout all the time of operation for all columns in series. The summary of basic features of all reactors is presented in table 3.1.

Figure 3.5: Low Depth (Reactor Set 2)
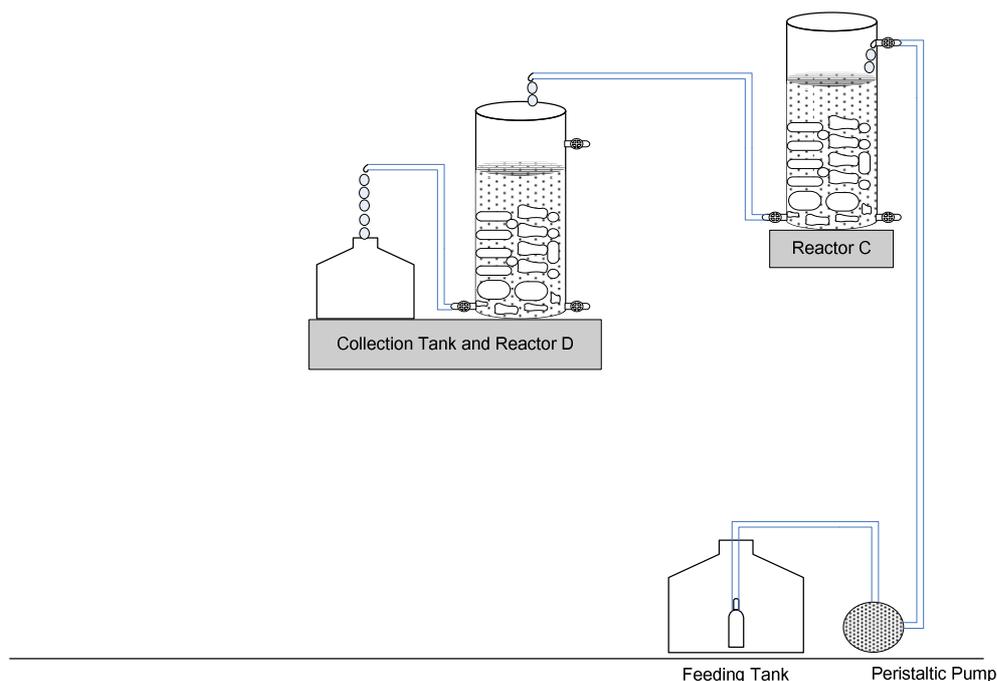
Medium Depth (Reactor Set 3)

Three columns; R1, R2 and R3 were connected in series for this third set of reactors. The entire columns in this reactor set were packed up to 10 cm with 120 cubic cm of activated carbon. The bed depth and amount of activated carbon in this set was kept double than low depth reactor set. This set was also operated at EBCT of 20 minute throughout the investigation for all columns. The summary of this set is also presented in table 3.1

Figure 3.6: Medium Depth (Reactor Set 3)
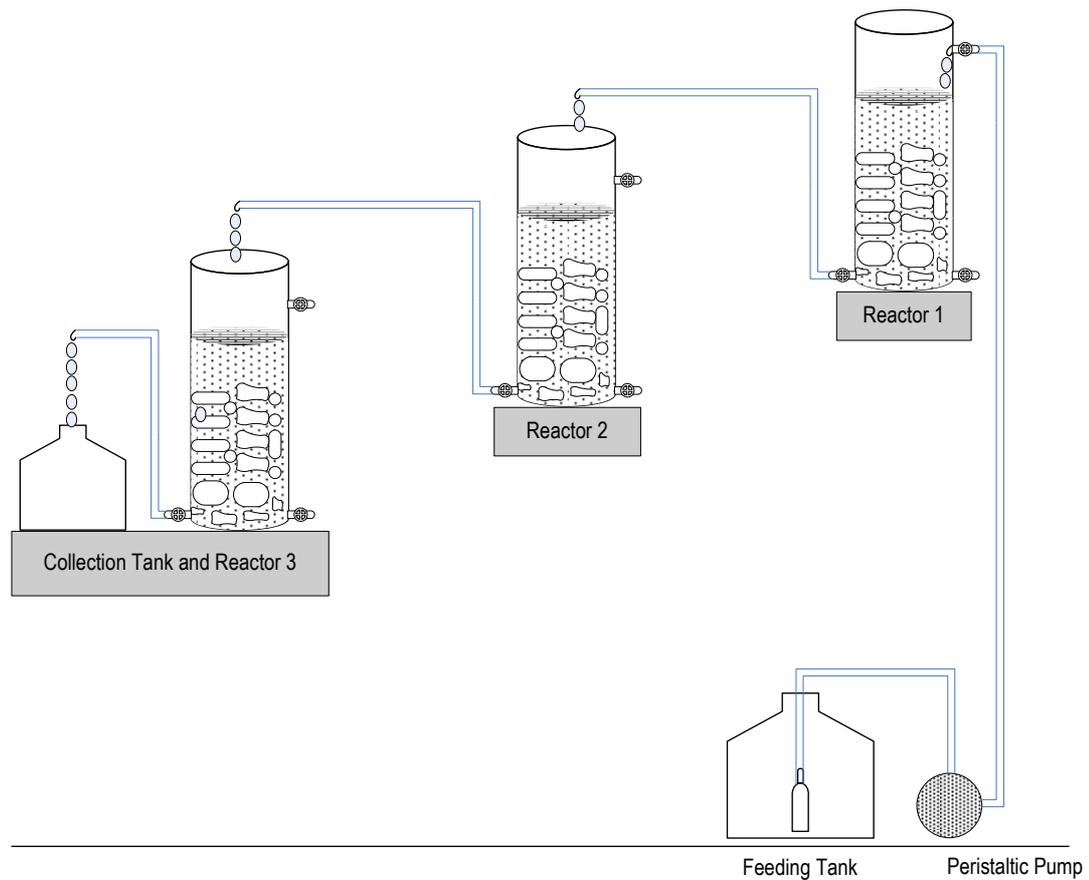
High Depth (Reactor Set 4)

Like in low depth reactor set, two BAC columns Ra and Rb were connected series but the column was packed up to 15 cm depth with 180 cubic cm of activated carbon, which was 3 times higher than the low depth reactor. The EBCT for this series was maintained 20 min for the first month and changed to 40 minutes for all the columns to see the effect of bed contact time in removal of organic matter from the wastewater. The features of this reactor set are summarized in table 3.1.

Figure 3.7: High Depth (Reactor 4)

Reactor A

Collection Tank and Reactor B

Feeding Tank   Peristaltic Pump
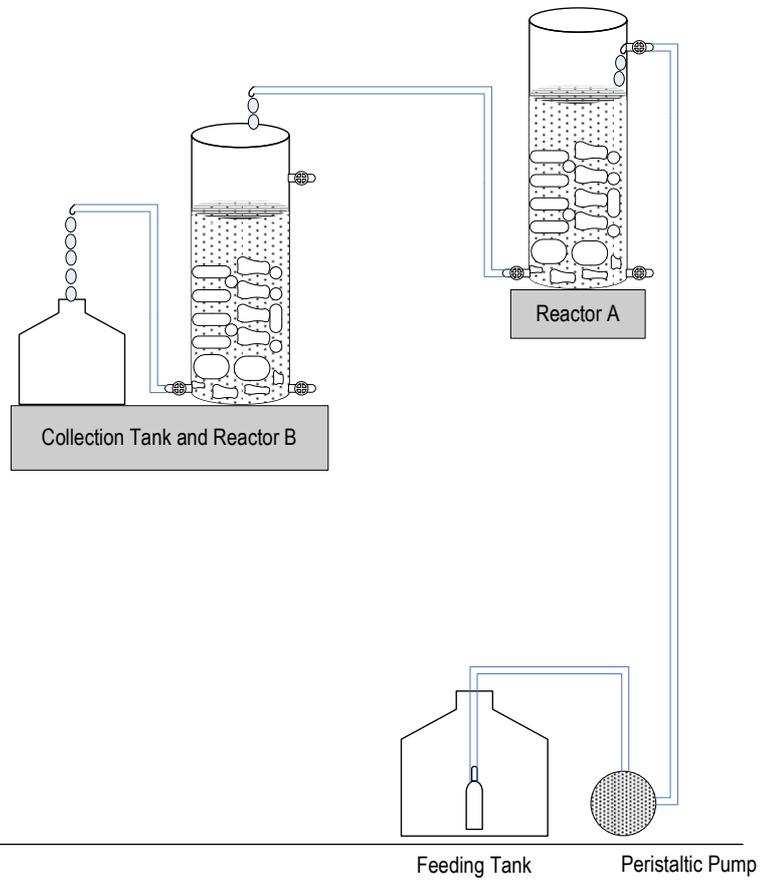
Table 3.1: BAC Reactor operating condition

SN	Reactor	Bed Depth (cm)	Bed Volume (Cubic cm)	EBCT (min)	No. of column used	Operating mode
1	Fully Aerated (Reactor Set 1)	10	120	20	1	Continuous
2	Low Depth (Reactor Set 2)	5	60	20	2 (Rc, Rd)	Continuous
3	Medium Depth (Reactor Set 3)	10	120	20	3 (R1,R2,R3)	Continuous
4	High Depth (Reactor Set 4)	15	180	20/40	2 (Ra, Rb)	Continuous

3.3 Analytical Measurements

Three parameters mainly DOC, Ultraviolet Absorbance at 254nm (UV254) and Specific UV Absorbance (SUVA) were measured for all the samples. SUVA was obtained by dividing UV by DOC. In addition to this, turbidity test was also carried out in some experiments. Effluent from the BAC was tested for ammonia, nitrite and nitrate and Dissolve Oxygen (DO) as well.

During the experiment, pH was measured using a Hach pH meter. Turbidity was measured using Hach 2100p turbidity meter and DO in the BAC effluent was measured using Hach DO meter. Similarly, DOC was measured using 5310C laboratory Total Carbon Analyser connected to auto sampler. The instrument measures Total Carbon (TC) an Inorganic Carbon (IC) and subtract IC from TC to determine DOC. As samples were analysed after filtering through the 0.45μm pre-washed Cellulose Acetate (CA) filter paper, the measured value are itself in DOC value. This machine use UV persulphate oxidation for the measurement of DOC. This instrument has an analytical range of 30 parts-per-million to 50 parts-per-million and utilizes SM5130 for USEPA compliance monitoring of raw and finished drinking water. It has only 5 percent error in measurement. UV absorbance was also measured using Helios Gamma Spectrophotometer (Thermoelectron) and measured by filtering the sample from 0.45μm CA filter media. The optical design of this instrument is single beam Seya Namioka monochromator and gives only 0.05% error in measurement. In addition to this, Aquakem 2000 was used for the measurement of ammonia, nitrite and nitrate of the sample. Aquakem is fully automated instrument which provides convenient automated photometric analysis of water sample. It performs analysis on optical multi-cell cuvette that provides true discrete analysis. So, the sample reacts with reagent first and develops a colour and it gives a result based on the photometric absorbance of that particular colour. This instrument can efficiently detect 3μg/L ammonia and nitrate and 0.25μg/L nitrite in the sample. The error on measurement of ammonia, nitrite and nitrate for this instrument is 1.5% on 95% confidence level. The maximum error for this instrument is only 2%.

For the pH variation during the coagulation and MIEX® treatment experiment, sulphuric acid and sodium hydroxide were used. Stock solution of 2M and 1M respectively was prepared and dosed in to the sample using micropipette.

CHAPTER 4

WASTEWATER PRE-TREATMENT INVESTIGATION

4.0 General

Wastewater reuse is increasingly acknowledged as an essential strategy for compensating the limited freshwater, and as means of preventing deterioration in the aquatic environment from wastewater disposal (Shon et al., 2005). However it is not an easy task as SWWE contains wide range of compounds measured in terms of DOC of both high and low molecular weight such as humic acids and fulvic acids, polysaccharides, proteins, nucleic acids, organic acids, enzymes and structural components of cells (Barker et al., 2000). Although, membrane can take all these impurities away from the wastewater by giving desired water quality level, its performance is affected greatly from fouling as secondary wastewater contains broad range of organic material. So, removing DOM from the wastewater prior to the membrane filtration can significantly reduce the membrane fouling by increasing the life of the membrane. For this pre-treatment of secondary wastewater is highly effective as it can effectively remove broad range of organic compounds.

4.1 Coagulation and Flocculation as Pre-treatment

DOC is principle membrane foulant and responsible for carcinogenic disinfection by product. At the same time, most organic compounds are found to be amenable to coagulation by hydrolysing metal salt. So, coagulation by ferric salt was investigated as one of the pre-treatment method to reduce membrane fouling in this study.

4.1.1 Result and Discussion

For this investigation, secondary wastewater form BWTP and WPWTP were used. Various parameters such as DOC, UV absorbance, and SUVA were carried out for analysis. The DOC removal was also modelled based on the DOC modelling prepared for surface water (Kastl et al., 2004).

4.1.1.1 DOC and UV254 Removal in Beenyup Secondary Wastewater

The effect of ferric dose ranging from 1.25mg/L to 160mg/L over a wide pH range between 4 and 9 was studied. Figure 4.1a and 4.1b presents the jar test results for DOC and UV254 as a function of ferric chloride dose. As shown in the Figure 4.1a, the DOC removal was achieved

of up to 61 percent while using 160mg/L coagulant in pH range of 5. However, most of the amenable part has already been removed by 80mg/L coagulant dose. Here increasing coagulant dose from 80 to 160mg/L achieved even less than 10 percent further removal of DOC. So, the most effective dose turns out to be around 80mg/L for the pH 5. Although, DOC removal in higher dose range goes as a function of coagulant, it shows anomalous behaviour for lower range of coagulant. The reason for this is described in detail in section 4.1.1.4. For most of the doses, UV removal appeared high in comparison to DOC removal. For the highest dose, it was obtained around 71 percent. On doubling the dose to 160mg/L gives only around 10 percent further UV removal as in DOC. So, these results suggest that preferential removal of UV absorbance over the DOC is due to the hydrophobic nature of UV absorbing substance and proclivity of these substances to preferentially react with coagulants. (Liang and Singer, 2003). The full set of results of this experiment is presented in Appendix 1.

Figure 4.1a: DOC Removal for Beenyup Secondary Wastewater
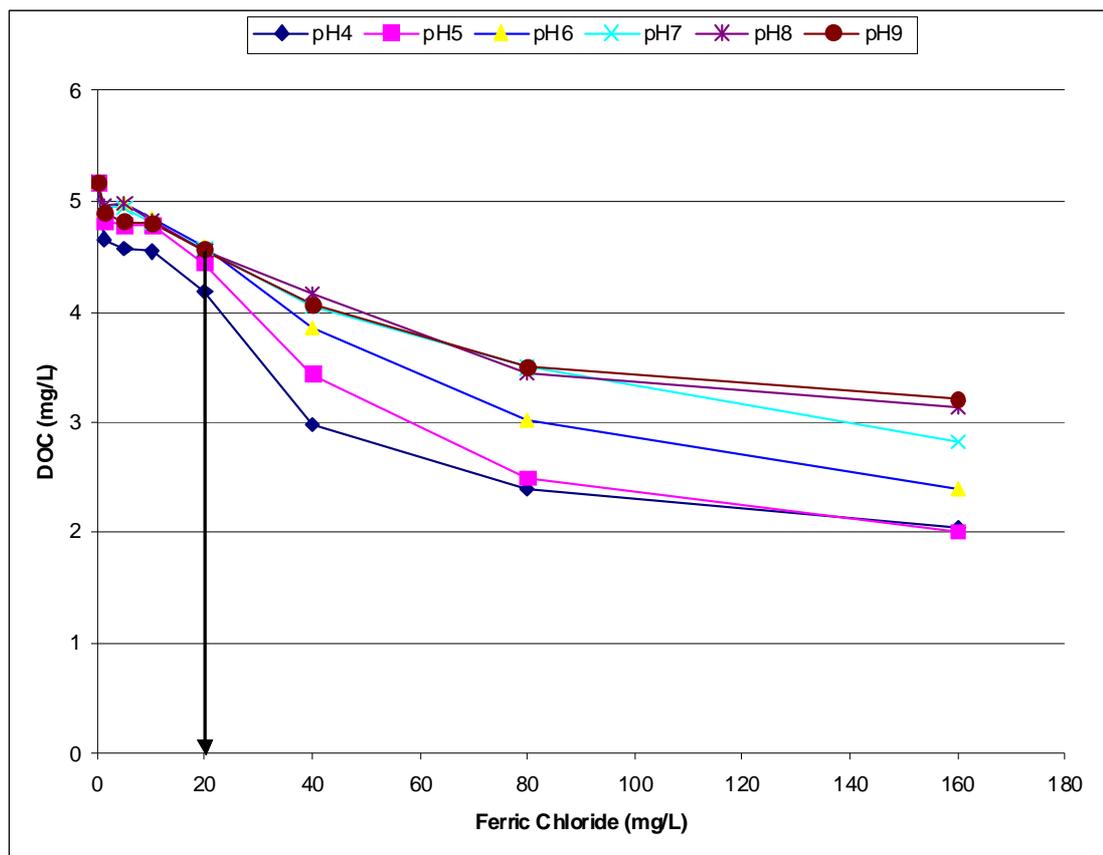
Figure 4.1b: UV Removal Trend for Beenyup Secondary Wastewater
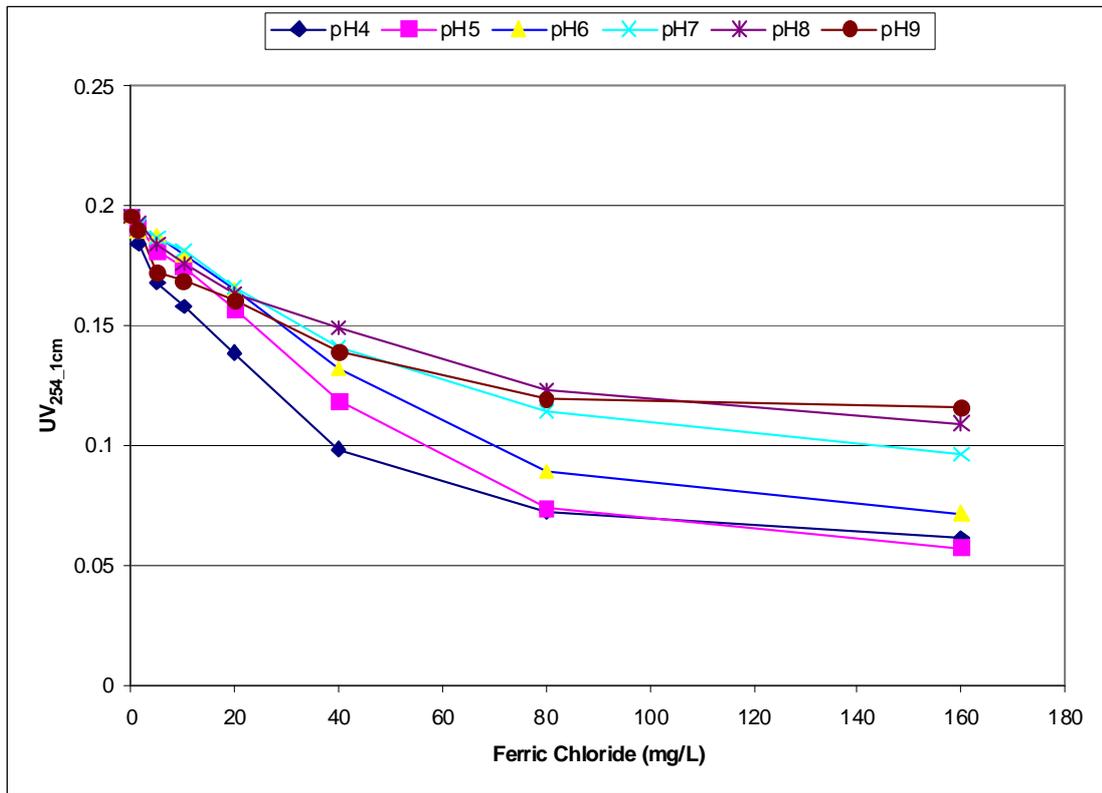
4.1.1.2 DOC and UV254 Removal in Woodman Point Secondary Wastewater

Wastewater from WPWTP was tested over a pH range of 4 to 9. As shown in wastewater from BWTP, it showed the similar DOC removal trend for both higher and lower ranges of coagulant. So, coagulant dose for this particular experiment was manipulated from 0 to 80mg/L but similar DOC removal trend was observed. As shown in Figures 4.2a and 4.2b, for the maximum coagulant dose of 80mg/L, the DOC was dropped from 8.89 mg/L to 3mg/L giving around 65 percent removal. The complete experimental result is also provided in Appendix 2.

Similarly, UV was also decreased significantly from 0.2477 to 0.0657 per cm and removed around 73 percent as shown in Figure 4.2b. The percentage of UV removal appeared higher than DOC removal for most of the coagulant doses indicating hydrophobic in nature as in coagulation of Beenyup secondary wastewater. For higher dose of coagulant, UV removal was up to 11 percent more than DOC removal.

Figure 4.2a: DOC Removal in Woodman Point Secondary Wastewater
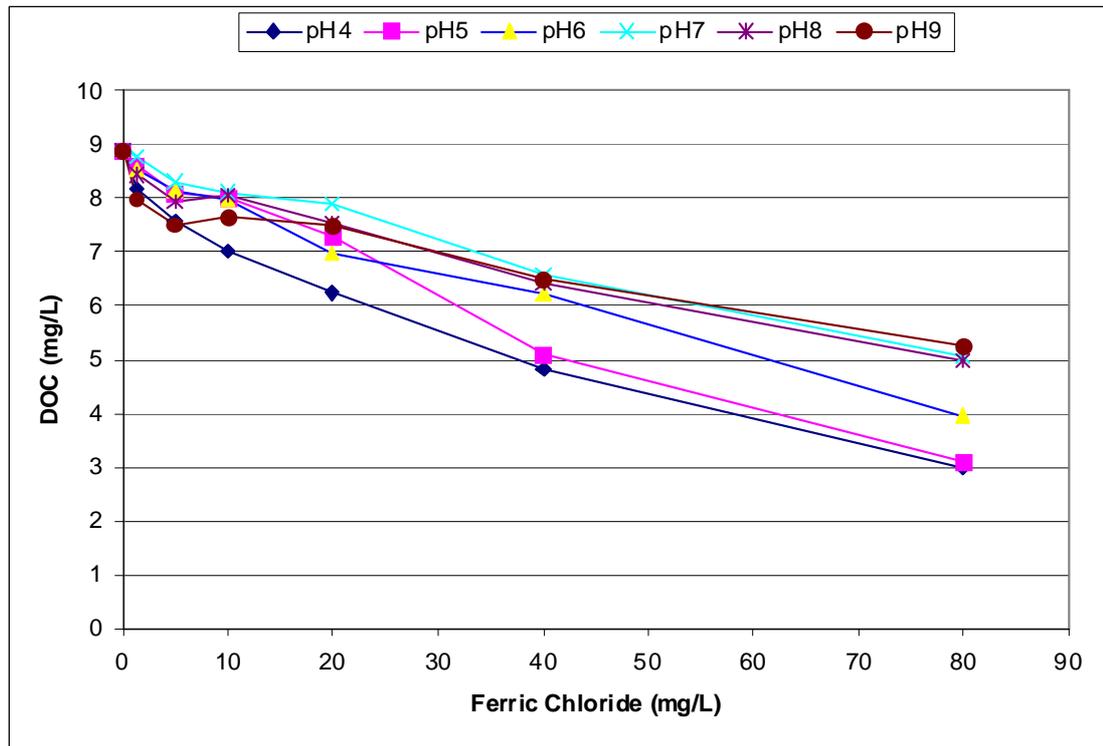
Figure 4.2b: UV Removal in Woodman Point Secondary Wastewater
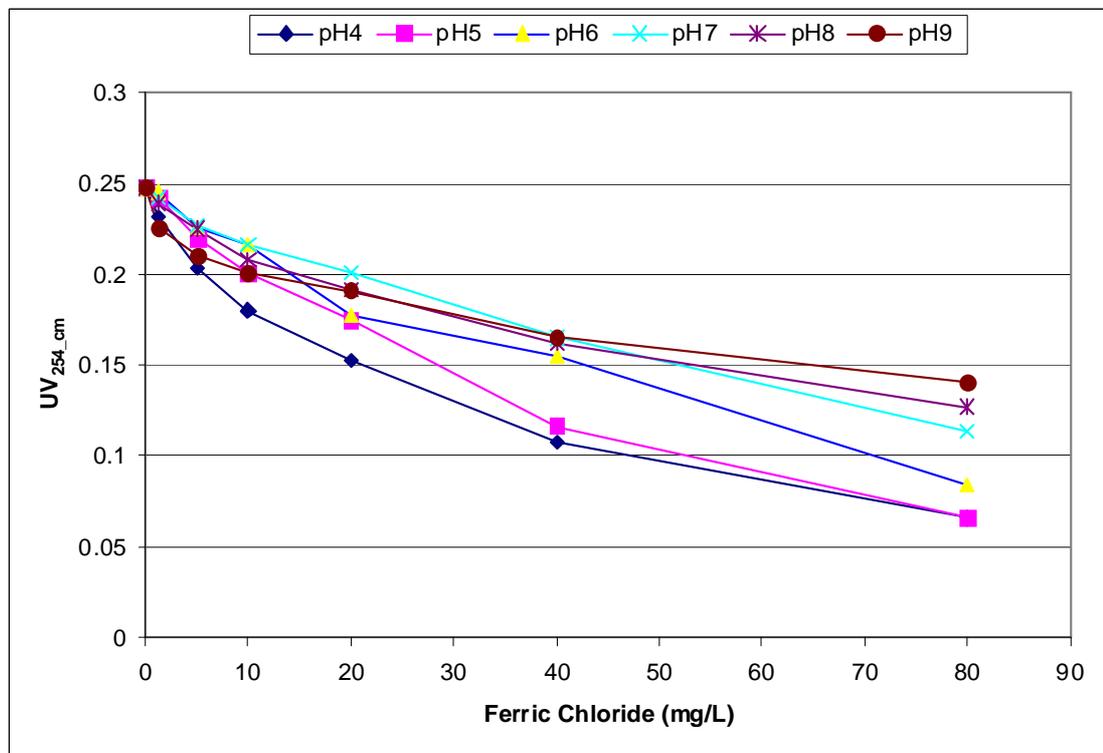
4.1.1.3 Comparison of Coagulant's Behaviour with BWTP and WPWTP Wastewater

Despite of same removal trend shown for all range of coagulant dose by both wastewaters used in this experiment, it behaved comparatively well with Woodman Point wastewater. Both DOC and UV removal appeared to be around 12 percent more than those in wastewater from Beenyup for the optimum coagulant dose. Similarly, they behaved in a same way for all pH range. The pH 4 appeared to be more effective for lower range coagulant but for the applied maximum dose, no significant difference was observed in terms of UV and DOC removal between the pH range of 4 and 5. In addition to this, for 80mg/L dose of coagulant, the decrease in SUVA found to be around 22 percent for both wastewaters from Beenyup and Woodman Point.

4.1.1.4 Anomalous Behaviour of Wastewater for Lower range of Coagulant

For both wastewaters, no significant removal was obtained up to the coagulant dose of 20mg/L although it worked very well for high dose of coagulant. In most of the cases, increasing the dose from 1.25mg/L to 20mg/L achieved only around 10 percent DOC removal, which was much lower than expected. In addition to this, despite of increasing coagulant dose, the DOC in the wastewater decreased only marginally within this lower range of coagulant dose. The Figure 4.3 presented below clearly reveals two different trends in DOC removal for lower and higher range of coagulant.

Figure 4.3: Response of Wastewater for Low Dose of Coagulant
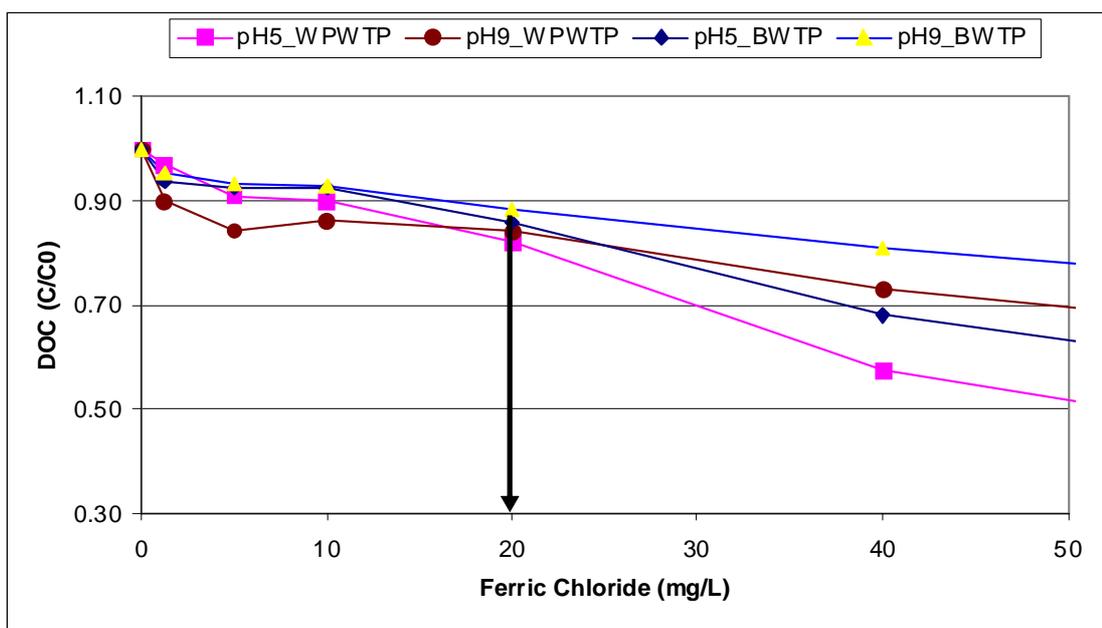
Only two range of pH is presented (Figure 4.3) to illustrate the trend clearly. The coagulant started to work effectively only beyond the range of 20mg/L. This clearly indicated that around 20mg/L of coagulant is being useless as something is prohibiting its effectiveness depriving the sufficient contact with wastewater to be treated. This means some portion of coagulant was being wasted just to overcome that resistance which need to be removed to achieve single trend of DOC removal throughout the applying range of coagulant.

For this reason, the possible role of suspended solid was tested, as they are present in wastewater. For this, wastewater from Beenyup treatment plant was filtered through 0.45µ cellulose acetate filter paper. Then it was adjusted to pH 5 and tested for the range of 1.25 to 80 mg/L of coagulant dose. On doing this, two different trends disappeared giving a single curve of DOC removal throughout the whole range of coagulant dose as shown in Figure 4.4.

Figure 4.4: Coagulation after Filtration
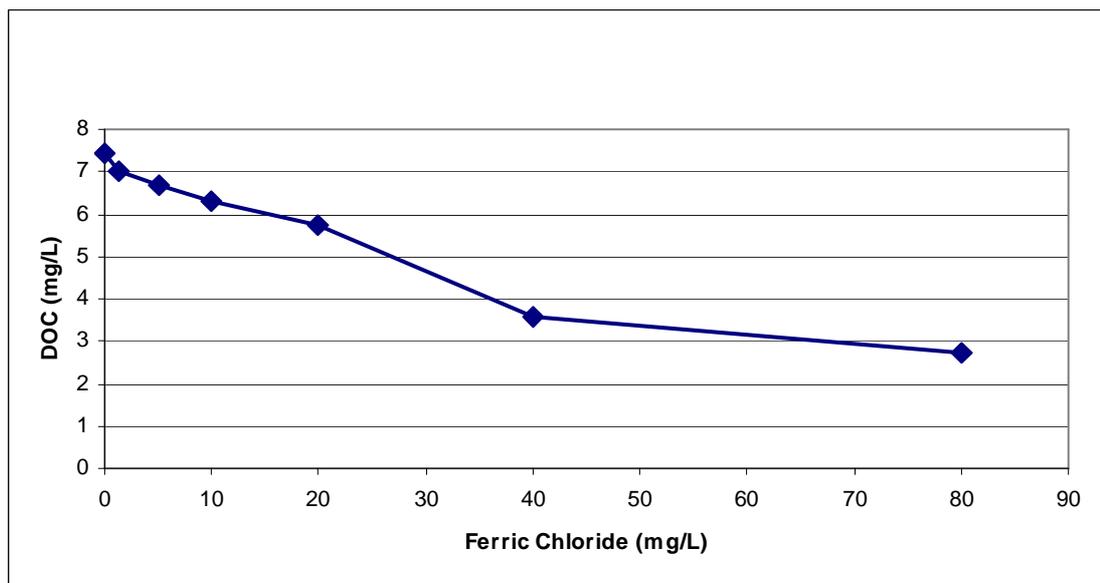
Thus, from this experiment it became clear that, the initial disturbance for the lower doses is due to suspended solid present in wastewater. As they retained certain amount of coagulant and consequently prohibited them from mixing very well, the initial lower coagulant dose became highly ineffective to remove organic matter from the wastewater. Apart from this, the efficiency of DOC removal also increased after the filtration of sample. The total removal efficiency at 80mg/L was achieved only around 52 percent before filtration, which increased to 63 percent after filtration. This clearly showed that, suspended solids hold the ferric chloride considerably and decrease the efficiency of coagulant.

4.1.1.5 Coagulation in Combination with BAC

The effect of coagulation in combination with BAC was also investigated with two different objectives: to observe its effectiveness in removing suspended solids and to see an effect on DOC removal in combination. Both secondary wastewater from Beenyup and Woodman Point was passed through two BAC columns connected in series through reactor set 4 (high depth reactor) as shown in Figure 3.7. For this experiment EBCT of 80 minute was maintained on the high depth BAC reactor that has already achieved steady state condition. Then wastewater was sent through it continuously and the sample was collected from the effluent tank. Then the coagulation using ferric chloride was done over a range of 1.25mg/L to 80mg/L. The effluent was adjusted to pH5 prior to coagulation as best effective condition was achieved at this pH in previous sets of experiment.

Figure 4.5a: Combined Effects of BAC and Ferric Chloride in DOC Removal
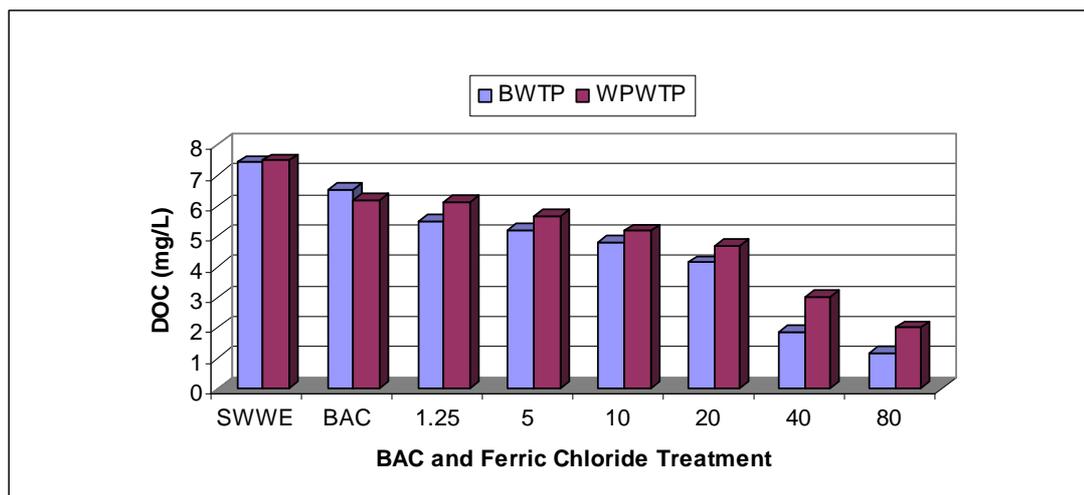
Altogether, this combination attained respectively 85 and 73 percent DOC removal for Beenyup and Woodman Point secondary wastewater. The DOC removal appeared around 12 percent higher in Beenyup wastewater for 80mg/L dose of ferric chloride for this particular combination. In addition to this, it also eliminated the initial ineffectiveness of lower doses. This means it removed the suspended solids as well in addition to other organic matter from wastewater. Similarly, for 80mg/L of ferric chloride dose in combination with BAC removed 86 percent of UV from both wastewaters. However, for rest of the doses, the UV removal in Woodman Point wastewater was found to be significantly lower than that of Beenyup wastewater. This is presented in Figures 4.5a and 4.5b and all the experiment results are provided on Appendix 3.

Figure 4.5b: Combine effect of BAC and Ferric Chloride in UV Removal
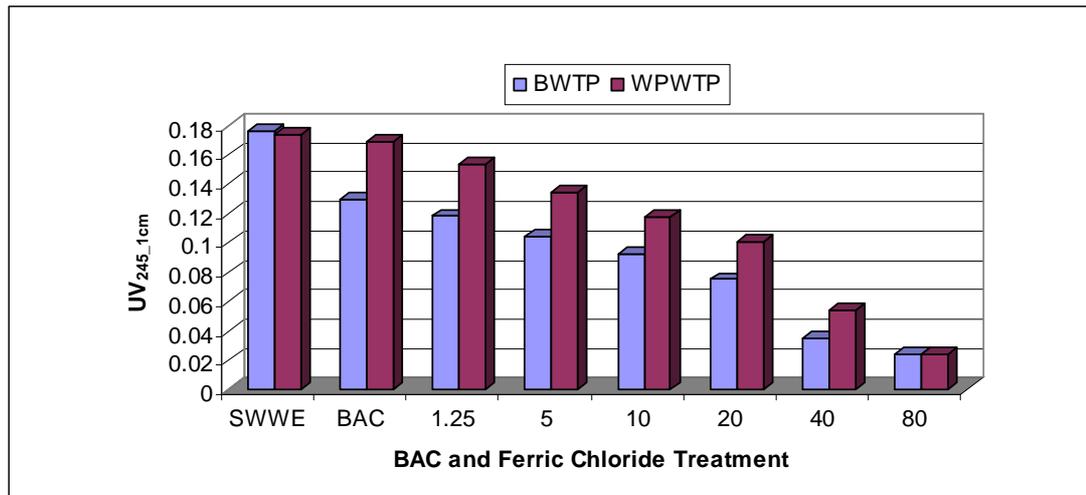
4.1.1.6 Synergistic Effect of BAC and Ferric Chloride

Secondary wastewater effluent from Beenyup was investigated to see the effect of BAC and Coagulation as pre-treatment in combination. The Figure 4.6 shows the performance of ferric chloride for three different conditions particularly unprocessed secondary wastewater effluent, secondary wastewater after filtration through 0.45µm filter paper and secondary wastewater after passing through BAC Column as described in section 4.1.1.5.

Figure 4.6: Effectiveness of Ferric Chloride in Combination with BAC
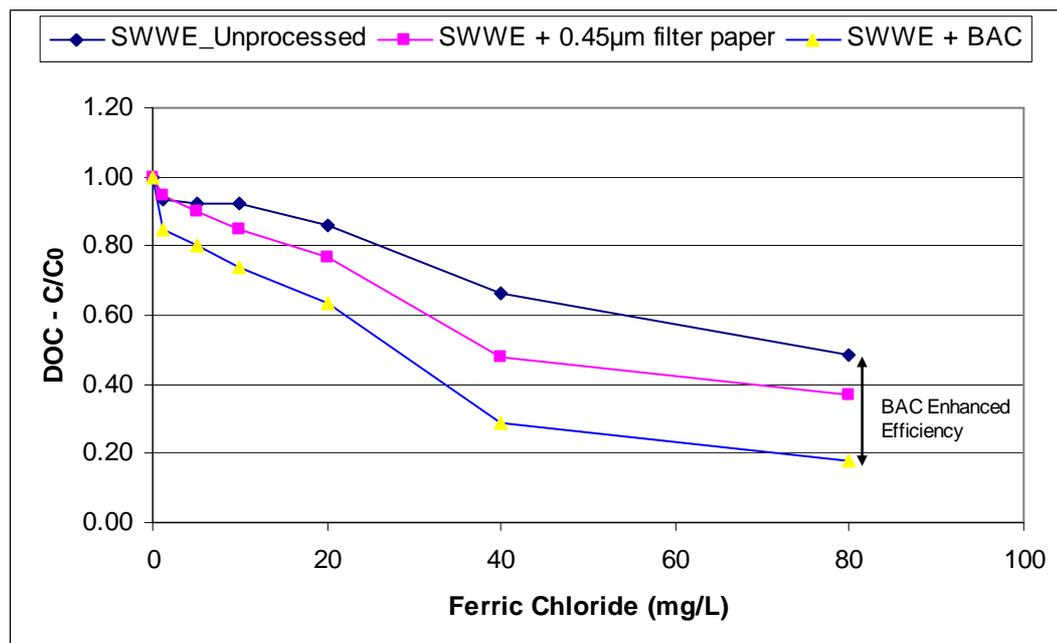
As shown in Figure 4.6, only 52% DOC removal was achieved when 80mg/L Ferric Chloride as coagulant was used alone. As described earlier, the presence of suspended solid creates hindrance for the effectiveness of coagulation. This can be overcome by filtering the sample through 0.45μm filter paper. This increased further 11 percent DOC removal. This means maximum efficiency for this particular dose of ferric chloride when used alone was limited to around 63 percent. However, for the effluent collected from BAC reactor, ferric chloride behaved very well. For the same dose of coagulant, it removed 82 percent DOC and DOC value dropped from 6.52mg/L to 1.15mg/L. This is 30 percent more when compared to the removal efficiency with unprocessed SWWE. Similarly, UV removal also found around 19 percent more than in unprocessed SWWE. This means, BAC treatment works very well in combination with ferric chloride as it increases coagulants efficiency in terms of DOC and UV removal from the secondary wastewater.

4.1.1.7 DOC Removal Model Fitting with Experimental Data

The DOC model prepared in surface water (Kastl et al., 2004) was then fitted to the experimental data. The model was developed for the two Australian waters; Happy Valley and North Richmond water, and was later tested for 17 US waters. This model was developed with the principles that DOC removal is mainly the result of adsorption of on metal hydroxide flocs formed during coagulation and can be described by the Langmuir isotherm, non sorbable fraction is not amenable to coagulation and adsorption capacity is function of pH. This same model was also tested against the secondary wastewater from Beenyup and Woodman Point.

For this, empirical value such as adsorption capacity, adsorption constant, humic acid fraction, non-polar fraction and sorbable fraction are re-calculated for both wastewaters form BWTP and WPWTP. The relative adsorption constant K was found to be close enough to 1 for this model as in the original model. These values are presented in table 4.1.

Table 4.1 Model Parameters and Errors for Beenyup Wastewter Treated with Ferric Coagulant

Parameters	Unit	BWTP	WPWTP
Adsorption Capacity (a)	mg-DOC/meq coagulant	92	34.99
Adsorption Constant (b)	L/mg-DOC	0.0105	0.085
Sorbable Fraction ($S_{orbable}$)		0.83	0.86
Humic Acid Fraction (f_{ha})		0.34	0.39
Non Polar Fraction ($f_{non\ polar}$)		0.49	0.47
Pka		5.82	5.75
$\sum$(Error in Prediction)2*		1.07	3.63
Number of Experimental Data		41	34
R^2		0.97	0.96
Standard deviation of errors in prediction	percent	4.22	4.91
Standard deviation of errors in prediction	mg/L-DOC	0.16	0.33
Maximum error in prediction	percent	10.64	13.10
Maximum error in prediction	mg/L-DOC	0.39	0.73
Estimated potential experimental error if instrumental error are combined**	mg/L-DOC	0.25	0.267

a - adsorption capacity in mg-DOC/meq coagulant; b - adsorption constant mL/mg-DOC, DOC - Dissolved organic carbon; f_{ha}- humic acid fraction; $f_{nonpolar}$ - nonpolar fraction; $f_{sorbable}$ - sorbable fraction

*Error in prediction is the difference found between each measured and modelled data

**Estimated potential experimental error is calculated by adding maximum error than can occur if pH measurement is 0.1 unit in error and DOC measurement error (Larger of 0.05 or 3 percent of DOC)

Figure 4.7: Comparison of remaining DOC (DOC meas) and model predicted final DOC (DOC model) for Beenyup Wastewater
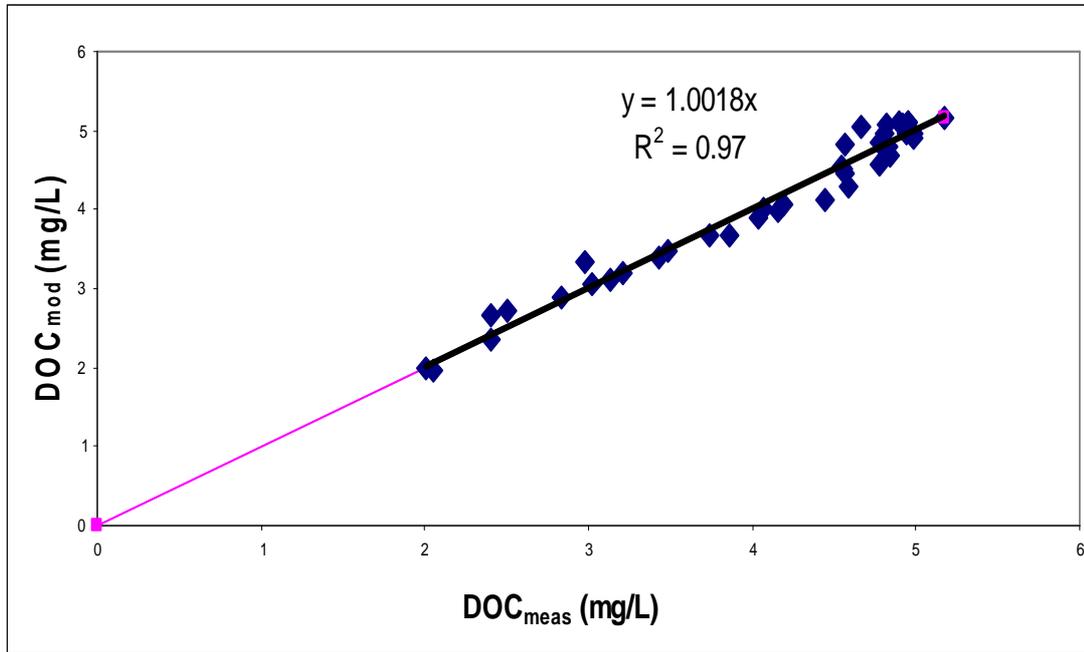
Figure 4.8: Model predicted final DOC (DOCmodel) for Beenyup Wastewater
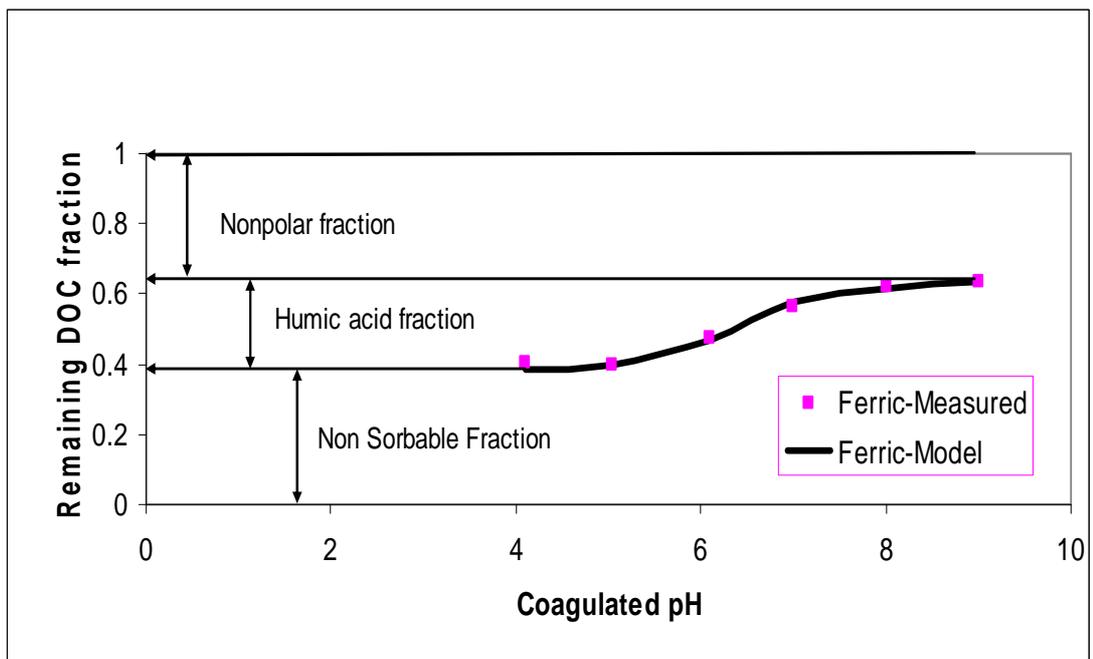
Ferric Chloride Dose 160mg/L, DOC – Dissolved Organic Carbon

Model outputs for the Beenyup wastewater is compared with experimental values in Figure 4.7 and 4.8, which shows the dependence of DOC removal on pH. The modelling of jar test results for the Beenyup wastewater offered the R^2 value of 0.97 and standard deviation of 0.16. Similarly, the maximum predictive error ranged around 10.64 with the errors on standard deviation 1.2 percent. The maximum error prediction for this water was found to be around 0.39 mg/L-DOC. The potential experimental error given in Table 4.1 is calculated considering the error in pH and DOC measurement as stated in the original model (Kastl et al., 2004).

The value of R^2 does not go very well beyond 0.97 for best fitting condition. The same model was also applied for Woodman Point Wastewater. All the calculated values of modelling parameter for both wastewaters are presented in Table 4.1 and charts for Woodman Point wastewater is presented in Appendix 4. As there was no significant improvement in DOC removal up to 20 mg/L dose, it gives two sets of curves each for lower and higher coagulant dose. As a result, the first curve for lower dose has not fitted in to the model very well. However, this model fits perfectly beyond 10 mg/L coagulant dose.

Figure 4.9: Residual DOC for various ferric chloride doses in Beenyup Wastewater
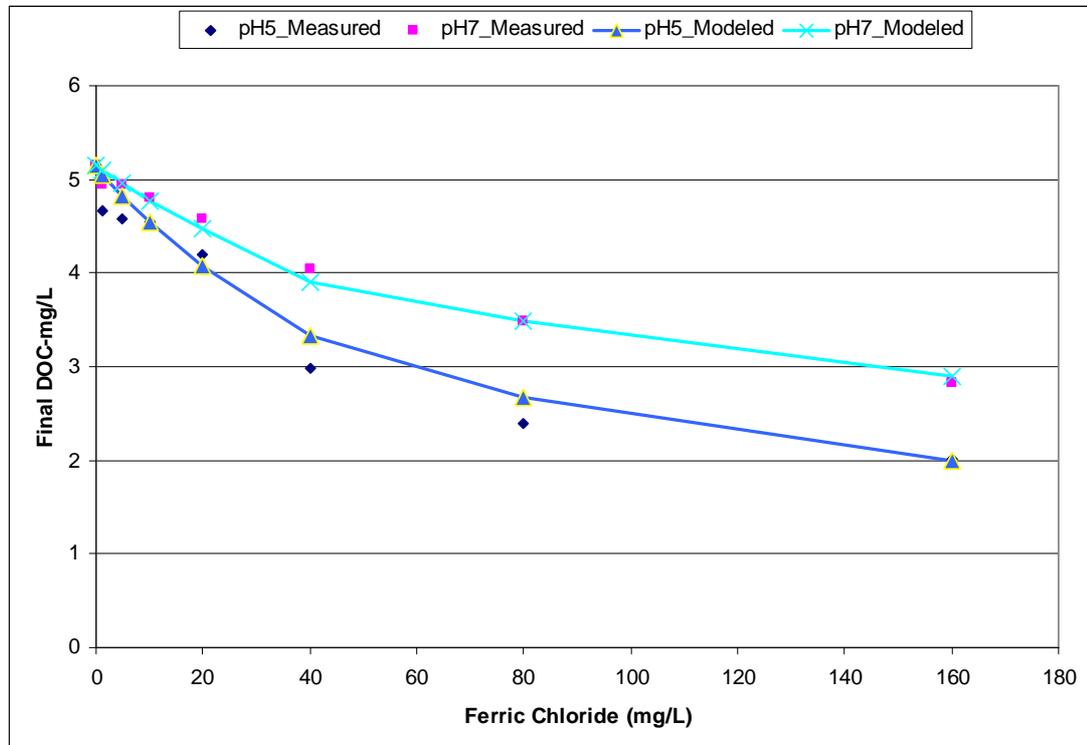
Figure 4.10: Comparison of Coagulant for Surface Water (Kastl et al., 2004) and Secondary Wastewater from Beenyup
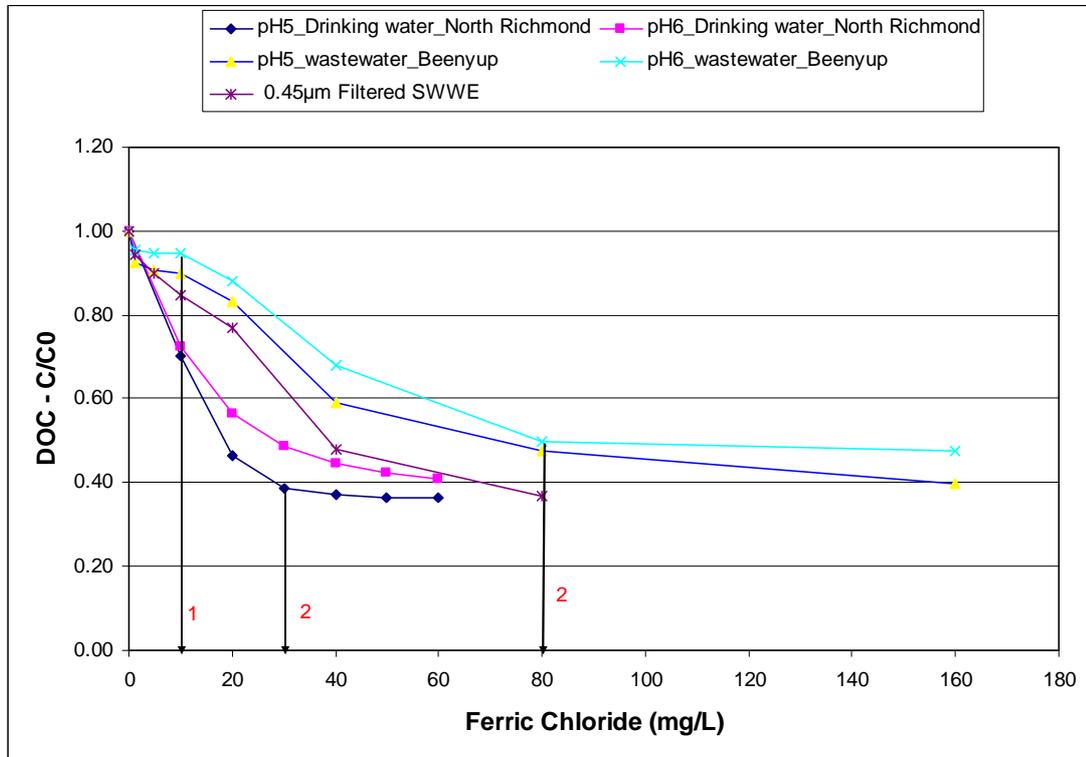
4.1.2 Comparison between Drinking water and Wastewater

As shown in Figure 4.10, DOC removal passes through various stages. During stage 1, addition of coagulant up to around 20mg/L could not effectively remove DOC and remained roughly constant whereas DOC removal significantly increased in drinking water with the same amount of coagulant. Similarly, in drinking water 30 mg/L has removed majority of the sorbable DOC and reached at stage 2 but wastewater reached this stage after addition of very high dose (80mg/L coagulant). As shown in Figure 4.10, the initial ineffectiveness disappeared after filtering the sample by 0.45µm filter paper. This means suspended solid played the major role to make the lower dose ineffective by creating the disturbance for the effectiveness of coagulant. Once they are removed prior to coagulation, it started to behave like drinking water although it required high amount of coagulant due to presence of large amount of organic matter in wastewater.

4.1.3 Conclusion

From this experiment following conclusion can be made.

- Coagulation can achieve up to 60 percent of DOC removal particularly by taking hydrophobic portion away from secondary wastewater that is responsible for severe membrane fouling.

- BAC followed by the coagulation was found to be more effective. This was possible because
  1. BAC can removes up to 45 percent DOC
  2. It also converts non-sorbable organic carbon in to sorbable organic carbon and hence increase the removal efficiency of coagulant

- The DOC removal model prepared for Australian Drinking Water (Kastl et al, 2004) also fits well for both secondary wastewater from Beenyup and Woodman Point WTP. From the analysis, it was found that despite larger errors in low dose range up to 10mg/L, it fits very well for the rest of the range of the coagulant.

- Although coagulation can remove all hydrophobic matter alone, it can be much more effective when it is used in combination with other pre-treatment like BAC as hydrophilic portion can also be removed in doing so. Although not in excess, hydrophilic organic matter also has some share on membrane fouling. In this context, combination of coagulation with BAC can be highly useful to reduce fouling on membrane.

4.2 MIEX® as Pre-treatment

As described in the literature review, MIEX® can remove all types of carbon irrespective of hydrophobic or hydrophilic nature. In this context, it can be used as an effective pre-treatment method when used in combination with other pre-treatment method. So, MIEX® as pre-treatment has been investigated in terms of DOC and UVA removal in this study.

4.2.1 Result and Discussion

Secondary wastewater from BWTP was used for this investigation as well. Test for DOC and UVA was carried out and results were also analysed using surrogate parameter by calculating SUVA for the treated samples. The experiment was conducted by varying the pH to see its effect on organic matter removal from the wastewater.

4.2.1.1 Comparison of DOC and UV$_{254}$, removals during MIEX® treatment

In this investigation preliminary jar test experiments were conducted in order to determine the effect of MIEX® dose over a wide range from 1ml/L to 32ml/L and studied against the DOC and UV removal. As can be seen from Figure 4.11a, the removal efficiency of DOC is increased with increase in MIEX® resin dose. However, it appears to be stabilizing from the range of 16 ml/L as the removal efficiency is not significant in comparison to increased dose of MIEX®.

Figure: 4.11a: Effect of MIEX® on DOC Removal
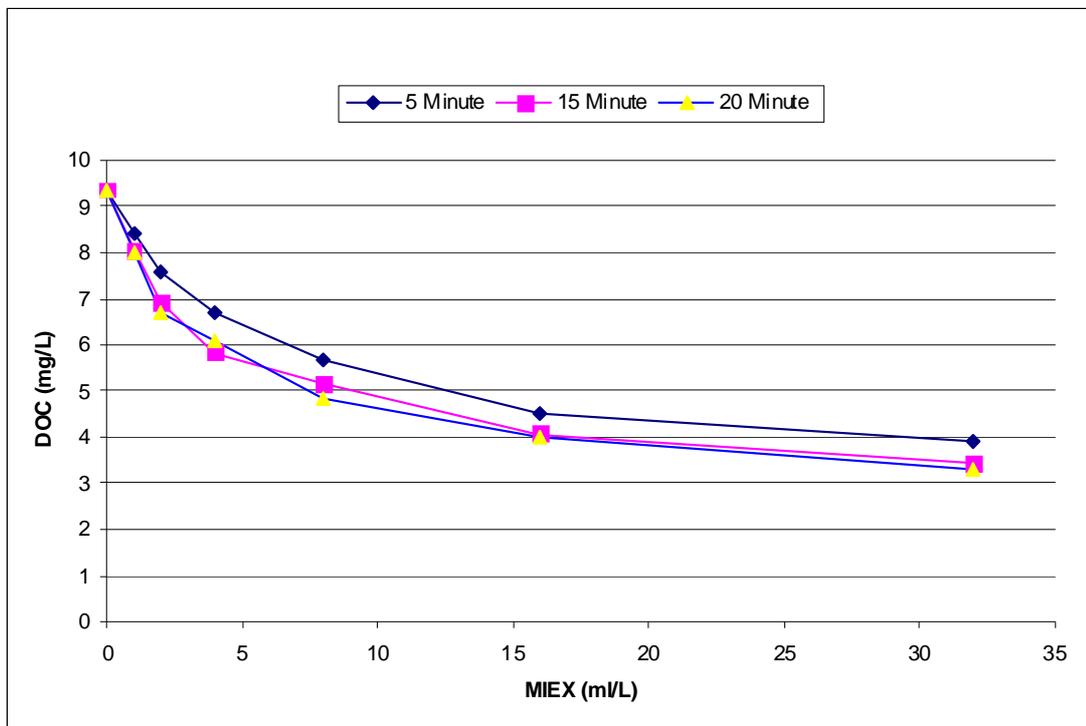
The percentage of UV removal was found to be higher than the DOC removal in the treated sample. This shows that MIEX® also takes hydrophobic and aromatic content away present in the secondary wastewater sample along with hydrophilic portion. The total DOC removal was achieved around 65 percent while using 32ml/L for 20 min resin contact time while UV removal was found around 74 percent under the same condition.

Figure: 4.11b: Effect of MIEX® on UV Removal
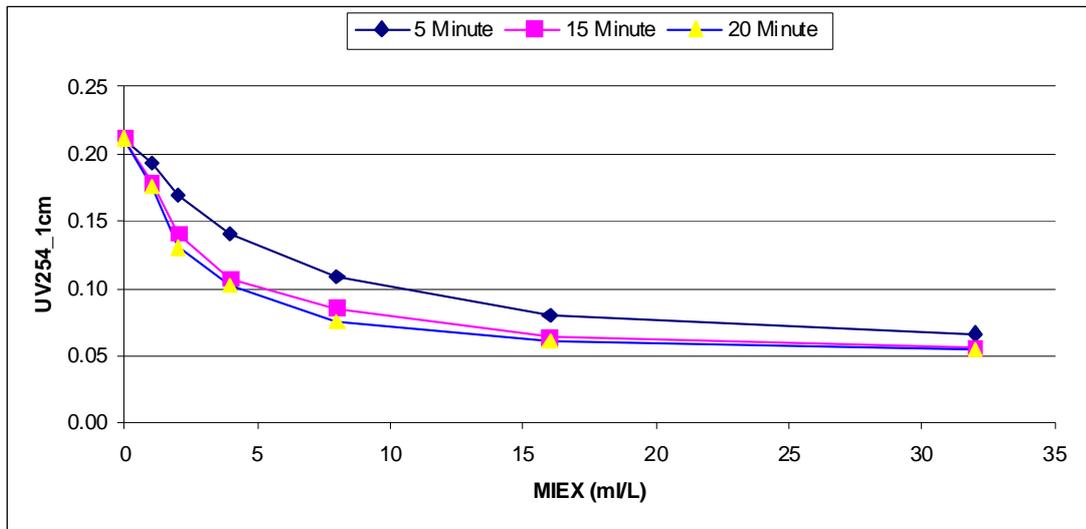
As shown in Figure 4.12a and 4.12b, it can be seen that most of the removal of both UV and DOC was achieved within five minutes regardless of high and low dose, which was considerably higher than the efficiency achieved after five minutes. While analysing the result, it was found that for lower doses up to 4 ml/L, DOC and UV removal efficiency was around 70 percent of the total removal of that particular dose for first five minutes while for higher doses this values rise up to 90 percent. This gives the clear idea that most of the ion exchange happens immediately after adding resin into the sample. This showed that optimum removal efficiency depends upon both dose and resin contact time that can be figured out based on the stabilization trend of the curve obtained from the jar tests.

Figure 4.12a: DOC Removal as a Function of Time
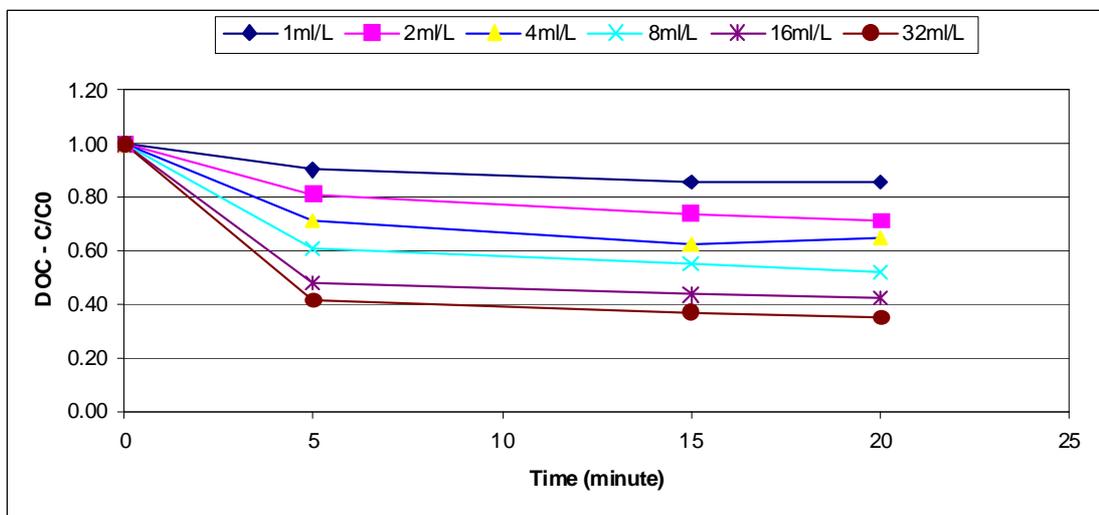
Figure 4.12b: UV removal as a Function of Time
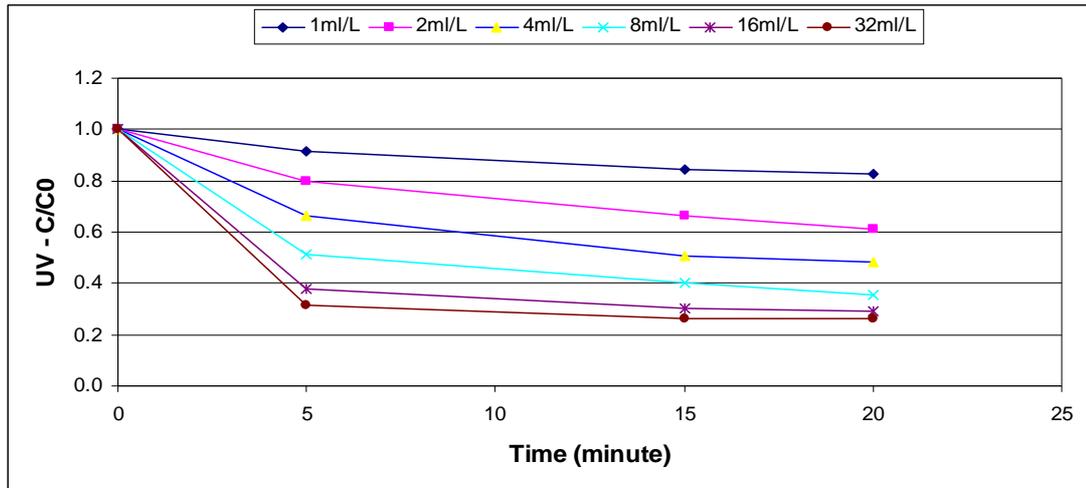
Based on the DOC and UV absorbance obtained for the treated sample, SUVA was also calculated. As shown in Figure 4.13, the value of SUVA generally decreased with increase in resin mixing time and dose into the sample. However, it was slightly increased when MIEX® dose was doubled from 16 to 32ml/L. Around 16ml/L dose; SUVA was removed efficiently in comparison to others. SUVA value decreased to 1.5, which was a significant drop from the secondary wastewater SUVA of 2.26 (Figure 4.13). While for the same water the value of SUVA was relatively higher when treated with ferric coagulant considering the 4 percent error in SUVA (instrumental error from DOC and UV measurement). This means MIEX® removes both hydrophilic and hydrophobic portion use to be present in wastewater. This indicates that, MIEX® in combination with some other treatment has good potential to reduce the membrane fouling that occurs due to organic carbon.

Figure 4.13: Effect of MIEX® on SUVA Removal
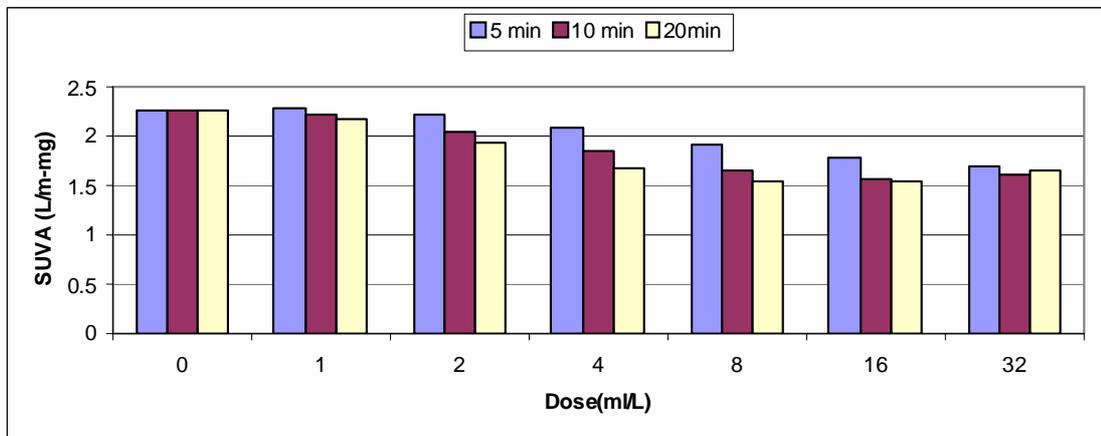
4.2.1.2 Effect of pH Variation on DOC and UV removal

The MIEX® resin has strong base functionality hence is capable of exchanging weak organic acid ions at the neutral pH for most raw waters. However, it was tested within a wide range of pH from 4 to 9 as shown in Figures 4.14a and 4.14b. In fact MIEX® is much more effective around neutral range. MIEX® of dose 16ml/L was tested for various level of pH. From the experiment it was found that, it did not improve the removal efficiency of organic material from the wastewater. When experiment was done without adjusting pH, the maximum DOC and UV removal was respectively 57 and 71 percent removal. But pH adjustment achieved only maximum of 51 and 65 percent removal for 20 minute mixing time. This clearly tells that making water acidic or basic further worsen the removal efficiency of organic material from the wastewater.

Figure 4.14a: Effect of pH variation in DOC Removal
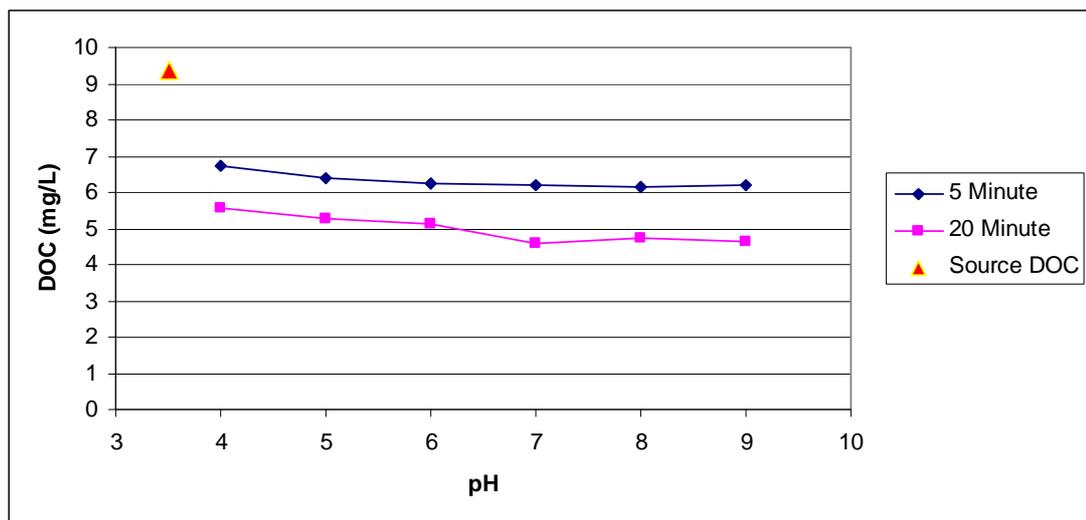
Figure 4.14b: Effect of pH Variation in UV Removal
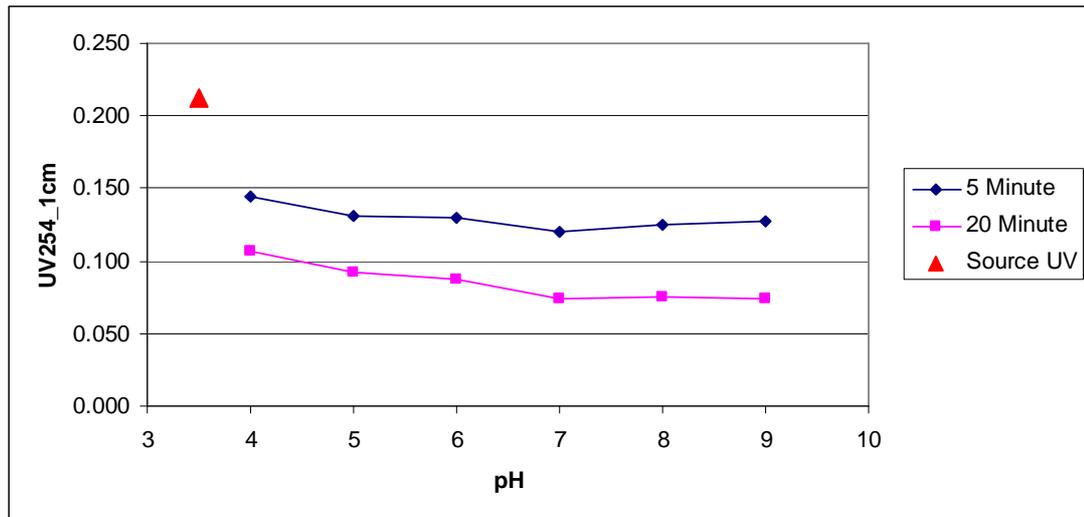
4.2.1.3 Comparison between Drinking Water and Wastewater

The Figure 4.15 presents the comparison of DOC removal between drinking water and secondary wastewater. Drinking water from Mundaring Reservoir, Perth and secondary wastewater from BWTP were used for the experiment. As can be seen from the Figure 4.15, DOC removal is much higher in drinking water. It seems that for less contact time, the percentage removal of DOC for both waters is same. However, when contact time was increased, the percentage removal of DOC in drinking water was found considerably higher than that of wastewater. Similarly, in Mundaring water 10ml/L MIEX® was removed almost 60 percent DOC while for same percentage removal Beenyup wastewater need 16ml/L MIEX® resin which is 50 percent more demand than the drinking water.

Figure 4.15: Comparison of DOC removal in Drinking and Wastewater
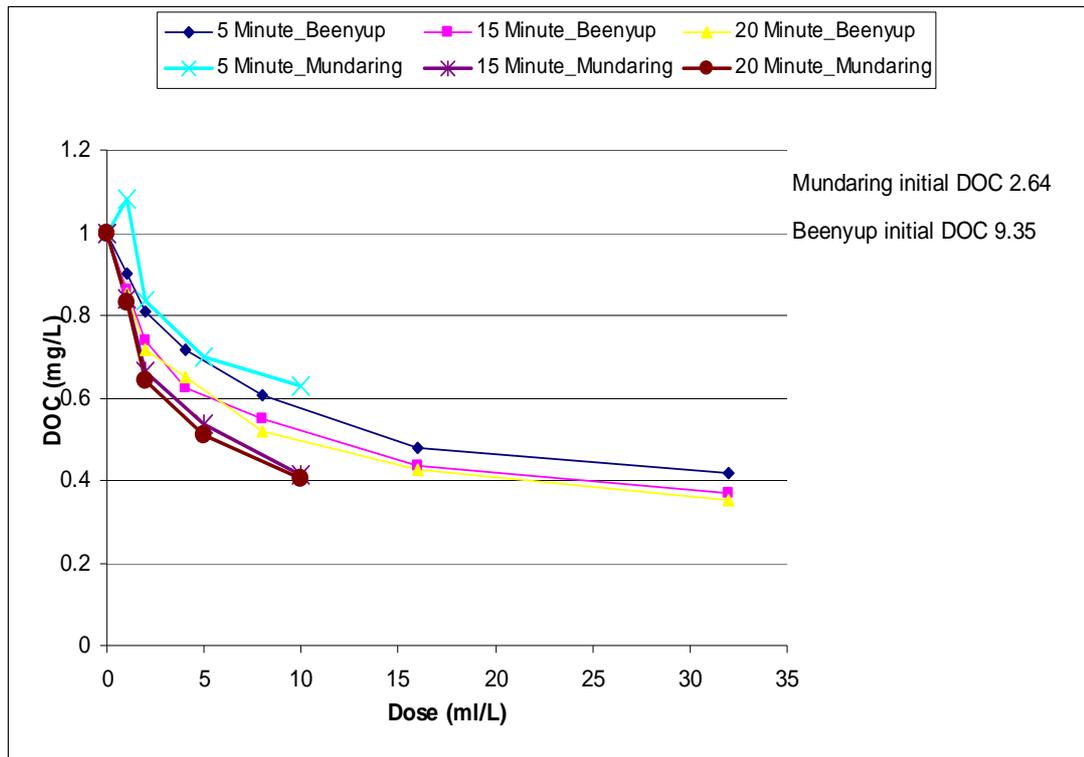
So, from this it might be said that, MIEX® behaved almost in the same manner regardless of drinking water and wastewater as it can take both hydrophilic and hydrophobic portion away from the water. Although, wastewater contains a lot of high molecular weight aromatic carbon than the hydrophilic part, no significant difference was found in the DOC removal trend in both types of water. As the drinking water contains significantly low DOC, the removal was achieved by low dose of MIEX® than wastewater. However, the trend seems similar.

4.2.3 Performance of MIEX® in Combination with Ferric Chloride

Performance of MIEX® in combination with ferric chloride was also tested. So, the secondary wastewater from Beenyup was treated with 16ml MIEX® for 5 minutes first. Then Ferric Chloride was added to the MIEX® treated sample. Two sets of samples were prepared. For one set, pH was adjusted at 5 while another sample was coagulated directly without adjusting the pH. However, both sets of experiment gave same results. The combination achieved around 70 percent DOC removal in total, while ferric chloride only achieved around 50 percent DOC removal for MIEX® treated sample. There was no difference in DOC removal for pH 5 and pH non-adjusted sample. It suggests that, MIEX® took away the non-polar fraction. This means MIEX® gave the similar results regardless of pH adjustment for ferric chloride. This

result suggests that, performance of ferric chloride does not improve when used in combination with MIEX®.

Figure 4.16: Performance of MIEX® in Combination with Ferric Chloride
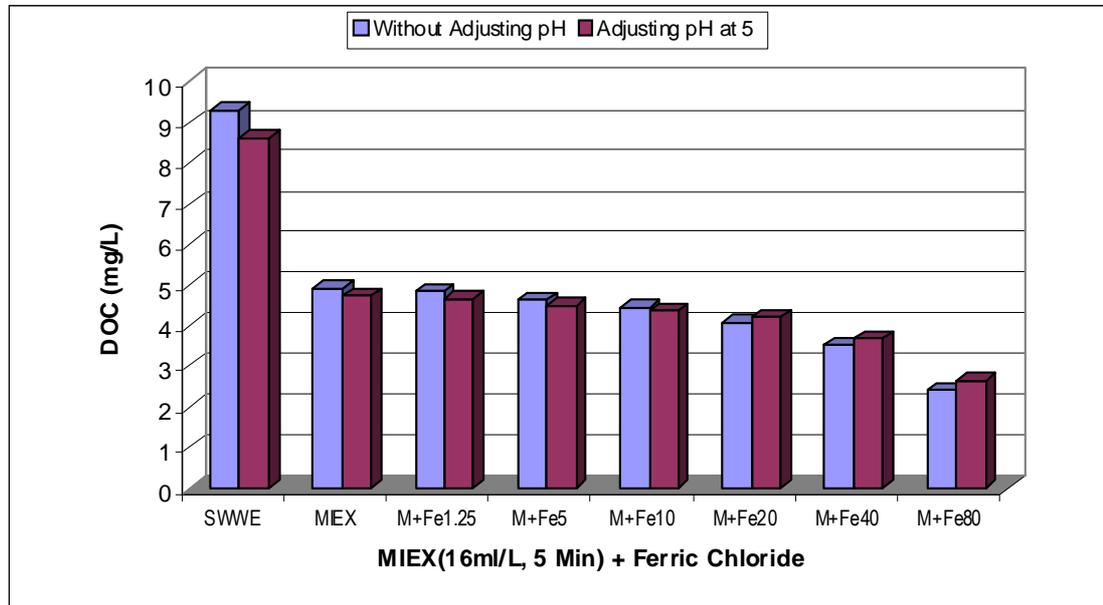
In this figure M represent 16ml MIEX® for 5minutes.

4.2.4 Conclusion

From this experiment, it can be concluded that the removal of organic matter present in wastewater is increased with increasing dose of MIEX® and resin contact time. However, it was also observed that most of the DOC and UV were removed within 5 minutes and after that MIEX® took very little amount of organic matter. This means little more dose of MIEX® for smaller contact time is the fast and effective way to get rid of dissolved organic matter from the wastewater. Similarly, during the experiment it was also found that no further achievement in DOC or UV removal by manipulating the pH as it further worsens the removal efficiency. In addition to this, combination of MIEX® with coagulation did not appear to be effective during the experiment. When coagulation was done followed by the MIEX® no significant increase in DOC removal was obtained.

4.3 BAC as Pre-treatment

In this study, secondary wastewater from Beenyup WTP was used for the investigation. BAC works on the principle of adsorption of substances and micro organisms along with degradation of organic material by microbial activities. Hence a broad range of organic

material can be removed for a long time with low maintenance cost. Due to concentrated microbiological activity in BAC, organic matter can also be converted to different forms, which may offer benefit in reducing disinfectant by-products, if they were to be used for ground water recharge and reuse. When wastewater was sent through the series of BAC reactor, it was found that the group of organics can be removed systematically one after another. So, BAC as pre-treatment can be effectively used to reduce the fouling on the membrane. In this study, BAC was studied for various conditions as described in section 3.2.2. The details are explained below.

4.3.1 Fully Aerated (Reactor Set 1)

In this experiment, reactor was operated in continuous mode. The EBCT was maintained 20 minutes with upward flow for this reactor. The treated water was collected from upper portion of the reactor. Initially, for the first few days, it was operated without supplying oxygen to find out the rate of DO consumption. During this period, the level of DO was almost same. However, as microbial activity started to increase inside the BAC reactor, the level of DO started to drop continuously as shown in Figure 4.17. As can be seen in Figure 4.17, after one week of operation, the DO level dropped to the lowest value of 1.58 mg/L. This significant drop in DO level indicated the excessive growth of micro organism inside the reactor which takes organic material as well as ammonia as their source of nutrients and oxidises them.

From this point, sufficient oxygen was supplied from the two different heights of reactor particularly from the bottom and middle part of the column to ensure sufficient amount of oxygen inside the reactor making DO level almost constant around 8 mg/L during the whole operation period to enhance bacterial activity. It assumed that, if the level of oxygen depletes during the process, the supply of sufficient oxygen can maintain the microbial activity significantly and hence can reduce the organic material present in wastewater. Based on this assumption, this reactor was run for one month, and tested for various parameters such as UV, DOC, ammonia, nitrite, and nitrate. It was operated under room temperature, averaging around 18 degree centigrade. The result of this experiment is discussed below.

Figure 4.17: Level of DO depletion for the first week of operation
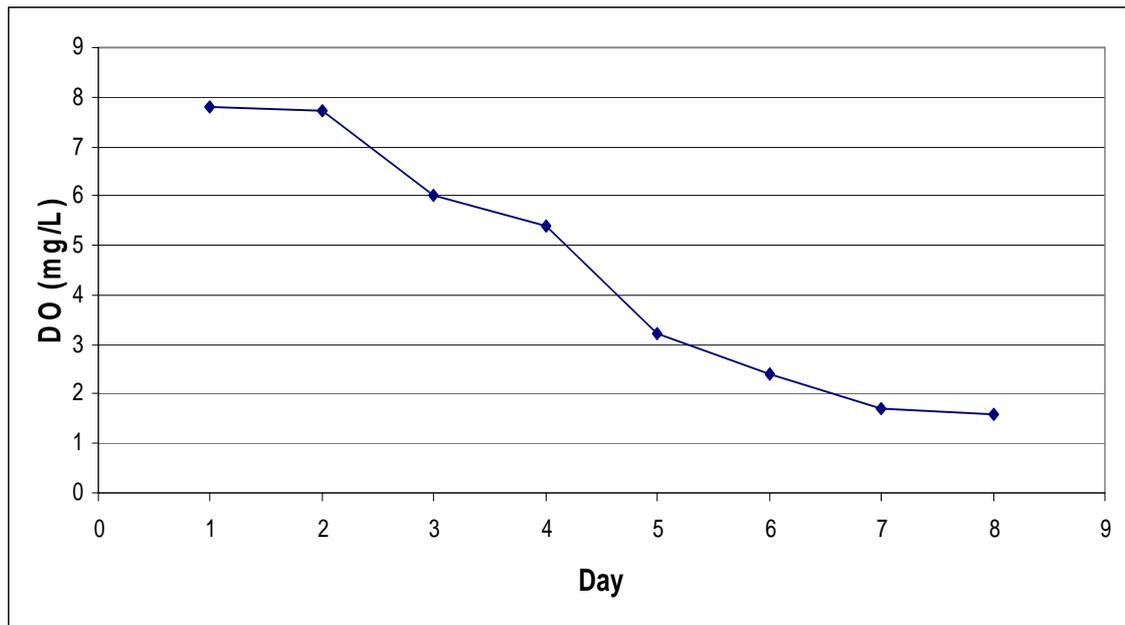
4.3.1.1 UV and DOC Removal in Fully Aerated Reactor

As shown in Figures 4.18a and 4.18b, the removal of UV absorbing organic material for the first day was found to be around 60 percent. However, the efficiency decreased gradually during the first week of operation. This may be explained as that the major mechanism of DOC removal was physical adsorption during the first week. It can be clearly seen that, decrease in efficiency of UV removal was the highest during the first week. This means, despite the drop in of physical adsorption capacity UV removal tended to stabilize due to the increased microbial activity. So, the removal during the second week of operation was due to both the physical and the microbial effects inside the reactor. Almost constant efficiency from the third week of operation was mainly due to microbial activities inside the reactor, although removal by adsorption may be present. From this point, the removal efficiency remained almost constant until the end of the operation with removal efficiency 25 percent.

It behaved in identical way for DOC removal like in UV removal. It can be seen from the Figure 4.18b, the DOC removal during the initial period was higher, which kept on decreasing and stabilized around the average of 20 percent for the last week of operation. Altogether, UV removal in this reactor set was found a bit higher around 5 percent than DOC removal.

Figure 4.18a: UV Removal Pattern in Fully Aerated Reactor
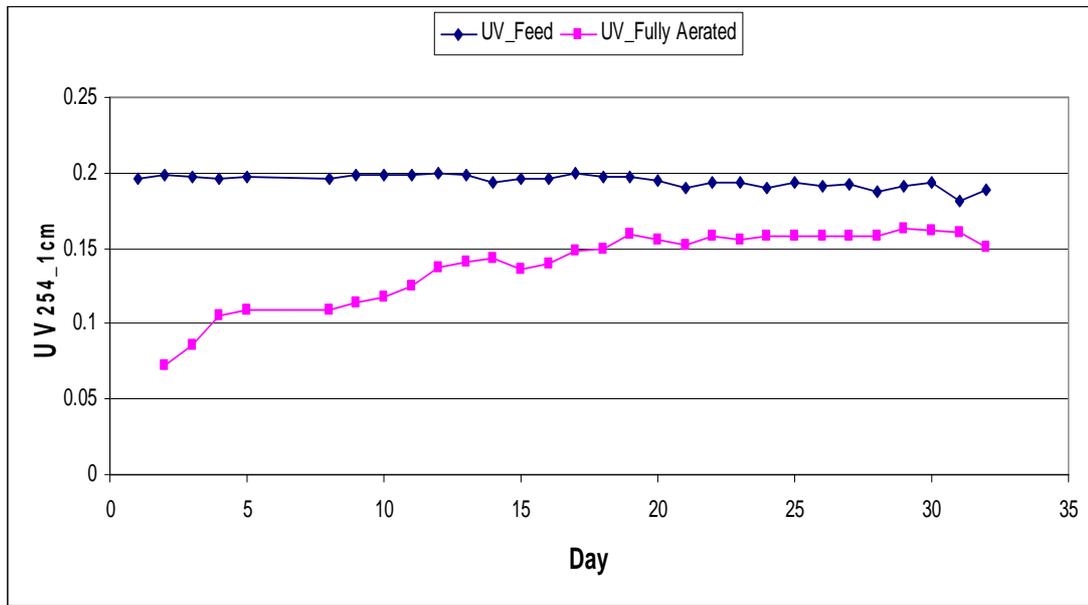
Figure 4.18b: DOC Removal in Fully Aerated Reactor
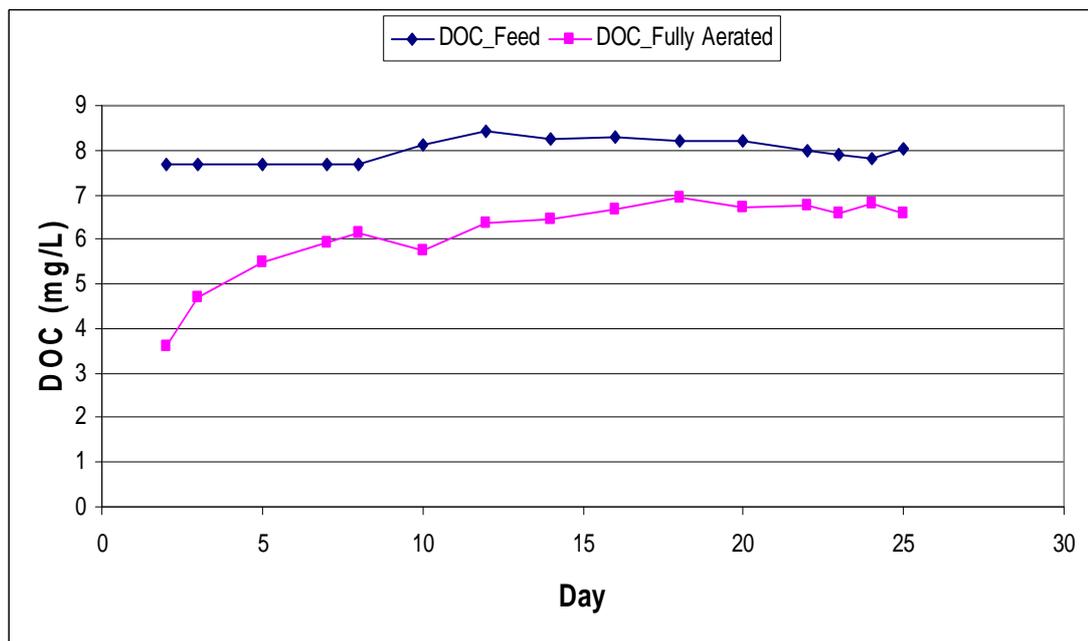
4.3.2 Reactor in Series

In this set of experiment, different reactors were kept in a series to remove organic material present in secondary wastewater sequentially through different reactor. The reactor in series was placed as described in section 3.2.2.2. Three sets of reactor particularly on Low Depth,

Medium Depth and High Depth in series were operated for the investigation. The feed and effluent water quality was measured each day until all the reactors were stabilized in terms of UV, DOC, Turbidity and SUVA. The analysis for all sets of reactor is done mainly based on the result of fore mentioned parameters during the stabilized periods or roughly last two weeks of operation. The averaged time is also presented in Table 4.2. The following section describes the reactor in series particularly Medium Depth (Reactor Set – 3) in detail. For the Low Depth and High Depth reactors set, only DOC and UV removal is discussed and rest of the results are presented in Appendix 9 and 10.

4.3.2.1 UV and DOC Removal in Low Depth Reactor

In this reactor set, two columns (Rc and Rd) were operated in series. As shown in Figure 4.19a and 4.19b, efficiency of both UV and DOC removal decreased continuously and started to stabilize after two weeks. As it contained less volume of activated carbon, it started to stabilize sooner than the medium and the high depth reactors. For the last two weeks after stabilization, average UV and DOC removal for this reactor set was achieved at around 14 and 21 percent respectively.

Figure 4.19a: UV Removal in Low Depth Reactor
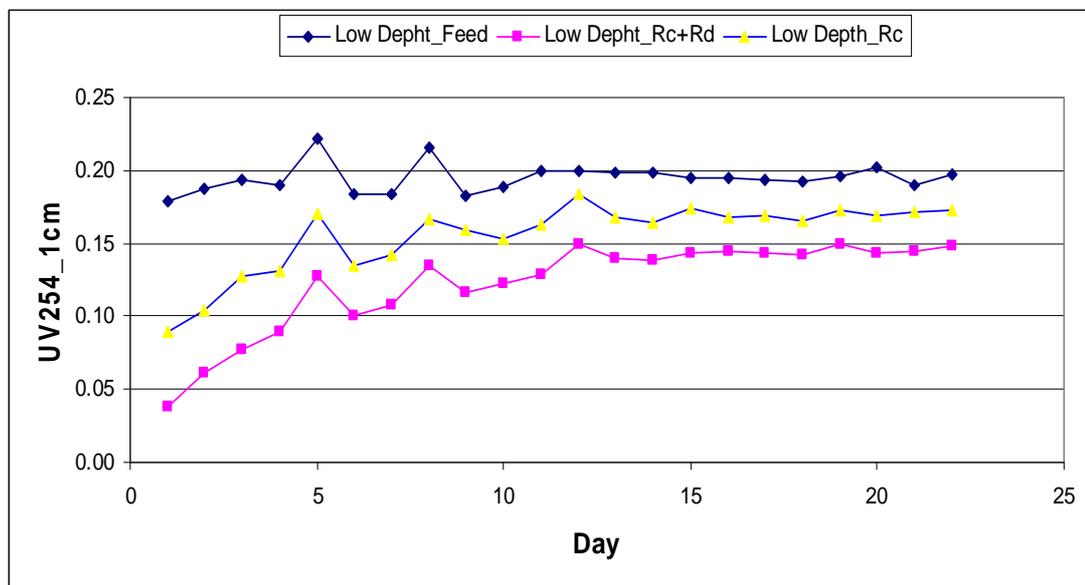
In this reactor set, both columns ended up with almost equal percentage of DOC and UV removal. The UV removal was recorded a bit higher than DOC removal in both reactor columns. The complete set of result for low depth reactor is also presented in Appendix 9 and 10.

Figure 4.19b: DOC Removal in Low Depth Reactor
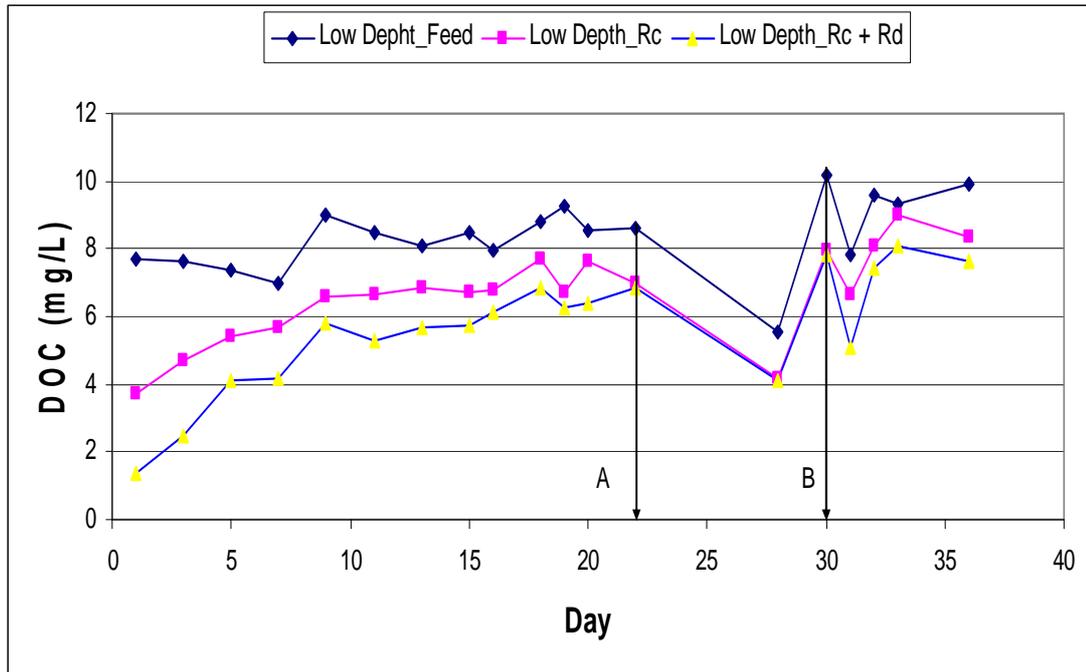
In Figure: BAC treated water was recycled back to the system again from Line A to Line B

The BAC treated water was also recycled to the system to observe the effect of UV removal on secondary wastewater. This gave little bit different removal pattern by showing more percentage of UV removal during second run than feeding SWWE. For the first set of recycling, 10 percent more UV removal was obtained on first column while for the second set, first column behaved normally but second column achieved 10 percent more UV removal than in fresh feed of SWWE. This indicates recycling BAC effluent could give more removal and might be helpful to reduce the EBCT by increasing number of cycle. However, detail experiment need to be carried out for the verification as this was just the result of only few days. The percentage removal during recycling is presented in appendix 14.

4.3.2.2 UV and DOC Removal in Medium Depth Reactor in Series

In this reactor set, three columns (R1, R2 and R3) were operated in series. The EBCT was maintained at 20 min in each reactor column by adjusting the flow. The first column stabilized after two weeks of operation while the second and the third columns took one more week to stabilize. As shown in Figure 4.20a, total UV removal by three reactor columns was up to 90 percent only due to physical adsorption in the initial period. However, the physical adsorption capacity decreased until it stabilized, when microbial community were active for the removal of

organic material from the wastewater. The removal efficiency appeared nearly constant from the third week until low pH water was added. The overall efficiency of three reactors in series combination was almost 50 percent of UV absorbing material from the secondary wastewater.

Figure 4.20a: Total UV Removal Obtained by Three Reactors in Series
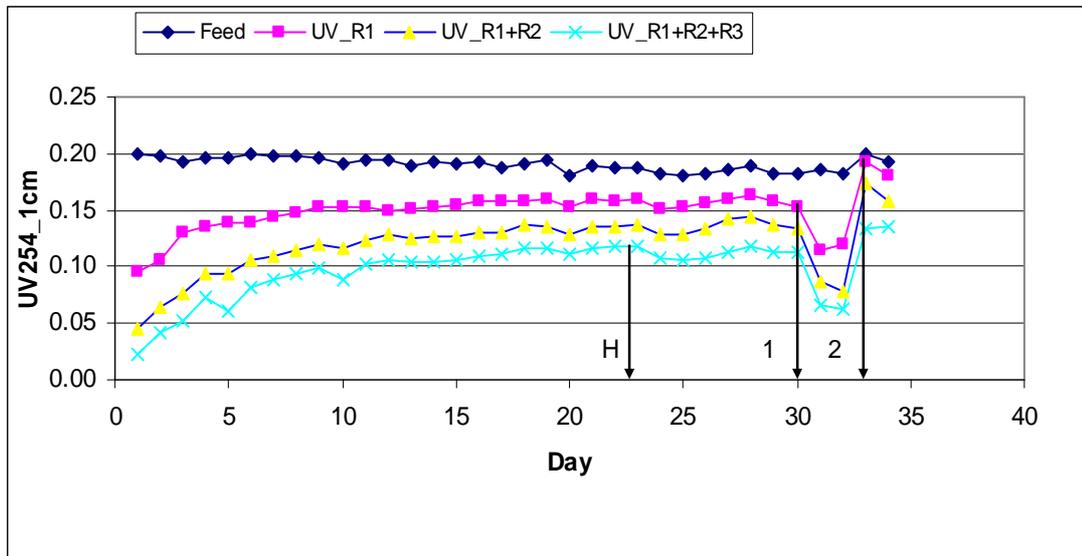
In figure Line H-Point of installing heater in third reactor column (R3), Arrow line 1-Point of dosing highly acidic water, Arrow line 2-Point of feeding SWWE again to quantify the performance of microbial community

Figure 4.20b: Total DOC Removal Obtained by Three Reactors in Series
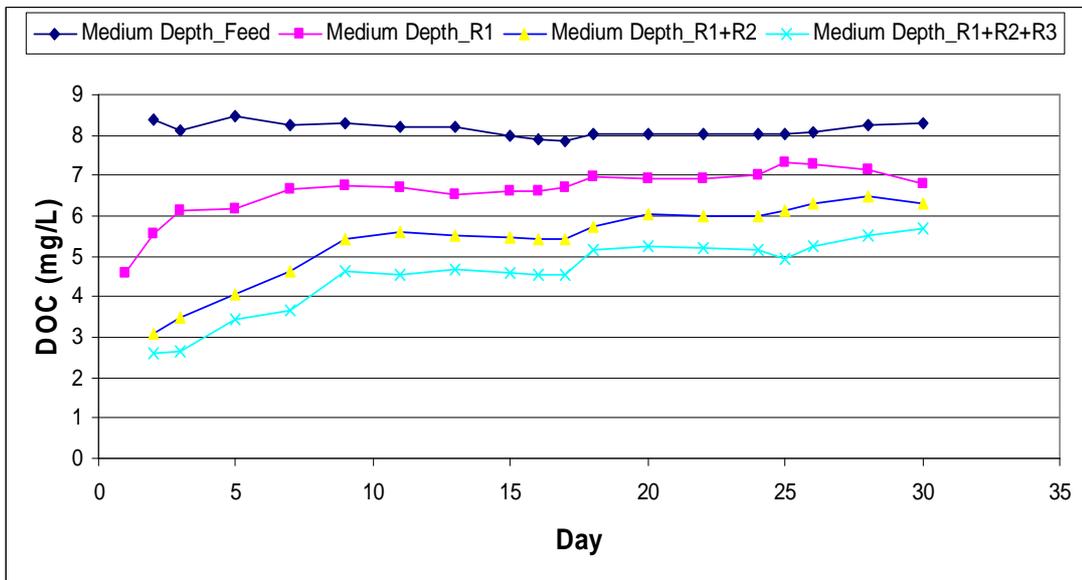
Like UV removal, DOC removal trend was almost similar for the medium depth reactor in series. However, the UV removal for the last weeks of stabilized period appeared to be around 5% higher than DOC removal indicating more removal of higher molecular weight organic

carbon. Altogether it was achieved at around 35 percent for the last weeks of stabilized period. The individual reactor performance remained around 15 to 20 percent as shown in Figure 4.20c. As shown in Figure 4.20c, once microbes are active, the percentage of removal organic material remained roughly the same throughout the operation period across all the reactor columns.

Figure 4.20c: DOC Removal Percentage Obtained from Each Reactor Column
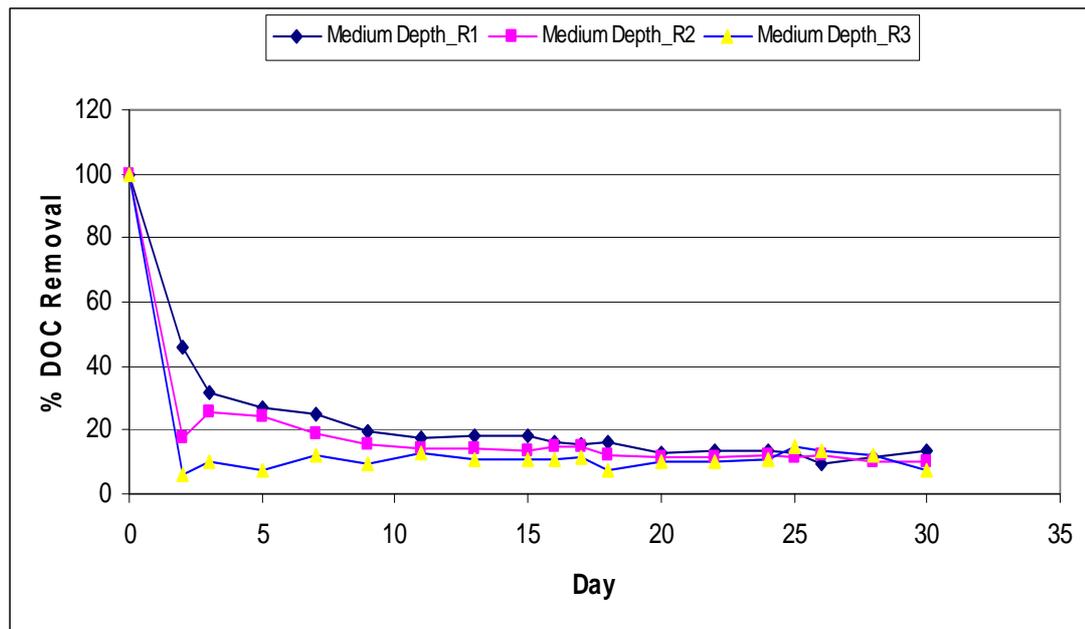
4.3.2.3 Effect of Acidic Wastewater in the BAC

This particular experiment was conducted based on the principle that, microbial activity can not occur under extremely low pH environment. So, after the stabilization of reactors, wastewater with extremely low pH was fed into the BAC columns and operated for two days to destroy all the microbes on and inside the activated carbon. Then, original secondary wastewater was again fed through the system. The microbial activity was quantified by calculating the difference between the combined result of physical adsorption with microbial activity and physical adsorption after killing all the microbes inside the reactor column.

Wastewater was adjusted to pH 2.9 and sent through columns for 2 days starting from day marked as '1' in Figure 4.20a in section 4.3.2.2. On day marked as '2', the wastewater with original pH was fed again to quantify the difference in UV removal by microbial community only. During this period, the UV removal was achieved around 66 percent. However, BAC acted as very good buffer and the pH value changed significantly as shown in Figure 4.21 and

remained highly acidic only in the first column. So, microbial community inside the first column only was fully affected.

Figure 4.21: pH Changes across the BAC Reactor in Series
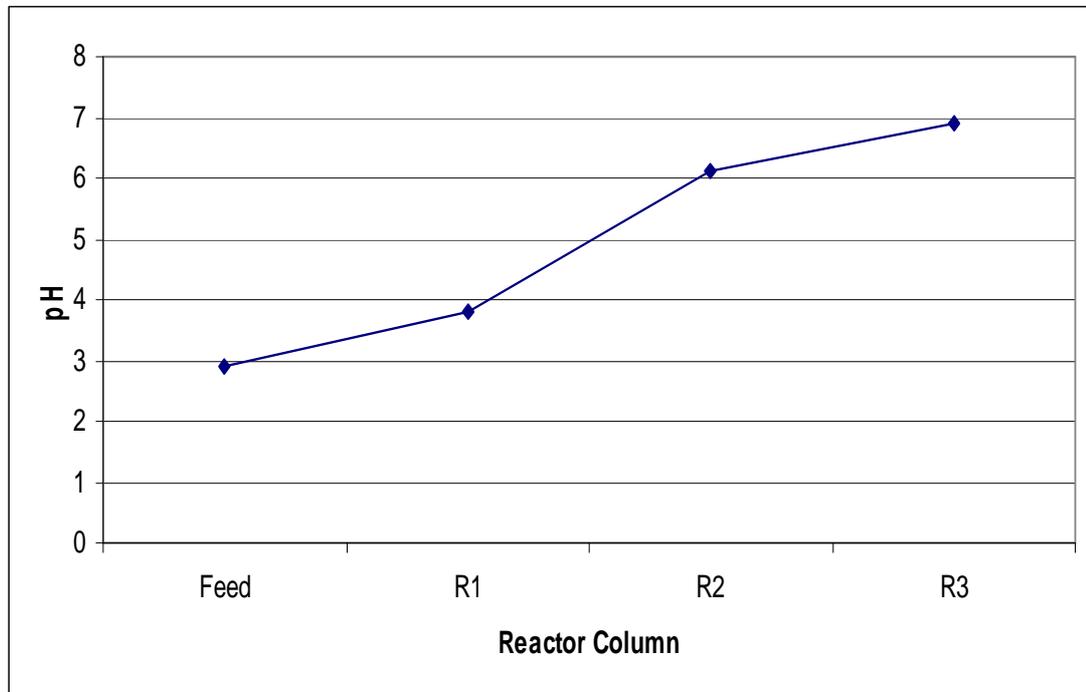
Feeding highly acidic wastewater enhanced the physical adsorption of organic material into the BAC bed while replacing all the microbial community inside the reactor as they can not survive in such condition. Under normal pH condition, the physical capacity of activated carbon was almost saturated. This becomes clear from the Figure 4.20a as the trend was almost straight for the last two weeks. In addition to that, further remaining physical adsorption sites were also utilized while exchanging ion with acidic wastewater. This means when normal wastewater was fed into the reactor, the removal should only be due to the physical adsorption as all the bacterial activity was already destroyed. Then the removal efficiency was measured again in terms of UV absorbance. It was found quite less around 3 percent inside the first reactor for given 20 min EBCT while UV removal was obtained around an average of 17 percent for the last two weeks of stabilization. This shows microbial community is responsible for almost 80 percent of the organic removal for final steady stage efficiency as shown in Figure 4.22.

Figure 4.22: Quantification of Microbial Community and Physical Adsorption
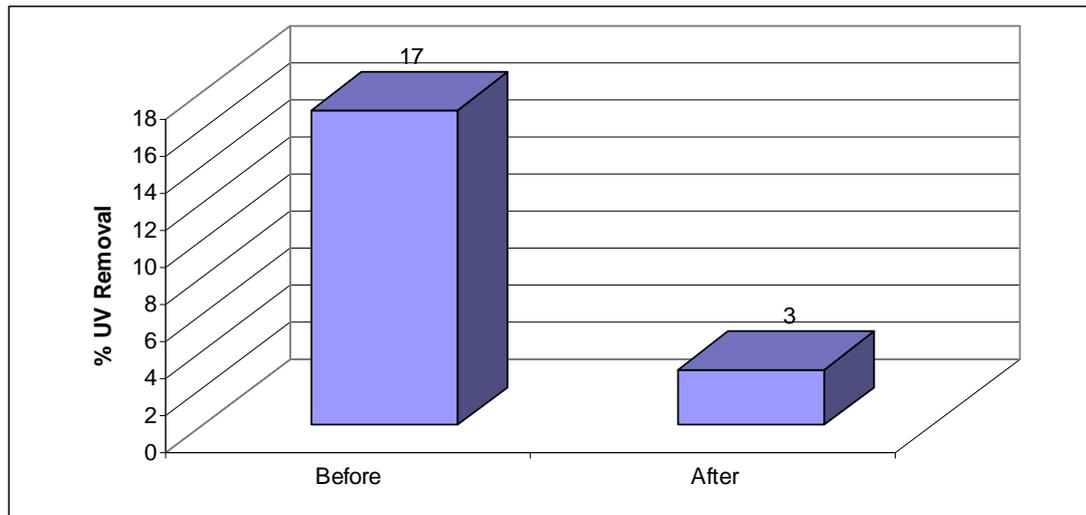
4.3.2.4 Effect of Temperature

Temperature effect was investigated only in the third column as all the columns were behaving in the same manner. So, a heater was installed inside the third column and the temperature was adjusted to 35°celsius. At the same time, rest of the reactors were left in the room temperature around 18 to 20°celsius. As presented in Figure 4.20a the heater was installed from the point H. After this, the UV removal efficiency was achieved slightly more than the past few days while it remained the same for the two reactors. This suggests that the removal of organic material may vary from time to time and season to season. However, a detail experiment is required to reach to the conclusion.

4.3.2.5 Effect of Backwashing

Back washing of all three columns was carried out with deionised water to remove suspended solids, sludge and unwanted protozoa from the system. This was done on weekly basis. However, no remarkable effect was observed in terms of both DOC and UV removal.

4.3.2.6 Effect on Turbidity Removal

The formation of cake layer due to the presence of suspended and colloid matter in water is also one of the problems during the operation of membrane filtration. They can be cleared by backwashing, but need to stop all the operations. In this context, removing the cake forming material prior to membrane filtration gives longer cycle with less number of requirements for membrane backwashing. So, the performance of BAC was also tested in terms of turbidity

removal. As shown in Figure 4.23, BAC was found partially effective for turbidity removal from the secondary wastewater.

Figure 4.23: Effect of Medium Depth BAC on Turbidity Removal
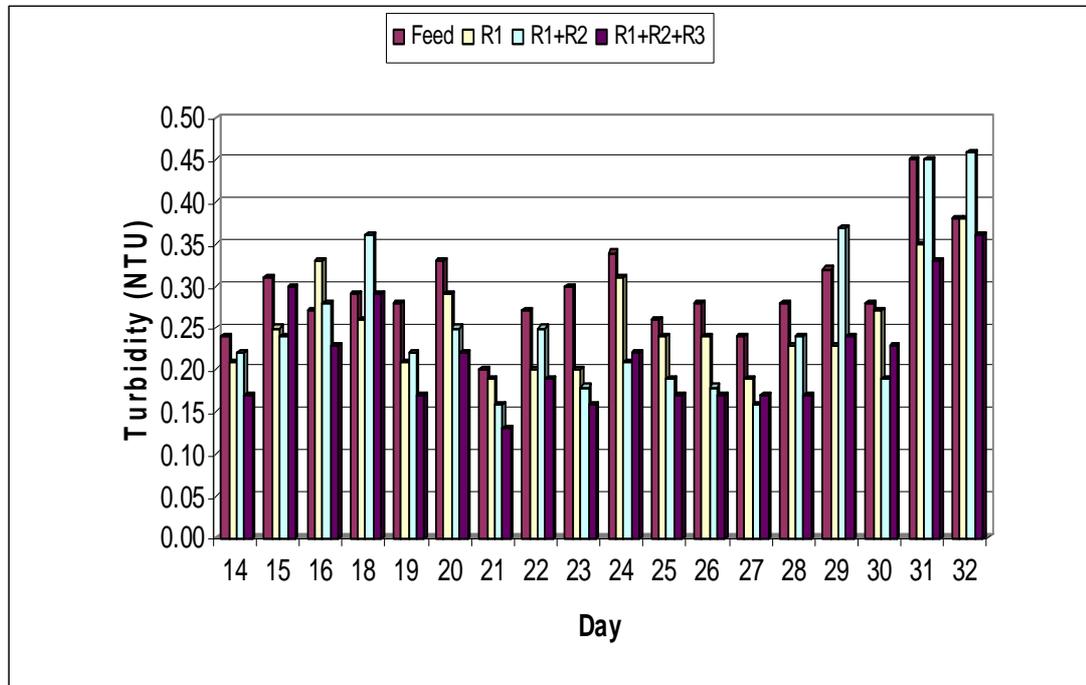
From the analysis, it is found that all the columns behave differently in this reactor set towards turbidity removal. The first column achieved around 16 percent of turbidity removal on average for the last two weeks of operation while the second column gave only around 3 followed by 11 percent for the third column. The detail data set for turbidity is provided on Appendix 12.

4.3.2.7 Effect BAC on Inorganic Nitrogen Moieties

In most of the cases, when wastewater passed through the series of reactors, changes in inorganic nitrogen moieties were noted particularly after reactors gained the steady state condition for last two weeks. From the principle, total inorganic nitrogen means sum of inorganic ammonia nitrogen, inorganic nitrite nitrogen and inorganic nitrate nitrogen. When wastewater was passes through the reactor, either nitrification or denitrification occurs based on the availability of oxygen. However, the amount of total inorganic nitrogen should be equal in both feed water and BAC effluent if there is no other conversion of organic to inorganic nitrogen inside the reactor. Figure 4.24 presents the difference in inorganic nitrogen between feed water and column of series. For most of the time it was found the amount of total

inorganic nitrogen was increasing. The maximum change was up to 37 percent. On average, it was 4 percent increase in inorganic nitrogen during steady state period. However it depends upon the amount present in feed water as well.   As shown in Figure 4.24, total inorganic nitrogen is measured more in first reactor than in feed.

Figure 4.24: Indication of Organic Nitrogen Conversion
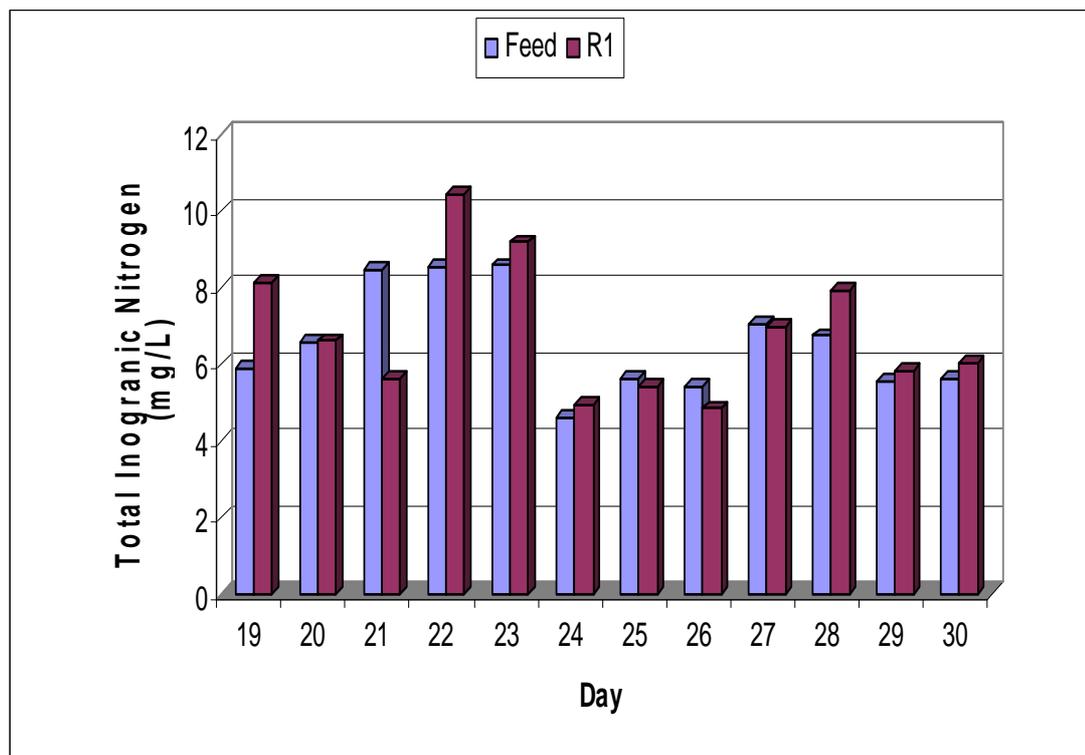
This indicates that, conversion of inorganic nitrogen could happen in the BAC system. However, a fluctuated trend was observed in the amount of total inorganic nitrogen. On this ground, it can not be concluded without measuring DON. It was not measured because of lack of DON measurement facility in the lab but was analysed in indirect way. This still shows the possibility that BAC might also be used for the removal of organic nitrogen from the wastewater. Organic nitrogen is suspected to be responsible for both irreversible fouling of membrane and for carcinogenic disinfection by products such as NDMA. Usually, NDMA is not removed by RO membrane. Hence, achieving better organic nitrogen removal is a must-to-do in better pre-treatment. Results indicated BAC might provide such advantage by converting organic nitrogen to inorganic nitrogen. However, detail investigation of DON is needed prior to this conclusion.

Figure 4.25: Effects of BAC on Ammonia Nitrogen
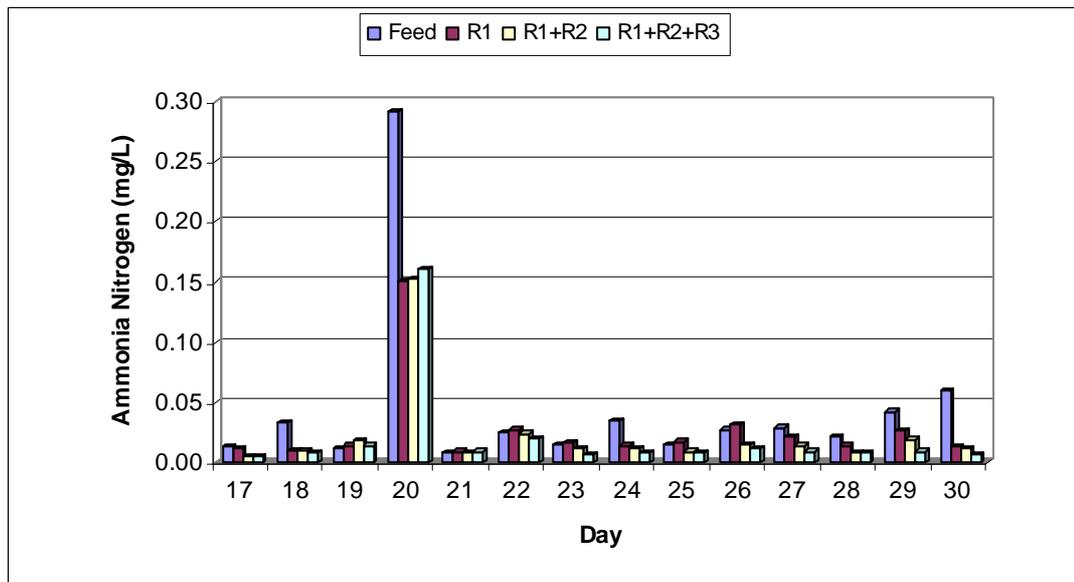
Similarly, the ammonia was found to be oxidized in all reactors. Figure 4.25 shows the behaviour of the medium depth reactor set towards ammonia nitrogen for the last two weeks of steady state period. It was found that, the amount of ammonia in most of the cases was decreased while passing though the different reactor columns. However, no consistent trend was found for Nitrite and Nitrate. They remained fluctuating throughout the operation. The result obtained for the last two weeks for Nitrite and Nitrate is presented in the Figure 4.26 and 4.27 and full data set for the whole operation period is provided in Appendix 12.

Figure.4.26: Effect of BAC on Nitrite Nitrogen
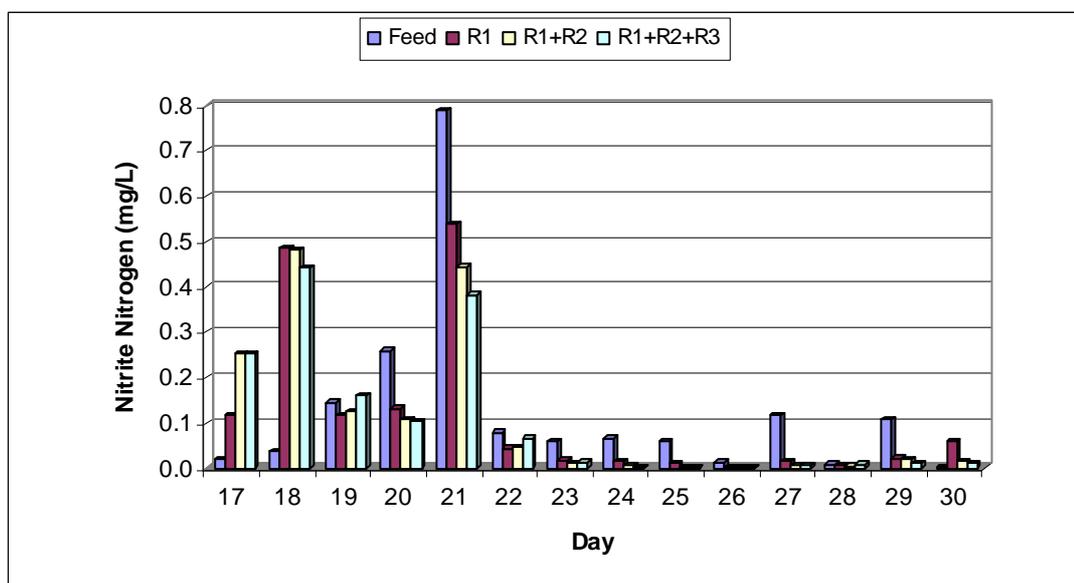
Figure 4.27: Effect of BAC on Nitrate Nitrogen
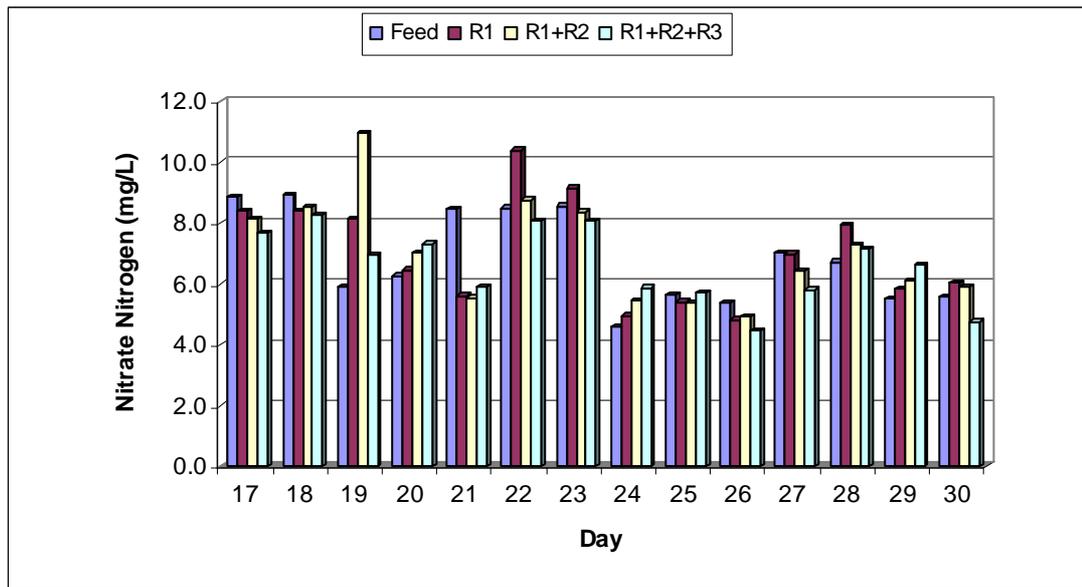
4.3.2.8 UV and DOC Removal in High Depth Reactor

In this set, two columns (Ra and Rb) were operated in series with bed depth of 15cm each. The EBCT was maintained 20 minutes approximately for the first three weeks and then doubled to 40 minutes to see the effect of bed contact time on removal of organic matter from the wastewater. This reactor was also started to stabilize from the third week of operation as shown in Figure 4.28a and 4.28b.

Figure 4.28a: UV removal Efficiency in High Depth BAC Reactor
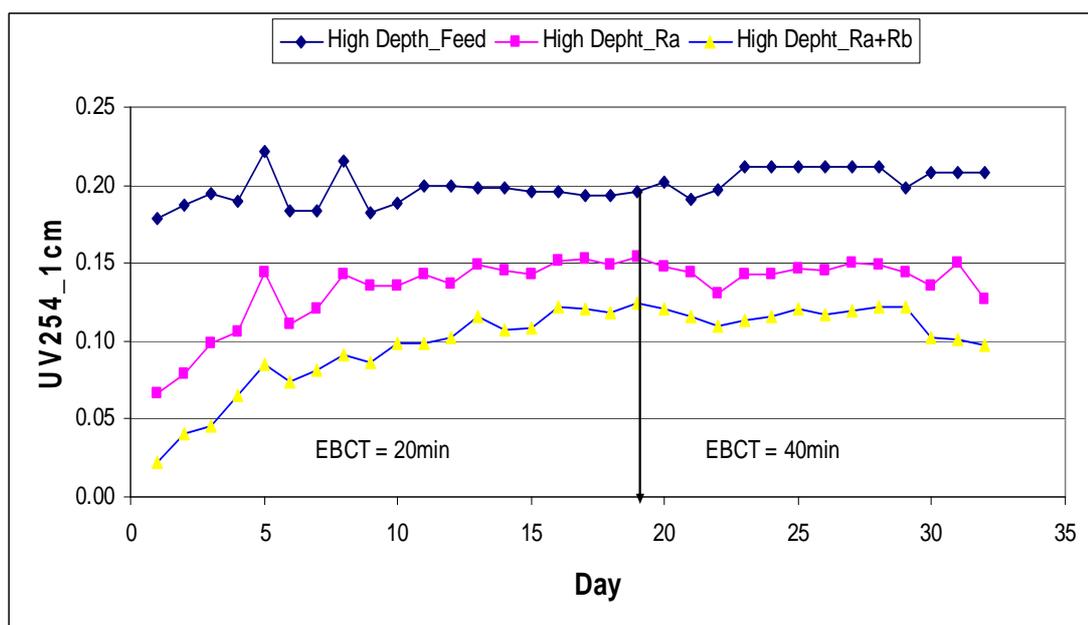
As in other reactor set, percentage of UV removal was more than DOC removal. For the 20-minute bed contact time DOC and UV removal was achieved around 33 and 38 percent respectively. The increase in bed contact time in this reactor gave increase in both UV and DOC removal. The removal percentage of UV and DOC was increased by 10% and 12% respectively. The detail result obtained during the operation is presented on Appendix 9 & 10.

Figure 4.28b: DOC removal Efficiency in High Depth BAC Reactor
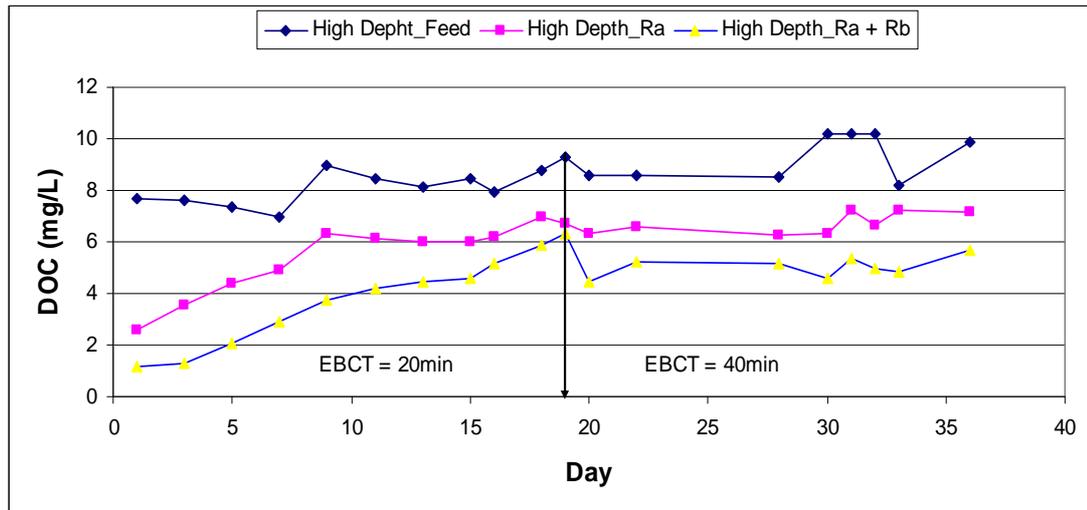
4.3.3 Comparison of Fully Aerated and Non Aerated Reactor

All the physical parameters for the fully aerated and non-aerated reactors were maintained same to see the effect of oxygen on microbial activity and hence respective effect on the removal of organic material from the wastewater.

Figure 4.29a: Comparison of UV removal in Fully Aerated and Non Aerated Reactor
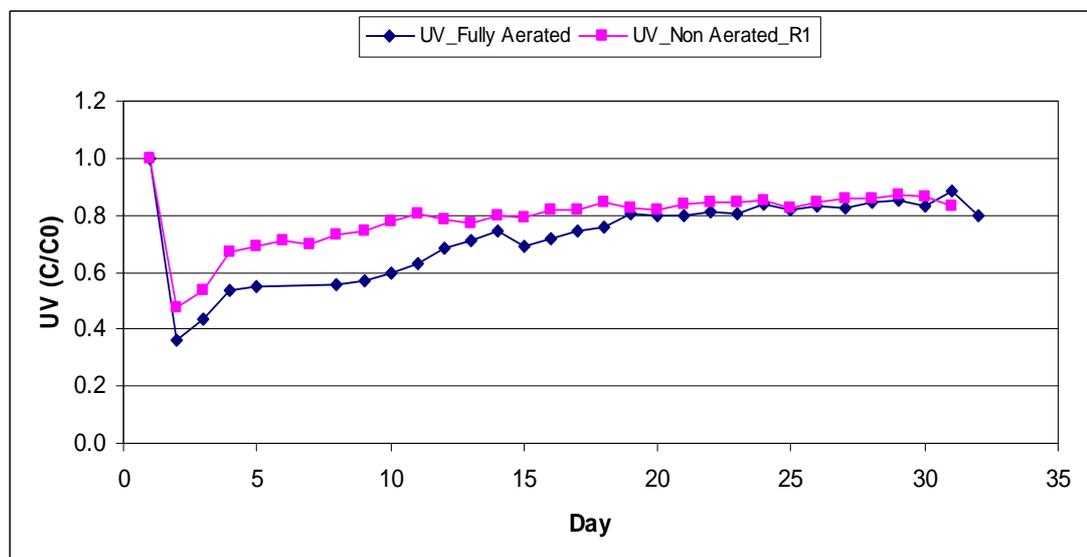
For these systems, bed contact time and bed depth were maintained same respectively 20 min and 10cm. Despite aerating one reactor up to full extent, no significant difference was observed in terms of both UV and DOC removal. As can be seen in the Figures 4.29a and 4.29b, both UV and DOC removal were stabilized around 20 percent for the last weeks of operation in both fully aerated and non-aerated conditions. However, from the Figure 4.29a, it can be seen that, the aerated reactor took one more week to achieve steady state. This means, the aeration slightly enhanced the physical adsorption without any significant effect on removal efficiency due to microbial community inside the reactor. Aeration did not impact on DOC or UV removal because oxygen demand by DOC (2mg/L) or ammonia (0.2mg/L) is very small compared to total oxygen availability.

Figure 4.29b: Comparison of DOC removal in Fully Aerated and Non Aerated Reactor
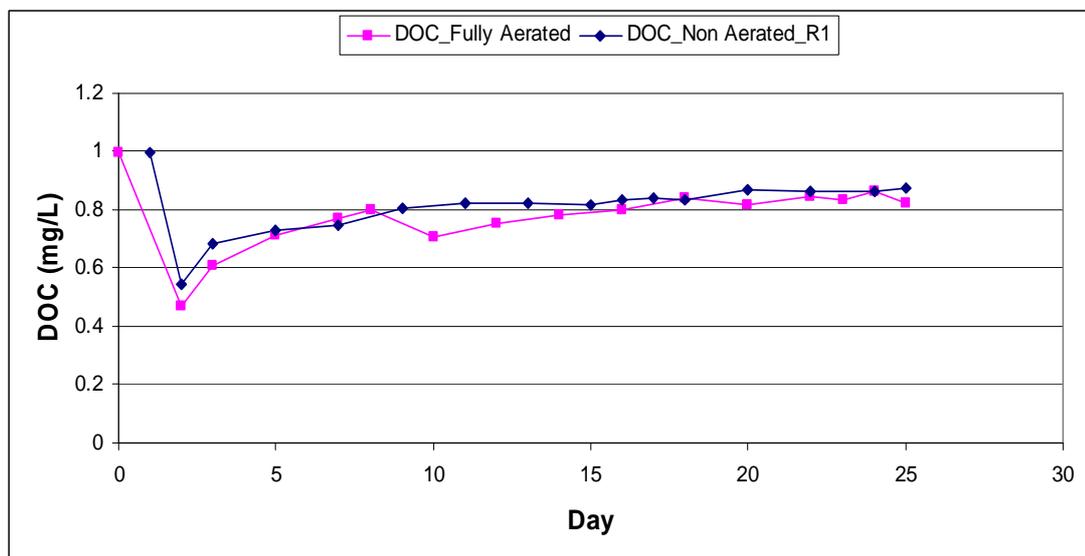
4.3.4 Comparison of Bed Depth for the Removal of Organic Material

The percentage of DOC and UV removal increased with increase in bed depth. However, no significant difference was observed on increasing the bed depth by two times and three times. As shown in Table 4.1, no increase in DOC removal was observed on increasing from 5cm to 15cm bed depth although UV removal increased by 7 percent for the last two weeks of steady state condition.

Table 4.2: Average Efficiency of Reactor during Steady State Condition

Reactor Column		R1		R1+R2		R1+R2+R3		Remarks
Type	EBCT	DOC	UV	DOC	UV	DOC	UV	
High Depth	20min	23	22	33	38			15-17 July for UV and (last 3 days), 14-17 July for DOC (Last 4 days)
	40 min	27	31	45	48			18 July-17 Aug (Last 21 days)
Medium Depth	20min	13	16	28	30	35	40	21 June-4July (Last 15 days)
Low Depth	20min	14	15	21	29			18 July-17 Aug (Last 21 days)

Figure 4.30a: UV Removal Efficiency in Various Bed Depth
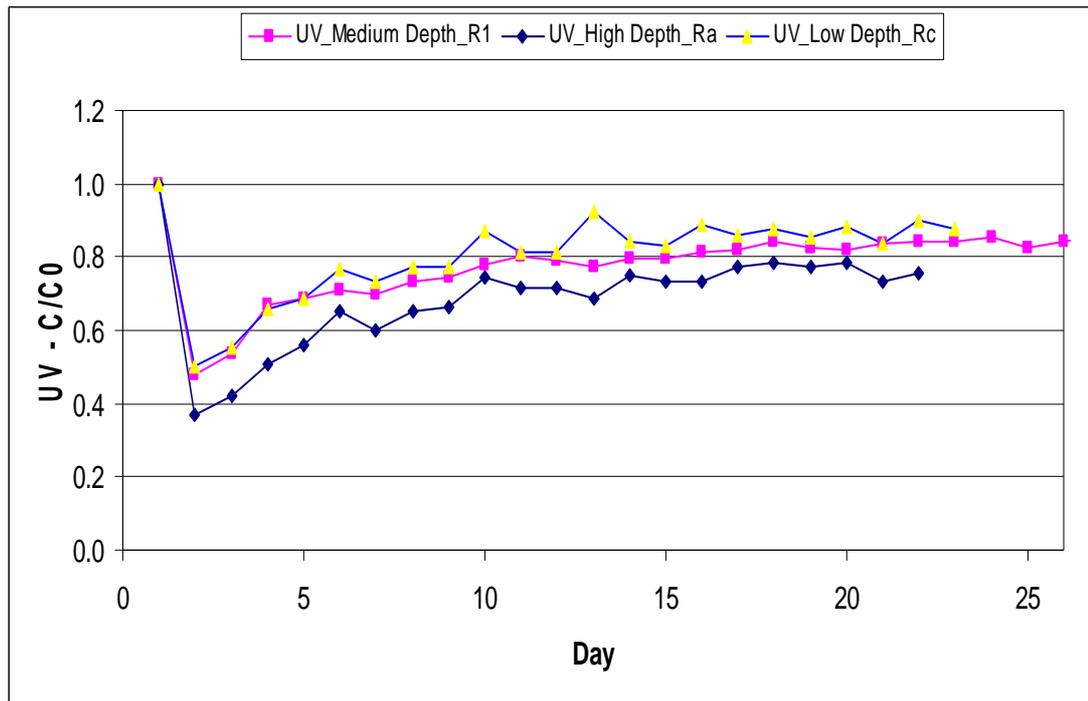
Figure 4.30b: DOC Removal Efficiency in Various Bed Depth
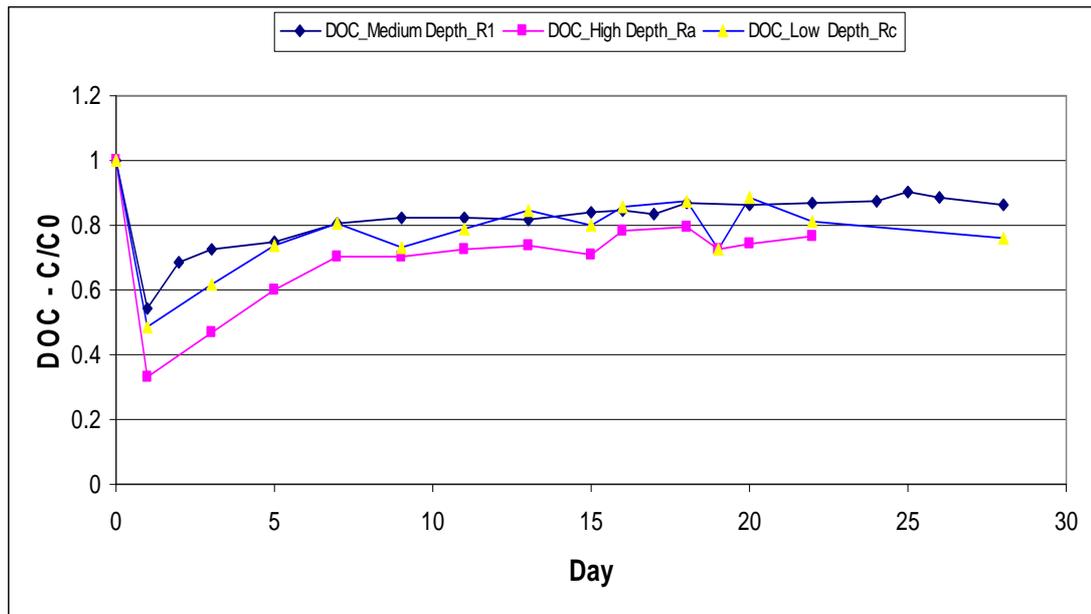
Overall, two columns in combination for the low depth achieved respectively 21 and 29 percent average UV and DOC removal. Doubling the depth to 10cm gave only 28 and 30 percent removal. Similarly, the 15 cm depth reactor set achieved around 33 and 38 percent removal of DOC and UV giving around just 10 percent further removal. The UV and DOC removal pattern for various depth reactors for the first column is also presented in Figure 4.30a and 4.30b. Only the results from the first column of reactors are presented in the Figure 4.30a and 4.30b for better presentability and illustration purpose.

4.3.5 Effect of Bed Contact Time

The effect of bed contact time was found to be proportional to the removal in organic material from the secondary wastewater. The EBCT was varied in high bed depth reactor series. Initially it was operated at 20 min bed contact time then it was increased by double to 40 min. As presented in Table 4.1 DOC removal was increased by 12 percent more. The reason is, as the microbial community in the reactor system gets more time, they degrade more organic matter and result in more efficiency. The Figure 4.28a and 4.28b shows increase in removal efficiency after increasing the bed contact time.

4.3.6 Conclusion

BAC as pre-treatment could be an effective solution. However, the adsorption capacity keeps decreasing as time goes by and microbial activity gives only a slim removal of organic matter present in the wastewater. It remained same even on increasing bed depth and contact time as all the reactors ended up within the same range of removal efficiency despite giving a bit more removal efficiency. However, they are still useful because they remove the large molecular aromatic carbon as indicated by higher UV removal efficiency. So, when BAC was used in combination with coagulation, it reduced the coagulant demand significantly and also gave much higher removal than coagulation alone as discussed in section 4.1.1.6. In addition to this, it also noticed higher removal while recycling the water for the second time. This gave a clue that expediting microbial activity might give better removal efficiency than optimising the physical parameters only. However, a detailed experiment is required for this verification. So, the activated carbon alone is less efficient on two grounds particularly increased bed depth did not significantly increase the removal and physical adsorption capacity quickly saturates.

The increase in EBCT increased removal efficiency indicating dominant microbiological activity. Such microbiological activities were found to be responsible for increasing coagulable organic carbon and reduction in turbidity. This also showed the possibility of conversion of organic nitrogen in to ammonia, which is reduced form of NDMA. So, it can be concluded that, when BAC is used alone or in combination with other pre-treatment method, it can prevent the fouling from cake formation on the surface of membrane, reduce the organic fouling by taking organic matter from the secondary wastewater away and also reduce bio fouling as it can reduce the organic nitrogen. This means BAC still can be used as an effective pre-treatment method in combination with others to reduce all types of fouling on and in the membrane.

CHAPTER 5: SUMMARY DISCUSSION AND RECOMMENDATIONS

5.1 Summary and Discussion

The number of experiments has been conducted ranging from physicochemical process to biological process as a pre-treatment of secondary wastewater effluent. They are analysed independently and in combination with other experiments in terms of organic matter removal. As it is already known that organic carbon and organic nitrogen present in the wastewater is responsible for organic and bio fouling on and in the membrane and nitrogenous DBPs formation upon application of chloramine, attempts were focused on reducing them from the secondary wastewater before sending it through the membrane. So, the result obtained during the pre-treatment experimental investigation provides the following conclusion.

1. Coagulation by ferric chloride can act as a good method of pre-treatment as it can remove organic matter particularly hydrophobic part from the wastewater, which is major foulant of membrane. It was found during the experiment that, the removal of organic matter basically depends on the pH and the dose of ferric salt, and found to be effective around pH range of 5. For the favourable pH range this gives up to 60 percent removal when it was used over a wide range from 1.25 to 160mg/L of coagulant.

2. The low dose up to 20mg/L did not appear to be effective as removal efficiency was not increased as a function of ferric chloride dose. During analysis it was found that, suspended solid present in the wastewater resisted the mixing of coagulant with sample and hence reduced the DOC removal efficiency.

3. The result of DOC modelling showed that, the model prepared for drinking water is valid for wastewater as well, as it fits very well for both secondary wastewaters from the Beenyup and the Woodman Point wastewater treatment plant. It gave only 0.39mg/L error in prediction despite the effect introduced by the presence of suspended solids in the lower range dose.

4. MIEX® is capable of removing both hydrophobic and hydrophilic part from the secondary wastewater and efficiently removes up to 65 percent DOC from secondary wastewater when it was dosed up to 32ml/L. Almost 80 percent of the total removal was found to be removed within first five minutes. So, instead of increasing contact time, increase in dose will be effective for MIEX® treatment.

5. The variation of pH in both acidic and basic range did not work very well for MIEX®. Both DOC and UV removal efficiency was even decreased due to manipulation of pH. In

addition, the combination of MIEX® followed by the ferric chloride also did not appear effective as no significant increase in DOC removal was achieved.

6. Based on the experiment conducted on aerated and non aerated condition, DO level dropped consistently. However, maintaining sufficient DO did not enhance the microbial activity in terms of removal of organic matter present in the secondary wastewater.

7. The removal of organic material present in the secondary wastewater depends upon the bed contact time and the bed depth. It was found the former one is more effective than later. However, the increase in efficiency was found to be very low in comparison to the capital cost.

8. The removal efficiency is found around 20 percent during the steady state condition for the BAC depth of 10 cm and 20 min bed contact time.

9. The increase in bed contact time from 20 to 40 minutes increased 12 percent DOC removal efficiency in high depth reactor set from 33 to 45 percent.

10. The increase in inorganic nitrogen in the BAC treated water hints the decrease in organic nitrogen in wastewater. As the organic nitrogen is the main source of bio fouling and carcinogenic DBPs, BAC as pre-treatment could be an effective solution to reduce bio fouling and formation DBPs such as NDMA, which passes through the RO membrane.

11. The BAC treatment was found to be highly effective when used in combination with coagulation with ferric chloride. This reduced the demand of coagulant significantly. The DOC removal by coagulant was found to increase significantly after treating the wastewater by BAC. This means the water passed through the BAC is much more amenable to coagulation as non sorbable portion (by ferric chloride) of organic matter in the wastewater is converted in to sorbable portion. This combination could be a very effective solution to reduce all types of fouling like organic fouling, bio fouling and fouling due to cake formation on the surface of membrane.

5.2 Recommendations for Future Studies

The experiments conducted during this research gave some promising results with respect to reducing the fouling along with creating plenty of avenues for further investigations to get rid of organic matter present in the secondary wastewater for the purpose of reusing it. As one of the main objectives of the research is to achieve economical and efficient way of wastewater pre-treatment, maximizing the efficiency of biological process could be a better solution because they need low maintenance cost and it operates for long time with same investment. During this research, only the preliminary investigation undertaken on and understood that there are promising aspects of BAC but detail research is needed to optimize it.

1. The increase in bed contact time gives just more time for microbial community. Holding wastewater in a real wastewater treatment plant for a long time is difficult, as it demands much more space and capacity. In this context, the microbial activity needs to be expedited.

2. The use of MBR in combination with BAC could be an effective solution as it retains all the microbial population inside the reactor. This might help to attain the desired removal within a short contact time by enhancing the bacterial activity.

3. When BAC treated water was again recycled in to the system of reactor, very unique trend was observed for number of times. From the result, it seems that the organic matters are not readily adsorbed by the activated carbon straight away. Instead, if it is decomposed first by the already acclimatized microbial environment, they could be adsorbed by the same column. Changing physical parameter gives only more time to microbial community but it cannot expedite the process. So, the investigation should be focused on rapid performance of microbial community by providing decomposed organic material as readily available substrate for already acclimatized bacterial community. As this is fully microbial activity, the efficiency can be achieved in consistent manner on providing favourable condition for them.

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List of Appendices

Appendix 1: Coagulation of Beenyup Wastewater

Name	pH	Ferric Chloride Dose (mg/L)	Source DOC (mg/L)	Remaining DOC (mg/L)	Remaining UV254_1cm	SUVA (L/m-mg)
Source			5.17		0.1961	3.793
pH4_Fe1.25	4	1.25	5.15	4.66	0.1847	3.964
pH4_Fe5	4	5	5.17	4.57	0.1678	3.672
pH4_Fe10	4	10	5.17	4.54	0.1586	3.493
pH4_Fe20	4	20	5.17	4.19	0.1388	3.313
pH4_Fe40	4	40	5.04	2.98	0.0987	3.312
pH4_Fe80	4	80	5.17	2.40	0.0725	3.021
pH4_Fe160	4	160	5.04	2.05	0.0621	3.029
pH5_Fe1.25	5	1.25	5.15	4.82	0.1907	3.956
pH5_Fe5	5	5	5.17	4.78	0.1815	3.797
pH5_Fe10	5	10	5.17	4.78	0.1745	3.651
pH5_Fe20	5	20	5.17	4.44	0.1571	3.538
pH5_Fe40	5	40	5.04	3.43	0.1189	3.466
pH5_Fe80	5	80	5.17	2.50	0.0740	2.960
pH5_Fe160	5	160	5.04	2.01	0.0576	2.866
pH6_Fe1.25	6	1.25	5.15	4.92	0.1892	3.846
pH6_Fe5	6	5	5.17	4.98	0.1877	3.769
pH6_Fe10	6	10	5.17	4.84	0.1796	3.711
pH6_Fe20	6	20	5.17	4.59	0.1652	3.599
pH6_Fe40	6	40	5.04	3.86	0.1322	3.425
pH6_Fe80	6	80	5.17	3.02	0.0896	2.967
pH6_Fe160	6	160	5.04	2.40	0.0720	3.000
pH7_Fe1.25	7	1.25	5.15	4.95	0.1918	3.875
pH7_Fe5	7	5	5.17	4.94	0.1870	3.785
pH7_Fe10	7	10	5.17	4.81	0.1812	3.767
pH7_Fe20	7	20	5.17	4.57	0.1662	3.637
pH7_Fe40	7	40	5.04	4.04	0.1415	3.502
pH7_Fe80	7	80	5.17	3.49	0.1148	3.289
pH7_Fe160	7	160	5.04	2.83	0.0966	3.413
pH8_Fe1.25	8	1.25	5.15	4.95	0.1930	3.899
pH8_Fe5	8	5	5.17	4.98	0.1843	3.701
pH8_Fe10	8	10	5.17	4.83	0.1761	3.646
pH8_Fe20	8	20	5.17	4.55	0.1639	3.602
pH8_Fe40	8	40	5.04	4.16	0.1488	3.577
pH8_Fe80	8	80	5.04	3.45	0.1235	3.580
pH8_Fe160	8	160	5.04	3.13	0.1093	3.492
pH9_Fe1.25	9	1.25	5.15	4.90	0.1903	3.884
pH9_Fe5	9	5	5.17	4.81	0.1727	3.590
pH9_Fe10	9	10	5.17	4.80	0.1684	3.508
pH9_Fe20	9	20	5.17	4.56	0.1605	3.520
pH9_Fe40	9	40	5.04	4.07	0.1393	3.423
pH9_Fe80	9	80	5.04	3.50	0.1198	3.423
pH9_Fe160	9	160	5.04	3.21	0.1162	3.620

Appendix 2: Coagulation of Woodman Point Wastewater

Sample			DOC (mg/L)	UV254_1cm	SUVA (L/m-mg)
Name	pH	Ferric Chloride Dose (mg/L)			
Source		0	8.89	2.477	2.786
pH4_Fe1.25	4	1.25	8.16	2.319	2.842
pH4_Fe5	4	5	7.58	2.034	2.683
pH4_Fe10	4	10	7.01	1.804	2.573
pH4_Fe20	4	20	6.24	1.529	2.450
pH4_Fe40	4	40	4.82	1.075	2.230
pH4_Fe80	4	80	2.99	0.657	2.197
pH5_Fe1.25	5	1.25	8.61	2.423	2.814
pH5_Fe5	5	5	8.09	2.191	2.708
pH5_Fe10	5	10	8	2.011	2.514
pH5_Fe20	5	20	7.29	1.748	2.398
pH5_Fe40	5	40	5.09	1.167	2.293
pH5_Fe80	5	80	3.08	0.665	2.159
pH6_Fe1.25	6	1.25	8.53	2.45	2.872
pH6_Fe5	6	5	8.12	2.26	2.783
pH6_Fe10	6	10	7.97	2.163	2.714
pH6_Fe20	6	20	6.99	1.772	2.535
pH6_Fe40	6	40	6.21	1.55	2.496
pH6_Fe80	6	80	3.95	0.842	2.132
pH7_Fe1.25	7	1.25	8.77	2.426	2.766
pH7_Fe5	7	5	8.3	2.273	2.739
pH7_Fe10	7	10	8.11	2.161	2.665
pH7_Fe20	7	20	7.88	2.011	2.552
pH7_Fe40	7	40	6.56	1.648	2.512
pH7_Fe80	7	80	5.06	1.136	2.245
pH8_Fe1.25	8	1.25	8.43	2.395	2.842
pH8_Fe5	8	5	7.92	2.251	2.841
pH8_Fe10	8	10	8.07	2.084	2.584
pH8_Fe20	8	20	7.54	1.918	2.542
pH8_Fe40	8	40	6.42	1.616	2.519
pH8_Fe80	8	80	5.00	1.269	2.540
pH9_Fe1.25	8	1.25	7.98	2.254	2.824
pH9_Fe5	8	5	7.50	2.104	2.805
pH9_Fe10	8	10	7.65	2.007	2.622
pH9_Fe20	8	20	7.48	1.91	2.552
pH9_Fe40	8	40	6.48	1.648	2.541
pH9_Fe80	8	80	5.26	1.404	2.668

Appendix 3a: BAC in Combination with Ferric Chloride

	Beenyup	Beenyup BAC	WPWTP	WPWTP BAC
DOC (mg/L)	7.44	6.52	7.49	7.49
UV254_1cm	0.1764	0.1296	0.1733	0.618
SUVA (L/m-mg)	2.371	1.988	2.314	8.251

Sample			UV254_1cm	DOC (mg/L)	SUVA (L/m-mg)	Remarks
Name	pH	Ferric Chloride Dose (mg/L)				
Source		0	1.296	6.52	1.988	Beenyup Wastewater after Treating with BAC
pH5_Fe1.25	5	1.25	1.181	5.52	2.139	
pH5_Fe5	5	5	1.044	5.21	2.004	
pH5_Fe10	5	10	0.921	4.8	1.919	
pH5_Fe20	5	20	0.75	4.15	1.807	
pH5_Fe40	5	40	0.351	1.87	1.877	
pH5_Fe80	5	80	0.244	1.15	2.122	
Source		0	1.694	6.18	2.741	Kwinana Wastewater after Treating with BAC
pH5_Fe1.25	5	1.25	1.536	6.15	2.498	
pH5_Fe5	5	5	1.347	5.69	2.367	
pH5_Fe10	5	10	1.175	5.18	2.268	
pH5_Fe20	5	20	1.005	4.7	2.138	
pH5_Fe40	5	40	0.542	3.04	1.783	
pH5_Fe80	5	80	0.239	2.01	1.189	

Appendix 3b: Coagulation after Filtration (Beenyup Wastewater)

Sample			UV254_1cm	DOC (mg/L)	SUVA (L/m-mg)	Remarks
Name	pH	Ferric Chloride Dose (mg/L)				
Source		0	1.764	7.44	2.371	Beenyup Wastewater after filtering through 0.45 micron CA filter paper
pH5_Fe1.25	5	1.25	1.579	7.03	2.246	
pH5_Fe5	5	5	1.457	6.7	2.175	
pH5_Fe10	5	10	1.336	6.31	2.117	
pH5_Fe20	5	20	1.208	5.73	2.108	
pH5_Fe40	5	40	0.686	3.56	1.927	
pH5_Fe80	5	80	0.516	2.75	1.876	

Appendix 4:Comparison of Remaining DOC (DOCmeas) and Model Predicted Final DOC (DOCmodel) for Woodman Point Wastewater

$y = 1.0071x$
$R^2 = 0.9604$
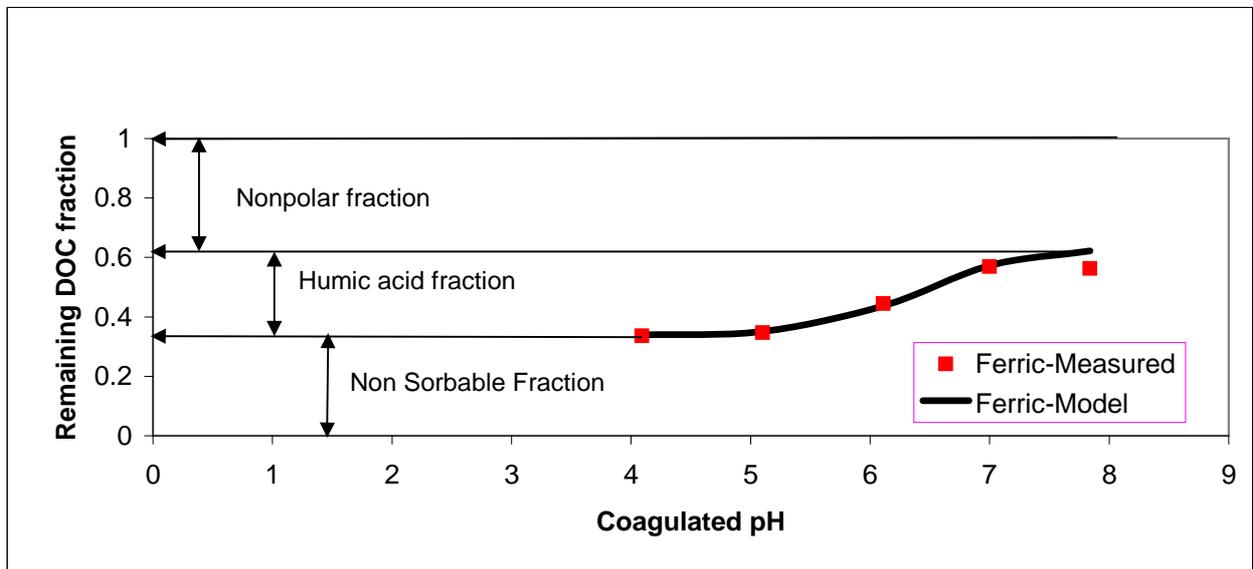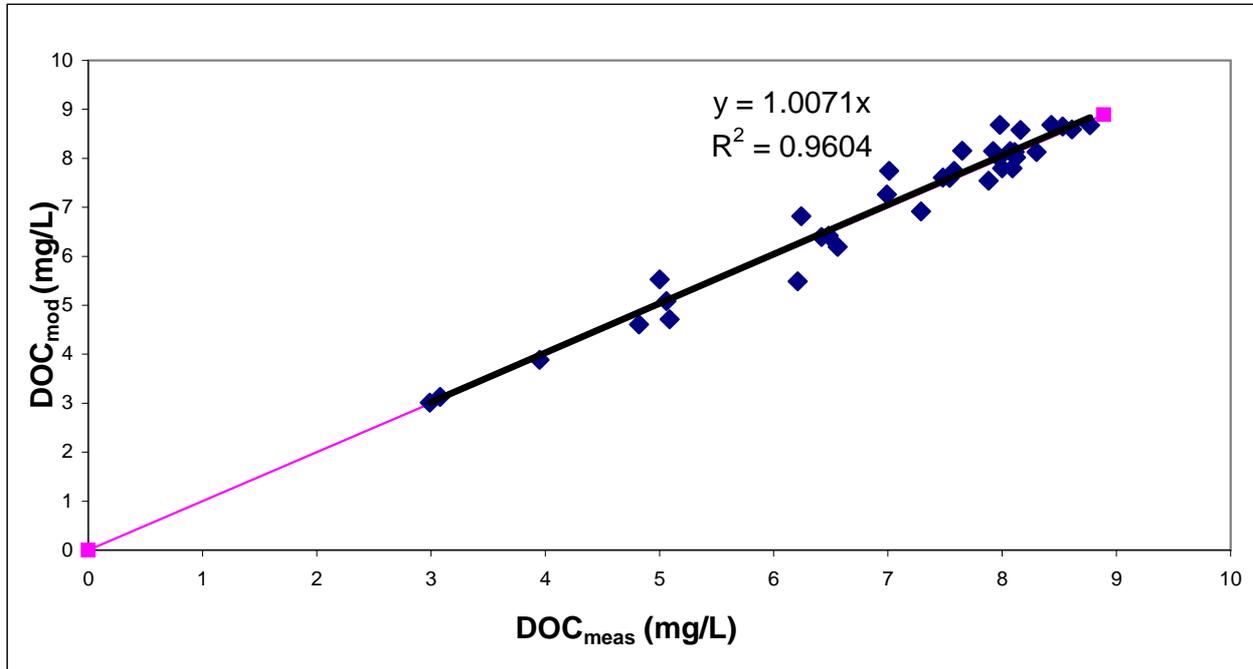
Ferric Chloride dose 80 mg/L, DOC - Dissolved Organic Carbon

Appendix 5: Chlorine decay in Beenyup Wastewater after Coagulation

Sample	pH7_Fe1.25		pH7_Fe5		pH7_Fe10		pH7_Fe20		pH7_Fe40		pH7_Fe80	
Time (hr)	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL
0	6.65		6.3	5.25	6.65	4.75	7.1	5.8	7.1	5.85	7.25	6.1
0.17	5.3	3.4	4.4	2.6	5.1	4.1	5.15	4.15	5.8	4.1	6.35	5.75
0.5	4.3	2.95	3.6	2.45	4.15	3.3	4.15	3.6	4.8	3.05	5.7	5.2
1	3.45	2.5	2.65	1.65	2.85	2.05	3.75	2.75	4.1	3.3	5	4.3
2	2.5	1.6	1.9	1.35	2.25	1.45	2.8	1.7	3.3	2.55	4.25	3.5
3	1.9	1.1	1.4	0.9	1.9	1.05	2.3	1.5	2.95	2.15	4.15	3.2
6	1.05	0.3	0.7	0.35	1.05	0.3	1.35	0.6	2.25	1.45	3.8	3
24	0.34	0	0.23	0	0.43	0	0.38	0	0.68	0.14	1.75	1.22
48	0.22	0	0.13	0	0.26	0	0.3	0		0	0.12	0
72	0.15	0	0.13	0	0.16	0	0.22	0	0.37	0	0.23	0
96	0.12	0	0.09	0	0.14	0	0.14	0	0.16	0	0.18	0
120	0.1	0	0.09	0	0.13	0	0.11	0	0.16	0	0.13	0

Sample	pH5_Fe1.25		pH5_Fe5		pH5_Fe10		pH5_Fe20		pH5_Fe40		pH5_Fe80	
Time (hr)	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL	TCL	FCL
0	6.55	4.8	7.1	5.4	5.85	3.15	7.8	6.3	8.1	4.2	8.35	6.35
0.17	5.1	4.05	5.3	4.25	3.4	2.5	5.55	4.6	6.45	5	7.05	5.15
0.5	4	3.05	4.1	3.1	2.75	1.85	4.4	3.6	5.05	4.4	6.7	5.65
1	3.2	1.85	3.4	2.5	2.1	1.3	4.15	3.35	4.25	3.35	6.35	5.5
2	2.4	1.35	2.65	1.7	1.45	0.75	3.25	2.4	4.05	3.15	5.75	4.95
3	1.2	0.55	2.1	1.25	0.9	0.25	2.6	1.85	3.65	2.65	5.55	4.3
6	1	0.18	1.18	0.39	0.66	0.13	1.6	0.98	2.77	1.99	4.5	3.2
24	0.15	0	0.32	0.05	0.24	0	0.49	0	1.05	0.42	4.2	2
48	0.12	0	0.19	0	0.17	0	0.32	0	0.61	0.1	1.36	0.79
72	0.1	0	0.11	0	0.1	0	0.17	0	0.28	0	0.95	0.56
96	0.08	0	0.1	0	0.08	0	0.12	0	0.19	0		

Note: All TCl and FCL in mg/L (TCL - Total Chlorine and FCL - Free Chlorine)

Appendix 6: UV$_{254}$ and DOC Removal by MIEX$^{®}$ for Beenyup Wastewater

SN	Sample Name	MIEX Dose (ml)	Time (min)	UV254$_{\_1cm}$	DOC (mg/L)	SUVA (L/m-mg)	pH
	SWWE	0	0	0.212	9.35	2.264	6.95
1	M1_T5	1	5	0.193	8.42	2.296	7.21
2	M2_T5	2	5	0.169	7.58	2.232	7.3
3	M4_T5	4	5	0.140	6.7	2.093	7.24
4	M8_T5	8	5	0.109	5.68	1.912	7.25
5	M16_T5	16	5	0.080	4.5	1.787	7.19
6	M32_T5	32	5	0.067	3.91	1.701	7.19
7	M1_T15	1	15	0.179	8.04	2.225	6.95
8	M2_T15	2	15	0.141	6.91	2.039	
9	M4_T15	4	15	0.108	5.82	1.847	
10	M8_T15	8	15	0.085	5.15	1.656	
11	M16_T15	16	15	0.064	4.06	1.571	
12	M32_T15	32	15	0.056	3.45	1.617	
13	M1_T20	1	20	0.175	7.98	2.193	
14	M2_T20	2	20	0.130	6.69	1.943	
15	M4_T20	4	20	0.103	6.09	1.685	
16	M8_T20	8	20	0.075	4.84	1.548	
17	M16_T20	16	20	0.062	3.98	1.545	
18	M32_T20	32	20	0.055	3.3	1.664	

Appendix 7a: UV$_{254}$ and DOC Removal by MIEX$^®$ on Varying pH (Beenyup Wastewater)

SN	Sample Name	pH	Time (min)	UV254_1cm	DOC (mg/L)	SUVA (L/m-mg)	Adjusted pH	Mixing pH (during 10 to 20 min)	Remarks
1	pH4_T5	4	5	0.1439	6.75	2.131852	4.01	4.71	
2	pH5_T5	5	5	0.1314	6.37	2.062794	5.08	5.72	
3	pH6_T5	6	5	0.1295	6.23	2.078652	6.07	6.5	
4	pH7_T5	7	5	0.1204	6.19	1.945073	6.91	7.48	
5	pH8_T5	8	5	0.1252	6.15	2.035772	7.93	8.03	
6	pH9_T5	9	5	0.1271	6.21	2.046699	8.9	8.65	16ml/L MIEX
7	pH4_T20	4	20	0.1074	5.58	1.924731			
8	pH5_T20	5	20	0.0919	5.29	1.73724			
9	pH6_T20	6	20	0.0871	5.1	1.707843			
10	pH7_T20	7	20	0.0745	4.58	1.626638			
11	pH8_T20	8	20	0.0757	4.72	1.603814			
12	pH9_T20	9	20	0.074	4.62	1.601732			

Appendix 7b: DOC Removal by MIEX® and Ferric Chloride in Combination

Sample Name	Ferric Chloride Dose (mg/L)	DOC (mg/L)		Remarks
		Without Adjusting pH	Adjusting pH at 5	
SWWE	0	9.33	8.63	
MIEX	0	4.92	4.74	
M+Fe1.25	1.25	4.83	4.65	
M+Fe5	5	4.62	4.5	16ml/L MIEX
M+Fe10	10	4.44	4.37	
M+Fe20	20	4.07	4.21	
M+Fe40	40	3.52	3.68	
M+Fe80	80	2.4	2.63	

Appendix 8: Result obtained for Fully Aerated Reacotor Set

SN	Date	DO (mg/L)	UV254_1cm		DOC (mg/L)		SUVA (L/m-mg)		Inorganic Nitrogen (mg/L)			Turbidity (NTU)
			Feed	Filtered	Feed	Filtered	Feed	Filtered	NH_3	NO_2	NO_X	
1	26-May	7.800	0.197		7.68				0.049	0.016	8.330	0.260
2	27-May	7.720	0.198	0.072	7.68	3.59	2.58	2.00	0.005	0.011	6.050	0.480
3	28-May	6.020	0.198	0.086	7.68	4.69	2.57	1.83	0.004	0.005	5.610	0.380
4	29-May	5.380	0.197	0.106					0.007	0.014	7.260	0.400
5	30-May	3.210	0.198	0.109					0.054	0.128	8.230	0.380
8	1-Jun		0.197	0.109					0.203	0.320	10.000	0.370
9	2-Jun	2.400	0.199	0.114	7.68	5.48	2.59	2.08	0.013	0.300	9.940	0.430
10	3-Jun	1.690	0.199	0.118					0.015	0.431	9.560	0.260
11	4-Jun	1.580	0.199	0.125	7.68	5.91	2.59	2.12	0.012	0.150	10.050	0.390
12	5-Jun	8.000	0.200	0.137	7.68	6.16	2.60	2.23	0.373	0.340	9.310	1.360
13	6-Jun	8.000	0.198	0.141					0.082	0.322	9.160	1.660
14	7-Jun	8.000	0.193	0.143	8.13	5.73	2.38	2.50	0.135	0.227	7.290	4.200
15	8-Jun	8.000	0.197	0.136					0.170	0.130	10.100	1.260
16	9-Jun	8.000	0.196	0.140	8.45	6.36	2.31	2.19	0.208	0.165	10.010	1.560
17	10-Jun	8.000	0.200	0.148					0.020	0.170	10.340	1.140
18	11-Jun	8.000	0.198	0.149	8.25	6.47	2.39	2.30	0.012	0.151	7.970	1.170
19	12-Jun	8.000	0.198	0.159					0.016	0.139	4.960	1.330
20	13-Jun	8.000	0.195	0.156	8.31	6.67	2.35	2.34	0.009	0.045	4.880	1.730
21	14-Jun	8.000	0.190	0.152					0.008	0.065	7.040	4.730
22	15-Jun	8.000	0.194	0.158	8.22	6.92	2.36	2.28	0.009	0.022	4.880	1.620
23	16-Jun	8.000	0.194	0.156					0.006	0.030	8.390	1.250
24	17-Jun	8.000	0.190	0.159	8.19	6.71	2.32	2.37	0.010	0.012	7.770	2.130
25	18-Jun	8.000	0.193	0.158					0.011	0.018	5.520	1.630
26	19-Jun	8.000	0.191	0.159	8.01	6.77	2.38	2.34	0.010	0.098	8.610	1.770
27	20-Jun	8.000	0.192	0.158	7.90	6.59	2.44	2.40	0.006	0.314	8.710	1.520
28	21-Jun	8.000	0.187	0.158	7.83	6.78	2.39	2.32	0.002	0.054	8.440	1.480
29	22-Jun	8.000	0.191	0.162	8.03	6.60	2.37	2.46	0.003	0.008	8.680	1.050
30	23-Jun	8.000	0.194	0.161					0.003	0.008	7.510	1.170
31	24-Jun	8.000	0.181	0.161	8.02	5.30	2.26	3.03	0.004	0.013	8.910	0.820
32	25-Jun	8.000	0.189	0.151					0.004	0.088	6.210	2.710

Appendix 9: UV254, DOC and SUVA in High and Low Depth Reactors

Day	Date	UV254_1cm						DOC (mg/L)						SUVA (L/m-mg)					
		High Depth			Low Depth			High Depth			Low Depth			High Depth			Low Depth		
		Feed	Ra	Rb	Feed	Rc	Rd	Feed	Ra	Rb	Feed	Rc	Rd	Feed	Ra	Rb	Feed	Rc	Rd
0																			
1	26-Jun	0.179	0.066	0.023	0.179	0.090	0.037	7.700	2.550	1.330	7.700	3.720	1.400	2.318	2.584	1.692	2.318	2.419	2.671
2	27-Jun	0.187	0.079	0.041	0.187	0.104	0.062												
3	28-Jun	0.194	0.099	0.046	0.194	0.128	0.078	7.640	3.560	1.320	7.640	4.720	2.480	2.539	2.767	3.477	2.539	2.712	3.133
4	29-Jun	0.190	0.106	0.066	0.190	0.131	0.090												
5	30-Jun	0.222	0.144	0.084	0.222	0.170	0.128	7.340	4.410	2.090	7.340	5.400	4.080	3.023	3.272	4.038	3.023	3.156	3.125
6	1-Jul	0.184	0.111	0.074	0.184	0.135	0.101												
7	2-Jul	0.184	0.120	0.081	0.184	0.142	0.108	7.000	4.920	2.910	7.000	5.650	4.170	2.630	2.447	2.777	2.630	2.510	2.590
8	3-Jul	0.215	0.143	0.091	0.215	0.167	0.134												
9	4-Jul	0.183	0.136	0.087	0.183	0.159	0.117	8.990	6.340	3.710	8.990	6.590	5.800	2.032	2.140	2.334	2.032	2.411	2.010
10	5-Jul	0.189	0.135	0.099	0.189	0.154	0.123												
11	6-Jul	0.199	0.142	0.099	0.199	0.163	0.128	8.470	6.150	4.170	8.470	6.680	5.280	2.353	2.314	2.372	2.353	2.433	2.428
12	7-Jul	0.200	0.137	0.102	0.200	0.184	0.150												
13	8-Jul	0.198	0.149	0.116	0.198	0.167	0.139	8.100	5.970	4.470	8.100	6.870	5.650	2.447	2.489	2.586	2.447	2.435	2.465
14	9-Jul	0.198	0.145	0.107	0.198	0.165	0.138												
15	10-Jul	0.195	0.143	0.109	0.195	0.174	0.143	8.450	5.970	4.570	8.450	6.740	5.710	2.312	2.397	2.381	2.312	2.576	2.506
16	14-Jul	0.195	0.151	0.122	0.195	0.168	0.144	7.940	6.220	5.160	7.940	6.790	6.130	2.461	2.429	2.355	2.461	2.474	2.352
17	15-Jul	0.194	0.152	0.120	0.194	0.170	0.144												
18	16-Jul	0.193	0.149	0.118	0.193	0.165	0.142	8.780	6.970	5.880	8.780	7.680	6.870	2.197	2.138	2.009	2.197	2.150	2.066
19	17-Jul	0.196	0.154	0.125	0.196	0.173	0.150	9.280	6.730	6.320	9.280	6.740	6.260	2.113	2.291	1.973	2.113	2.570	2.388
20	18-Jul	0.202	0.148	0.120	0.202	0.169	0.143	8.570	6.350	4.470	8.570	7.610	6.420	2.355	2.331	2.689	2.355	2.216	2.227
21	19-Jul	0.191	0.144	0.115	0.191	0.172	0.145												
22	20-Jul	0.197	0.130	0.109	0.197	0.173	0.149	8.580	6.560	5.230	8.580	6.980	6.860	2.293	1.982	2.090	2.293	2.471	2.165
23	26-Jul	0.211	0.143	0.114	0.211	0.161	0.102	8.530	6.240	5.130	5.520	4.200	4.090	2.478	2.292	2.220	3.830	3.821	2.487
24	27-Jul	0.211	0.143	0.116	0.151	0.101	0.098												
25	28-Jul	0.211	0.146	0.121	0.211	0.188	0.163	10.200	6.320	4.580	10.200	7.970	7.850	2.073	2.315	2.631	2.073	2.358	2.076
26	29-Jul	0.211	0.145	0.117	0.145	0.133	0.103	10.200	7.230	5.350	7.850	6.680	5.080	2.073	2.006	2.187	1.420	1.991	2.018
27	31-Jul	0.211	0.150	0.120	0.211	0.186	0.166	10.200	6.640	5.000	9.600	8.080	7.440	2.073	2.261	2.394	2.073	2.304	2.233
28	2-Aug	0.212	0.149	0.122	0.217	0.193	0.172	8.170	7.220	4.860	9.330	8.980	8.110	2.594	2.060	2.510	2.324	2.154	2.116
29	4-Aug	0.198	0.144	0.122	0.198														
30	5-Aug	0.208	0.136	0.102	0.208	0.181	0.150	9.900	7.150	5.700	9.900	8.380	7.630	1.442	1.897	1.796	1.442	2.161	1.959
31	6-Aug	0.208	0.150	0.102	0.208														
32	7-Aug	0.209	0.127	0.098	0.209														

Appendix 10: Inorganic Nitrogen and Turbidity in High and Low Depth Reactors

SN	Date	Feed				High Depth Reactor								High Depth Reactor							
						Ra				Rb				Rc				Rd			
		NH3	No2	Nox	Turbidity	NH3	No2	Nox	Turbidity	NH3	No2	Nox	Turbidity	NH3	No2	Nox	Turbidity	NH3	No2	Nox	Turbidity
1	26-Jun	0.051	0.022	5.52	0.27	0.048	0.031	4.20	0.25	0.040	0.033	3.40	0.24	0.040	0.031	5.00	0.20	0.037	0.034	0.42	0.19
2	27-Jun	0.068	0.236	5.40	0.22	0.054	0.220	4.59	0.18	0.064	0.201	3.52	0.31	0.009	0.239	4.96	0.20	0.011	0.221	4.43	0.24
3	28-Jun	0.383	0.014	10.10	0.38	0.127	0.072	6.20	0.28	0.059	0.117	4.80	0.24	0.073	0.412	6.80	0.25	0.048	0.676	0.54	0.25
4	29-Jun	0.167	0.035	11.10	0.27	0.032	0.050	8.80	0.42	0.032	0.071	8.10	0.27	0.018	0.060	8.30	0.24	0.024	0.116	0.80	0.25
5	30-Jun	0.044	0.010	7.70	0.28	0.019	0.012	7.60	0.21	0.010	0.015	7.20	0.18	0.010	0.027	8.30	0.18	0.009	0.027	0.75	0.22
6	1-Jul	0.112	0.025		0.43	0.017	0.032		0.24	0.016	0.028		0.37	0.024	0.021		0.30	0.025	0.025		0.31
7	2-Jul	0.032	0.015	6.40	0.35	0.009	0.016	6.10	0.28	0.008	0.017	4.70	0.19	0.014	0.013	5.70	0.26	0.016	0.016	0.63	0.24
8	3-Jul	0.095	0.038	6.30	0.35	0.013	0.082	5.60	0.19	0.009	0.043	5.30	0.21	0.017	0.023	6.30	0.33	0.020	0.028	0.64	0.24
9	4-Jul	6.820	0.402	12.10	0.28	5.060	0.453	10.00	0.41	5.002	0.431	6.90	0.30	4.963	0.580	10.30	0.44	4.782	0.592	0.97	0.35
10	5-Jul	0.738	0.103		0.27	0.479	0.206		0.25	0.478	0.197		0.18	0.391	0.235		0.23	0.378	0.234		0.21
11	6-Jul	5.268	0.340	17.00	0.30	3.911	0.431	10.10	0.44	1.696	0.294	9.30	0.22	4.775	1.075	14.30	0.31	2.567	0.608	1.27	0.25
12	7-Jul	5.055	0.287	13.40	0.30	4.961	0.436	10.20	0.28	4.812	0.504	9.50	0.23	5.138	0.257	10.10	0.31	5.024	0.280	10.41	0.28
13	8-Jul	5.011	0.252	10.40	0.31	4.823	0.433	9.70	0.29	4.598	0.590	10.20	0.28	4.978	0.290	10.80	0.28	4.856	0.417	1.07	0.24
14	9-Jul	5.028	0.365	10.60	0.39	4.982	0.544	10.40	0.27	4.679	0.816	10.20	0.16	5.012	0.528	10.90	0.33	4.953	1.562	1.09	0.23
15	10-Jul	5.501	1.450	10.50	0.31	5.206	0.429	10.30	0.31	4.548	0.857	10.10	0.21	5.402	0.868	10.20	0.35	4.908	0.242	1.01	0.27
19	14-Jul	3.193	0.212	13.90	0.30	2.981	0.350	10.90	0.23	2.450	0.722	10.70	0.18	3.365	0.291	11.10	0.31	2.735	0.702	1.06	0.35
20	15-Jul	1.090	0.238	13.30	0.32	4.441	0.448	10.40	0.30	3.803	0.919	10.40	0.23	4.869	0.339	10.80	0.33	4.336	0.959	1.04	0.29
21	16-Jul	5.969	0.171	13.50	0.24	5.440	0.540	10.40	0.17	4.462	1.347	9.90	0.14	5.290	0.333	10.80	0.20	4.647	1.783	0.98	0.21
22	17-Jul	4.905	0.200	11.40	0.28	4.137	0.528	9.50	0.23	3.020	1.399	8.40	0.15	4.730	0.267	11.10	0.30	3.606	1.251	0.92	0.20
23	18-Jul	4.951	0.044	12.40	0.44	5.367	0.180	11.00	0.36	3.384	1.679	10.80	0.27	5.427	0.166	12.00	0.54	4.072	1.200	1.12	0.30
24	19-Jul	3.383	0.026	19.90	0.48	3.690	0.271	12.00	0.34	3.312	1.679	11.30	0.22	4.119	0.256	12.80	0.33	3.578	1.301	1.16	0.28
25	20-Jul	3.383	0.026	12.70	0.38	2.907	0.570	12.20	0.33	3.921	1.736	12.00	0.23	3.221	0.298	11.90	0.31	4.486	1.340	1.13	0.25
26	21-Jul	2.520	1.355	13.10	0.21	2.536	0.424	13.10	0.58	1.172	1.773	12.70	0.30	2.219	0.554	13.00	0.40	1.068	1.416	1.30	0.21
28	23-Jul	1.352	1.980	15.00	0.28	0.822	1.991	14.30	0.25	-0.002	0.874	14.00	0.24	0.967	2.029	14.80	0.35	0.028	2.423	1.46	0.30
29	24-Jul	0.714	2.360	13.70	0.25	0.116	0.968	13.30	0.35	0.112	1.055	5.10	0.27	0.308	1.783	12.70	0.33	0.135	1.565	1.16	0.26

Remarks: Unit for NH_3, NO_2, NOx are in mg/L, and Turbidity is in NTU

Appendix 11: UV$_{254}$ and DOC for Medium Depth Reactor Set

SN	Day	UV254_1cm				DOC (mg/L)				SUVA (L/m-mg)			
		Feed	R1	R2	R3	Feed	R1	R2	R3	Feed	R1	R2	R3
1	5-Jun	0.200	0.095	0.046	0.023								
2	6-Jun	0.198	0.106	0.064	0.041	8.39	4.57	3.11	2.6	2.384	2.085	1.466	0.873
3	7-Jun	0.193	0.130	0.077	0.051	8.13	5.56	3.47	2.66	2.440	1.910	1.844	1.549
4	8-Jun	0.197	0.135	0.094	0.074								
5	9-Jun	0.196	0.139	0.094	0.060	8.45	6.15	4.08	3.46	2.327	2.198	2.314	2.130
6	10-Jun	0.200	0.139	0.106	0.082								
7	11-Jun	0.198	0.144	0.109	0.088	8.25	6.17	4.64	3.66	2.421	2.258	2.276	2.251
8	12-Jun	0.198	0.148	0.115	0.093								
9	13-Jun	0.195	0.152	0.121	0.099	8.31	6.68	5.41	4.64	2.380	2.211	2.123	2.010
10	14-Jun	0.190	0.152	0.117	0.088								
11	15-Jun	0.194	0.153	0.123	0.102	8.22	6.77	5.59	4.53	2.314	2.251	2.090	1.938
12	16-Jun	0.194	0.150	0.129	0.106								
13	17-Jun	0.190	0.151	0.124	0.105	8.19	6.72	5.54	4.66	2.364	2.231	2.335	2.266
14	18-Jun	0.193	0.154	0.126	0.105								
15	19-Jun	0.191	0.155	0.126	0.106	8.01	6.55	5.46	4.60	2.415	2.345	2.310	2.279
16	20-Jun	0.192	0.158	0.131	0.110	7.90	6.61	5.42	4.54	2.414	2.348	2.327	2.322
17	21-Jun	0.187	0.158	0.131	0.111	7.83	6.61	3.91	3.53	2.456	2.392	3.348	3.122
18	22-Jun	0.191	0.158	0.137	0.117	8.03	6.71	5.75	5.18	2.333	2.349	2.272	2.152
19	23-Jun	0.194	0.159	0.135	0.116								
20	24-Jun	0.181	0.152	0.129	0.110	8.02	6.98	6.04	5.24	2.418	2.279	2.235	2.208
21	25-Jun	0.189	0.159	0.135	0.117								
22	26-Jun	0.188	0.158	0.136	0.118	8.01	6.91	5.99	5.19	2.356	2.305	2.258	2.253
23	27-Jun	0.187	0.160	0.137	0.118								
24	28-Jun	0.182	0.151	0.129	0.108	8.02	6.94	6.00	5.15	2.337	2.301	2.281	2.290
25	29-Jun	0.181	0.153	0.129	0.106	8.05	7.03	6.11	4.92	2.261	2.142	2.110	2.195
26	30-Jun	0.183	0.157	0.133	0.107	8.08	7.30	6.31	5.23	2.240	2.088	2.045	2.016
27	1-Jul	0.186	0.160	0.142	0.114								
28	2-Jul	0.189	0.164	0.144	0.117	8.27	7.30	6.47	5.49	2.255	2.197	2.189	2.068
29	3-Jul	0.183	0.159	0.137	0.112								
30	4-Jul	0.183	0.152	0.134	0.112	8.29	7.17	6.31	5.69	2.204	2.212	2.179	1.968
31	5-Jul	0.186	0.114	0.087	0.067								
32	6-Jul	0.183	0.120	0.078	0.062	8.50	6.78	4.75	4.05	2.187	1.684	1.832	1.644
33	7-Jul	0.199	0.193	0.173	0.134								
34	9-Jul	0.193	0.181	0.158	0.136								

Appendix 12: Inorganic Nitrogen in Medium Depth Reactor Set

SN	Date	Feed (mg/L)			R1 (mg/L)			R2 (mg/L)			R3(mg/L)			Total Inorganic Nitrogen (mg/L)			
		NH3	NO2	Nox	NH3	NO2	Nox	NH3	NO2	Nox	NH3	NO2	Nox	Feed	R1	R2	R3
1	5-Jun	0.385	0.130	9.44	0.215	0.354	8.11	0.222	0.294	6.40	0.221	0.275	5.14	9.825	8.325	6.622	5.361
2	6-Jun	0.494	0.646	9.58	0.470	0.701	7.89	0.412	0.522	7.77	0.359	0.472	4.69	10.074	8.360	8.182	5.049
3	7-Jun	0.562	0.125	10.30	0.306	0.745	9.28	0.257	0.759	8.59	0.204	0.750	7.79	10.862	9.586	8.847	7.994
4	8-Jun	0.130	0.704	9.61	0.115	0.693	10.11	0.111	0.722	7.18	0.100	0.798	8.44	9.740	10.225	7.291	8.540
5	9-Jun	0.438	0.086	10.28	0.279	0.516	10.00	0.247	0.534	9.54	0.168	0.582	9.61	10.718	10.279	9.787	9.778
6	10-Jun	0.088	1.353	8.35	0.067	0.877	10.36	0.068	0.927	10.67	0.064	0.930	8.35	8.438	10.427	10.738	8.414
7	11-Jun	0.036	1.243	3.99	0.032	1.436	4.27	0.029	1.558	5.99	0.014	1.557	5.16	4.026	4.302	6.019	5.174
8	12-Jun	0.060	0.265	6.24	0.030	0.614	3.88	0.033	0.813	4.87	0.027	0.956	4.82	6.300	3.910	4.903	4.847
9	13-Jun	0.026	0.099	9.05	0.017	0.167	6.68	0.016	0.127	3.65	0.015	0.373	4.34	9.076	6.697	3.666	4.355
10	14-Jun	0.025	0.037	8.67	0.013	0.119	7.23	0.017	0.199	7.59	0.010	0.268	7.04	8.695	7.243	7.607	7.050
11	15-Jun	0.018	0.535	5.33	0.011	0.489	4.34	0.011	0.455	4.39	0.013	0.022	4.36	5.348	4.351	4.401	4.373
12	16-Jun	0.022	0.064	8.71	0.011	0.195	7.86	0.007	0.255	7.32	0.002	0.324	7.04	8.732	7.871	7.327	7.042
13	17-Jun	0.020	0.129	8.15	0.015	0.077	5.14	0.004	0.084	6.65	0.011	0.108	4.37	8.170	5.155	6.654	4.381
14	18-Jun	0.016	1.067	5.23	0.013	0.899	8.02	0.012	0.833	3.84	0.011	0.791	5.09	5.246	8.033	3.852	5.101
15	19-Jun	0.019	0.010	8.61	0.016	0.597	7.69	0.014	0.683	7.97	0.011	0.734	7.73	8.629	7.706	7.984	7.741
16	20-Jun	0.013	0.645	8.39	0.017	0.616	8.47	0.015	0.693	8.70	0.011	0.743	7.39	8.403	8.487	8.715	7.401
17	21-Jun	0.013	0.020	8.87	0.011	0.115	8.38	0.005	0.253	8.15	0.005	0.253	7.66	8.883	8.391	8.155	7.665
18	22-Jun	0.033	0.038	8.91	0.010	0.486	8.41	0.010	0.481	8.55	0.008	0.442	8.28	8.943	8.420	8.560	8.288
19	23-Jun	0.012	0.145	5.90	0.014	0.115	8.13	0.018	0.124	10.96	0.014	0.159	6.93	5.912	8.144	10.978	6.944
20	24-Jun	0.292	0.259	6.27	0.151	0.131	6.46	0.153	0.106	7.00	0.161	0.103	7.32	6.562	6.611	7.153	7.481
21	25-Jun	0.008	0.790	8.46	0.009	0.539	5.60	0.008	0.444	5.54	0.009	0.383	5.92	8.468	5.609	5.548	5.929
22	26-Jun	0.025	0.079	8.50	0.027	0.044	10.40	0.024	0.046	8.76	0.020	0.065	8.05	8.525	10.427	8.784	8.070
23	27-Jun	0.015	0.060	8.56	0.016	0.017	9.16	0.011	0.010	8.37	0.007	0.013	8.05	8.575	9.176	8.381	8.057
24	28-Jun	0.035	0.065	4.57	0.014	0.015	4.95	0.011	0.005	5.42	0.008	0.003	5.87	4.605	4.964	5.431	5.878
25	29-Jun	0.015	0.058	5.63	0.017	0.009	5.41	0.009	0.002	5.40	0.008	0.002	5.70	5.645	5.427	5.409	5.708
26	30-Jun	0.027	0.012	5.38	0.031	0.003	4.81	0.015	0.002	4.94	0.012	0.002	4.45	5.407	4.841	4.955	4.462
27	1-Jul	0.029	0.116	7.04	0.021	0.014	6.98	0.014	0.007	6.44	0.009	0.007	5.80	7.069	7.001	6.454	5.809
28	2-Jul	0.021	0.008	6.73	0.014	0.005	7.93	0.008	0.004	7.29	0.008	0.008	7.13	6.751	7.944	7.298	7.138
29	3-Jul	0.042	0.107	5.51	0.026	0.022	5.82	0.019	0.019	6.08	0.009	0.009	6.63	5.552	5.846	6.099	6.639
30	4-Jul	0.059	0.003	5.59	0.013	0.060	6.04	0.011	0.015	5.88	0.006	0.009	4.76	5.649	6.053	5.891	4.766

Appendix 13: Turbidity Removal in Medium Depth Reactor Set

SN	Day	Feed	R1	R1+R2	R1+R2+R3
1	5-Jun	0.33	0.41	0.47	0.47
2	6-Jun	0.34	0.36	0.31	0.28
3	7-Jun	0.40	0.31	0.31	0.41
4	8-Jun	0.37	0.29	0.26	0.25
5	9-Jun	0.30	0.21	0.26	0.21
6	10-Jun	0.33	0.27	0.20	0.21
7	11-Jun	0.39	0.27	0.27	0.21
8	12-Jun	0.38	0.22	0.21	0.20
9	13-Jun	0.30	0.31	0.24	0.24
10	14-Jun	0.30	0.25	0.22	0.22
11	15-Jun	0.36	0.32	0.31	0.24
12	16-Jun	0.29	0.27	0.23	0.24
13	17-Jun	0.20	0.21	0.14	0.17
14	18-Jun	0.24	0.21	0.22	0.17
15	19-Jun	0.31	0.25	0.24	0.30
16	20-Jun	0.27	0.33	0.28	0.23
18	22-Jun	0.29	0.26	0.36	0.29
19	23-Jun	0.28	0.21	0.22	0.17
20	24-Jun	0.33	0.29	0.25	0.22
21	25-Jun	0.20	0.19	0.16	0.13
22	26-Jun	0.27	0.20	0.25	0.19
23	27-Jun	0.30	0.20	0.18	0.16
24	28-Jun	0.34	0.31	0.21	0.22
25	29-Jun	0.26	0.24	0.19	0.17
26	30-Jun	0.28	0.24	0.18	0.17
27	1-Jul	0.24	0.19	0.16	0.17
28	2-Jul	0.28	0.23	0.24	0.17
29	3-Jul	0.32	0.23	0.37	0.24
30	4-Jul	0.28	0.27	0.19	0.23
31	5-Jul	0.45	0.35	0.45	0.33
32	6-Jul	0.38	0.38	0.46	0.36

Remarks: Unit for Turbidity is in NTU

Appendix: 14 UV Removal Percentage during Recycling

Date	UV254_1cm		Removal Percentage		
	Feed	Rc	Rd	Rc	Rd
26-Jul	0.211	0.161	0.102	24	37
27-Jul	0.151	0.101	0.098	33	3
28-Jul	0.211	0.188	0.163	11	13
29-Jul	0.145	0.133	0.103	8	23