ADSORPTION AND BIOLOGICAL FILTRATION IN WASTEWATER TREATMENT

J. Kandasamy, S. Vigneswaran, T. T. L. Hoang
Faculty of Engineering and Information Technology, University of Technology, Sydney

D.N.S Chaudhary
Maunsell AECOM, Sydney, Australia

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Contents

Summary

Over the last few decades adsorption has gained paramount importance in industry and environmental protection. Adsorption processes are widely applied for separation and purification because of the high reliability, energy efficiency, design flexibility, technological maturity and the ability to regenerate the exhausted adsorbent. One method of important extending the adsorption treatment processes is biofiltration. The biological filter relies on the activities of the community of micro-organisms that become attached onto the filter media. Microbes oxidize organic matters in water to produce energy and therefore available nutrients sources in feed water are essential for their development. Biofiltration can effectively remove organic matter that is not able to be removed from water and biologically treated sewage effluent in conventional sewage treatment. The microbial attachment process, the factors that influence biological filtration, the kinetics of microbial growth and details of the microbial community in the biofilter are discussed in detail. There are several types of biofilters including submerged filters, trickling filter, bed filter, fluidised bed. The different biofilters are described and a comparison between them is provided. The application of biofilters for treating various types of wastewater effluent is detailed.

1. Adsorption

Over the last few decades adsorption has gained paramount importance in industry and environmental protection. As a purification and separation process, the capability of adsorption based on technological, environmental and biological aspects will never be in doubt.

Adsorption works on the principle of adhesion. The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The process can take place in any of the following systems: liquid-gas, liquid-liquid, solid-liquid and solid-gas. The adsorbing phase is the 'adsorbent', and the material concentrated or adsorbed at the surface of adsorbing phase is the 'adsorbate'. (Slejko, 1985; Suzuki, 1990).

Adsorption can result either from the universal Van der Waals interactions and electrostatic forces between adsorbate molecules and the atoms of the adsorbent surface (physical adsorption, physisorption), or it can have the character of a chemical process (chemical adsorption or chemisorption). Contrary to physisorption, chemisorption occurs only as a monolayer, (Adamson, 1990). Physical adsorption can be compared to the condensation process.

Most of the solid adsorbents possess a complex porous structure that consists of pores of different sizes and shapes. In terms of the science of adsorption, total porosity is usually classified into three groups; micropores (smaller than 2 nm), mesopores (in the range of 2 to 50 nm) and macropores (larger than 50 nm) (RJPAC, 1985). The adsorption in micropores is essentially a pore-filling process, because sizes of micropores are comparable to those of adsorbate molecules. All atoms or molecules of the adsorbent can interact with the adsorbate species. That is the fundamental difference between adsorption in micropores and larger pores like meso- and macropores. Thus, the size of the micropores determines the accessibility of adsorbate molecules to the internal adsorption surface The pore size distribution of micropores is another important property for characterising adsorptivity of adsorbents. (Dubinin, 1975; Slejko, 1985; Suzuki, 1990).

In the case of mesopores whose walls are formed by a great number of adsorbent atoms or molecules, the boundary of interphases (adsorbent surface area) has a distinct physical meaning. The action of adsorption forces occurs at a close distance from mesopores walls. Therefore, the mono- and multilayer adsorption takes place successively on the surface of mesopores, and their final fill proceeds according to the mechanism of capillary adsorbate condensation (Ocik, 1982). The basic parameters characterising mesopores are: specific surface area, pore volume and pore-size or pore-volume distribution. Mesopores, like macropores, play also an essential role in the transport of adsorbate molecules inside the micropore volume. The mechanism of adsorption on the surface of macropores does not differ from that which occurs on flat surfaces. Since the specific surface area of macroporous solids is very small, adsorption on this surface is usually neglected. Similarly, the capillary adsorbate condensation does not occur in macropores.

1.1 Application of Adsorption

Adsorption plays a significant role in the environmental pollution control and life supporting systems or planetary bases, where adsorbents may be used to process the habitat air or to recover useful substances from the local environments. Adsorption processes are good candidates for separation and purification by virtue of the high reliability, energy efficiency, design flexibility, technological maturity and the ability to regenerate the process by regenerating the exhausted adsorbent. The most important practical applications of adsorption and related areas are summarized (Dabrowski, 2001) is shown in Table 1.

Development and application of adsorption cannot be considered separately from development of technology used to manufacture adsorbents applied both on laboratory and industrial scales. The adsorbents can take a broad range of chemical forms and different geometrical surface structures. Table 2 gives basic types of adsorbents (Dbrowski, 2001).

A large specific surface area of adsorbent pores provides a large adsorption capacity. The creation of a large internal surface area in a limited volume inevitably gives rise to large numbers of small sized pores between adsorption surfaces. Materials such as activated carbon and zeolite can be specifically engineered with precise pore size distributions and hence tuned for a particular separation application (Slejko, 1985 and Suzuki, 1990).

1.2 Activated Carbon

Areas	**Application**
Flue gas treatment	SO_x, NO_x and mercury emissions removal
Wastewater treatment	Organics, nitrogen and phosphorus removal, i.e. removal and recovery of nutrients from wastewater
Drinking water production	Amelioration of water sources, advanced treatment of wastewater, etc.
Desiccant dehumidification	Improvement of indoor air quality and removal of Technology air pollutants and the number of microorganisms either removed or killed by desiccants due to co-adsorption by desiccant materials.
Global warming control	Emission control of ‘greenhouse’ gases ($C0_2$, CH_4, N_20); utilization of CH_4

Table 1 The practical applications of adsorption and related areas

Carbon adsorbents	**Mineral adsorbents**	**Other adsorbents**
Active carbons Mesocarbon microbeads Fullerenes Carbonaceous Nanomaterials	Activated alumina Oxides of metals Hydroxides of metals Zeolites Clay minerals Porous clay heterostructures (PCHs)	Synthetic polymers Composite adsorbents

Table 2 Basic types of common adsorbents

Since early history, activated carbon was the first widely used adsorbent. Its application in the form of carbonised wood (charcoal) has been described as early as 3750 BC in an ancient Egyptian papyrus. The use of activated carbon is perhaps the best broad-spectrum technology available at present to control contamination of water by organic pollutants.

Activated carbon is an excellent adsorbent because it has a strong affinity for binding organic substances, even at low concentrations. It has a vast network of pores of varying size to accept both large and small contaminant molecules and these pores give activated carbon a very large surface area. The larger percentage of the total surface area is believed to be of the planar surface type with few attached functional groups (Snoeyink and Weber, 1967) and hence, the majority of the adsorption on the surface is considered to be due to the relatively weak physical or Van der Waal forces (Van der Plas, 1968). On the other hand, the sides of these planar surfaces are attached with many functional groups such as organic carboxyl, phenolic and carbonyl groups (Mattson and Mark, 1971) and inorganic oxygen complexes (Snoeyink and Weber, 1967). Therefore a rather high polarity for the surfaces is provided, and some electrolytes may then be chemically attracted by the carbon surface for adsorption (chemisorption).

Once the surface of the pores is covered with adsorbed material, the carbon loses its ability to adsorb. The spent carbon can then be reactivated by essentially the same process as the original activation, or it can be discarded and replaced with fresh carbon. There are many commercially available activated carbons manufactured from various carbonaceous substances, which increases the surface area and porosity of the material.

Activated carbon can be made from a variety of materials such as wood, coals (anthracite, bituminous and lignite), coconut shells, peat, and petroleum residues. Most carbonaceous materials have an internal surface area around 10 m^2/g. After the activation process, the carbons will acquire an internal surface area of 500 to 1500 m^2/g (experimental activated carbon has been made with over 3000 m^2/g surface area) (Juntgen, 1975). Hence, adsorption capacity of activated carbon can reach up to 0.30 g (organic matter)/g (carbon) or even more. For example, 1 kg of activated carbon can trap and hold over 0.5 kg of carbon tetrachioride (Chow, 1975).

2. Biological Filtration

Biological filtration or biofiltration is one water treatment process that can effectively remove organic matter that is not able to be removed from water and biologically treated sewage effluent in conventional sewage treatment (Carlson and Amy, 1998). The biological filter mainly relies on the activities of the community of micro-organisms that are attached onto the filter media. The activities of microbes determine the performance of biological filtration. Microbes oxidize organic matters in water to produce energy and therefore available nutrients sources in feed water is essential for their development. In addition, the parameters such as hydraulic loading rate, back washing techniques, temperature and pH etc. can affect the growth of biomass onto GAC in the biofilter. Moreover, biological filtration is economical and safe for environment. Biofiltration is more suitable than other treatment methods in terms of removing organic matter.

Any type of filter with an attached biomass on the filter-media can be defined as a biofilter. It can be the trickling filter in the wastewater treatment plant, or horizontal rock filter in a polluted stream, or granular activated carbon (GAC) or sand filter in a water treatment plant. Biofilter has been successfully used for air, water, and wastewater treatment. Originally, biofilter was developed using rock or slag as the filter media, however at present, several types and shapes of plastic media are also used. There are a number of small package treatment plants currently available in the market where different shaped plastic materials are packed as filter media and are mainly used for treating a small amount of wastewater (e.g. from household or hotel scale). The basic principle in a biofilter is the biodegradations of pollutants by the micro-organisms attached onto the filter media.

The biological filtration using granular activated carbon (GAC) is an efficient process in drinking water treatment. Even though it has high adsorption capacity, GAC can only maintain its adsorption for a short time of biofilter operation before its adsorption capacity becomes exhausted, leading to a lower treatment efficiency. To recover its capacity, GAC can be regenerated by different methods such as thermal, hydrothermal, chemical and ultrasonic regeneration. However, regeneration usually reduces GAC adsorption capacity and requires a high energy expense. Another way to extend GAC life is using exhausted GAC as support filter media for biological filtration. GAC provides a huge surface area for microorganism growth and development in the biofilter. In this case, both adsorption and biological degradation take part in the treatment processes. Adsorption is more dominant in the first stage or acclimatising stage when GAC is in full adsorption capacity and microbes start to attach to surface of the filter media and begin to grow. The latter stage or pseudo steady state is controlled by microbiological activity (Dussert and Stone, 1994). In this stage, biological degradation plays a major role in biofilters and therefore maintaining sufficient biomass is very important. Applying backwash is an effective method to control the accumulation of excess biomass that can cause clogging of the biofilter. It is also useful in maintaining the balance of microbiological community in a biofilter by removing dead cells and end products that may poison the microbiological environment and create free sites for new organisms.

The wide range of application of the biofilter has resulted in many studies on the system in last few decades (Table 3). Despite this it is still theoretically difficult to fully explain the behavior of a biofilter. The growth of different types of microorganisms in different working conditions makes it impossible to generalize the microbial activities in a biofilter. The biofilters operated at different filtration rates and influent characteristics can have diverse efficiency for different target pollutants. Besides, due to some of the operational drawbacks of the biofilter such as performance fluctuation, maintenance of biomass, and disinfection adequacy of the biofilter effluent, research on biofiltration process has become imperative.

Researcher, source	**Filter medium**	**Experimental parameter**		**Major observation**
		Organic	**Biomass**	
Abmad et al. [1998], water	Anthracite$^+$ sand	AOC-P17, AOC-NOX, NPOC, turbidity	HPC	Backwashing technique and hydraulic transient can affect the performance of a biofilter.
Boon et al. [1997], wastewater	Granite, blast-furnace slag	BOD, ammonia, SS	None	Performance a biofilter depends on organic loading rate, temperature, and filter design configuration.
Carison and Amy [1998], water	Anthracite	DOC, BDOC	Phospho-lipid analysis	DOC removal is controlled by biomass. The filter acclimatized at higher HLR had a substantially higher cumulative biomass.
Hozaiski and Bouwer [1998], synthetic water, NOM	Glass beads$^+$ sand	TOC	HPC bacterial count	Biomass accumulation is not impaired by back-wash with water
Yang et al. [2001], aquaculture water	Plastic media-3 different shapes	BOD_5, SS, NH_3-N, $N0_3$-N, NO,-N, $P0_4^3$	None	Characteristics of filter media are more critical than the flow scheme to the biofilter in affecting the performance of the biofilter.

Niquette et al. [1998], water	GAC	DOC, DO, NH$_3$, NO,	Bacterial count	Shut down of biofilter promotes anaerobic conditions reducing the quality of the effluent. The biofilter should be backwashed when anaerobic condition occurs.
Servais et al. [1994], water	GAC	DOC, BDOC, NBDOC	^{14}C-Glucose respiration	Removal efficiency of a biofilter depends on EBCT, not on filtration rate
Wang et al. [1995a, b]	Anthracite$^+$ sand, GAC$^+$ sand, sand	TOC, BDOC, aldehydes, AOC-NOX, THM and TOX formation potential	Phospho-lipid analysis	GAC contained 3-8 times more biomass than anthracite or sand

AOC=Assimilable organic carbon, BOD5=Biochemical oxygen demand, SS=suspended solid, DBP=Disinfection by-product, DOC=Dissolved organic carbon, DO=Dissolved oxygen, BDOC=Biodegradable dissolved organic carbon, NBDOC=Non-biodegradable dissolved organic carbon, THMFP=Trihalomethane formation potential, TOXFP=Total organic halide formation potential, HPC=Heterotrophic plate count, NPOC=Non-purgeable organic carbon, HLR=hydraulic loading rate, NOX=Nitrogen oxides.

Table 3 Summary of the past studies on biofiltration system with water and wastewater

2.1 Biological Attachment Processes

The attachment of microorganisms onto the surface of filter media to form a biofilm is a complex process. It has been studied by many methods such as scanning confocal laser microscopy, microbalance applications, microelectrode analysis, high resolution video microscopy, atomic force microscopy and scanning electron microscopy (Percival et al., 2000).

There are several elements that take part in microbial attachment to a surface in which the strength of the attachment relies on environmental conditions, type of micro organisms, surface properties and fluid characteristics.

The attachment of microorganisms to the surface of the filter media can be divided into five steps: development of a surface-conditioning film, transportation of cells to a surface, adhesion, surface colonization and detachment (Percival et al., 2000).

Figure 1 describes the attachment of microorganisms to the surface of supported media.

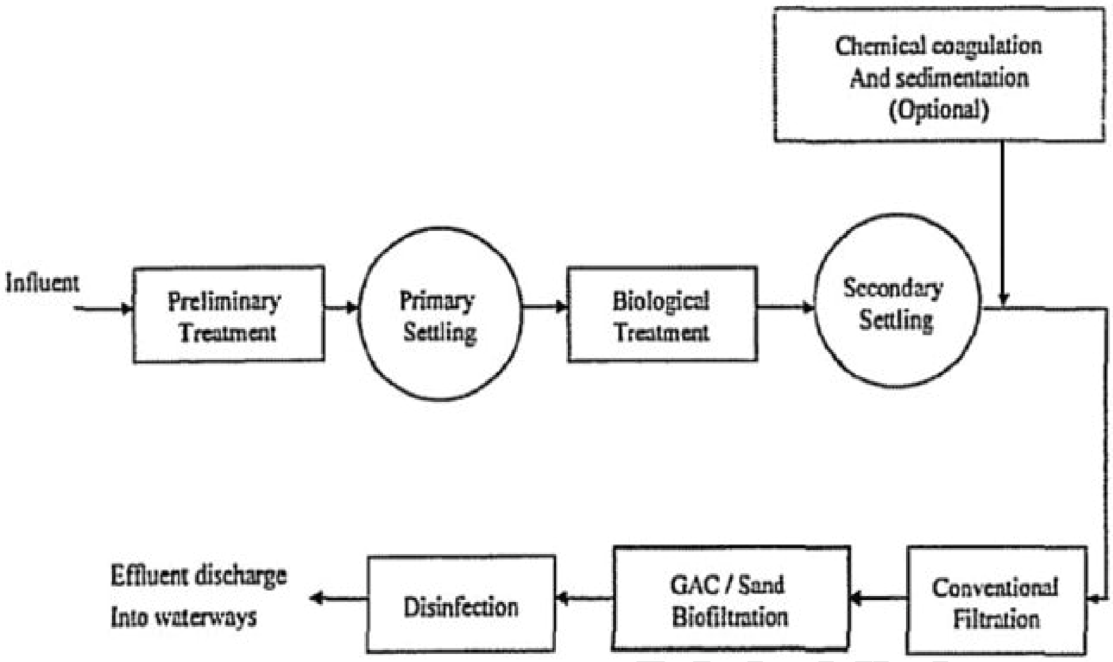

Figure 1 Schematic of biofilm formation.

2.1.1 Surface-Conditioning Film

When a clean surface is exposed to a bathing fluid in the first few minutes, it becomes conditioned with nutrients by the transport of organics and some microbial cells. The details of this process is still unclear but in general, the development of the conditioning film is acknowledged as chaotic and dynamic. The surface-conditioning film contains glycoproteins, proteins and humic substances with the thickness ranging from 30-80 nm. These components can react with surface appendages of some bacterial species in latter stages. It is presumed that the conditioning film acts as a controlling factor that adjusts the amount of bacterial attachment to surfaces.

In the biological adsorption process, the roles of surface-conditioning film include: modifying physico-chemical properties of the substratum; acting as concentrated nutrient source; suppressing the release of toxic metal ions; adsorption and detoxification of dissolved inhibitory substances and supply of required metal trace elements (Percival et al., 2000).

2.1.2 Transport of Cells to the Surface

Microorganisms in liquid reach and attach to the surface of the media by mass transport, thermal effects (Brown ion motion, molecular diffusion) and gravity effects (settling and sedimentation). Diffusive transport is a slow process occurring randomly among small bacteria and interfaces which can be observed under the microscope. Diffusive transport is significant in stagnant states and influences the sedimentation of bacteria due to gravity while a convective transport is dominant in flowing liquids. In the latter, some mobile bacteria can reach a media surface by active movement, which can happen by chance, or in response to any concentration gradient (Loosdrecht et al., 1990).

Mass transport is strongly influenced by fluid mixing (laminar or turbulent flow) and water flow rate (Percival et al., 2000). While laminar flow is slow and smooth with a little mixing, turbulent movement is random and chaotic and can increase the adhesion of microorganisms to the media surface, but the risk of detachment is also high when a thick biofilm formed.

2.1.3 Adhesion

When bacteria reach the surface of the media, initial adhesion will occurs by physicochemical processes. Bacteria still exhibit Brownian motion in this stage but they can be detached by shear or bacterial mobility. According to the DLVO (named after Derjaguin, Landau, Verwey and Overbeek) theory, depending on the balance between electrostatic double layer forces and Van der Waals at different ionic strengths, initial adhesion can be reversible or irreversible (Loosdecht et al., 1990). Van der Waals attraction also relates to the effective size of bacteria but does not include the space occupied by appendages such as flagellum, pili, fimbriae and exopolysaccharides. These appendages form bridges that increase the effective distance (Percival et al, 2000). Electrostatic interactions with ionic and hydrogen bonding are not very strong individually but can form a firm attachment when they occur in large amounts. These bonds will be stronger if the surface of the medium is positively charged because most microorganisms' surfaces are negatively charged (Cohen, 2001).

Busscher and Weerkamp (1987) suggested a three-point hypothesis where the distance between cells and surface can decide the kinds of interaction between them. Van der Waals attraction exists at distances greater than 50nm and both Van der Waals and electrostatic interaction occur within the distance of 10-20nm creating reversible and irreversible adhesion. Van der Waals, electrostatic and specific interaction produce irreversible binding and form exopolysaccharides.

Firm attachment happens after bacteria deposit on the media and strong bonds between reactive groups on the surfaces of bacteria and media are formed. During this process, the occurrence of polysaccharides is necessary for the development of biofilm. Chemical and physical properties of the supported media have great influence to the adhesion of microbes into the surface. Normally, surfaces with a high degree of hydrophobicity and roughness, carrying divalent cations (such as Ca^+ and Mg^+) will promote the attachment of bacteria to the surface (Wuertz et al., 2003).

2.1.4 Detachment of Biomass

Detachment of biofilm is a common phenomenon, which always happens during the biofilm formation process. Biofilm detachment occurs through different processes. Detachment of biofilm by abrasion, erosion, sloughing, occurs when there is shear stresses, and lack of nutrient and oxygen in the biological filter. Abrasion and erosion leads to the removal of small groups of cells from biofilm while sloughing results in the detachment of a relatively large fraction of the biofilm. Porosity and roughness of the surface supporting the biofilm plays an important role in protecting the biofilm from hydrodynamic shear and abrasion (Wuertz et al., 2003). Human intervention can lead to the detachment process. Predator razing is also another factor that causes biofilm detachment with the involvement of protozoa, snails and worms (Percival et al, 2000). The detachment process has a significant impairment to the distribution of microorganisms within the biofilm and its structure. On the other hand, detachment removes dead microbes and creates free sites for new organisms to attach, thus microorganisms can quickly be replaced to retain the stability of the microorganism community and their activity (Percival et al., 2000; Wuertz et al., 2003).

The success of a biofilter highly depends on the efficient maintenance of biomass attached to the filter media. Biomass detachment is one of the most important mechanisms that can affect the maintenance of biomass in a biofilter. Erosion, abrasion, sloughing, grazing or predation and filter backwashing are the most common detachment mechanisms. Erosion of biomass occurs due to fluid shear whereas abrasion of the biomass is the process of scraping the biocell off the surface by collision with external particles. Similarly, large patches of biomass are detached by sloughing and a part of biomass especially on the outer surface of the biofilm may be lost due to the grazing of protozoa. Evaluation of the biomass lost due to filter backwashing is very important from an operational point of view. Backwash bed expansion, mode of backwash such as air scour or chlorinated water backwash may affect the biomass during backwashing. However, a previous study has shown that the effective biomass is not lost during normal filter backwash (Ahmad et al., 1998).

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Bibliography

Agrawal, L.K., Ohashi, Y., Mochida, E., Okui, H., Ueki, Y., Harada, H. and Ohashi, A. (1997). Treatment of Raw Sewage in a Temperate Climate Using a UASB Reactor and the Hanging Sponge Cubes Process. Water Science and Technology 36(6-7): 433-440. [this paper details the use of sponge as a biofilter media]

Allison, D. G. (1998). Exopolysaccharide Production in Bacterial Biofilms. Biofilm 3, BF98002.

Ahmad, R, Amirtharajah, A., A1-Shawwa, A. and Huck, P. M., (1998). Effects of Backwashing on Biological Filters. J. AWWA, 90(12), 62(1998). [this paper details the various parameters that effect backwashing in biofilters]

Bauer, M. J., Colbourne, J. S., Chipps, M.J.**,** Colbourne**,** J.S**.** and Foster, D.M. (1996). GAC Enhanced Slow sand Filtration (GAC Sandwich). In Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [This chapter gives details on the operation of a full scale GAC sandwich biofilter (sand and GAC)]

Bernardo, L. D. and A. E. Rivera (1996). Influence of Sand Uniformity Coefficient on Slow Sand Filtration Performance. In Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [this paper details the various parameters that effect the performance of sand filters]

Binnie, C., M. Kimber, Smethurst, G. (2002). Basic Water Treatment. London, Thomas Telford. [a text book on water treatment]

Busscher, H. J. and A. H. Weerkamp (1987). Specific and Non-specific Interactions in Bacterial Adhesion to Solid Substrata. FEMS Microbiol Rev 46: 165–173. [this paper details the interaction of forces between cells and surfaces]

Boon, A. G., Hermfrey, J., Boon, K and Brown, M., (1997). Recent Developments in the Biological Filtration of Sewage to Produce High-Quality Nitrified Effluents, J. Chart. Inst. Water Env Manag., 11(12), 393 (1997). [this paper details the performance of a full-scale biofilters columns treating high strength wastewater]

Carlson, K. H. and G. L. Amy (1998). NOM Removal during Biofiltration. American Water Works Association. (90): 43-52. [this paper details the removal of NOM using biofilters]

Carlson, K. H., G. L. Amy, Garside, J., Blais, G. (1996). Ozone-Induced Biodegradation and Removal of NOM and Ozonation By-products in Biological Filters. Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [this chapter details the removal of NOM using biofilters]

Chaudhary, D. S., Vigneswaran, S., Ngo, H. and Jegatheesan, V, Applicability of Granular Activated Carbon (GAC) Biofilter in Waste-water Treatment and Reuse, Proceedings of Asian Waterqual 2001, IWA Asia-Pacific Regional Conference, Fukuoka, Japan, 2,685 (2001). [this paper details the suitability of GAC biofilters in treating wastewater for reuse purposes]

Chaudhary, D. S. (2003). Adsorption-Filtration Hybrid System in Water Treatment and Reuse. PhD Thesis, University of Technology, Sydney. [this thesis is a study on the use of adsorption and filtration processes to treat wastewater]

Chow, D.K. (1975). Activated carbon adsorption in municipal wastewater treatment and reuse systems, Ph.D. Dissertation, University of Washington, Xerox University Microfilms, and UMI Services printed in 2000. [this thesis is a study on the use of adsorption and filtration processes to treat wastewater]

Clark, R. M. and Boutin, B.K. (2001). Controlling Disinfection By-Products and Microbial Contaminant in Drinking Water. Ohio, U.S EPA. [this report gives comprehensive information on removing by products and contaminants in drinking water treatment]

Cohen, Y. (2001). Biofiltration- The Treatment of Fluids by Microorganisms Immobilized into the Filter Bedding Material: a Review. Bioresource Technology 77: 257-274. [this is a good review of biofiltration for treatment of wastewater]

Dabrowski, A. (2001). Adsorption- from theory to practice. Advances in Colloid and Interface Science, vol. 93, pp. 135-224. [this paper gives information on the physics of adsorption and its application]

Daifullah, A. A., Girgis, B.S., (2004). A Study of the Factors Affecting the Removal of Humic Acid by Activated Carbon Prepared from Biomass Material. Colloids and surfaces A: Physicochemical and Engineering Aspects 235(1-3): 1-10. [this paper details a study on the removal of humic acid with biofilters]

Dubinin, M.M. (1975). Adsorption and porosity. Military Technical Academy, Warsaw. [this book gives a good review of adsorption processes]

Duncan, A. (1988). The Ecology of Slow Sand Filters. In H. J. D. Graham (ed.). Slow Sand Filtration. Horwood, Chichester, United Kingdom. 163-180. [this chapter the operation of sand filters and the development of biomass]

Dussert, B. W., Stone, G. R. V., (1994). The Biological Activated Carbon Process for Water Purification. Water Engineering and Management 141(12). [this paper outlines the various stages of the operation of a biofilter for water treatment]

Dussert, B. W. Tramposch, W.G., (1996). Impact of Support Media and properties on the Biological Treatment of Drinking Water. In Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [this chapter outlines the operation of various support media used in biofilters used for water treatment]

Grady, C. P. L. (1983). Modeling of Biological Fixed Films - A State-of - the - Art Review. Fixed film biological processes for wastewater treatment. Y. C. Wu and E. D. Smith. New Jersey. [this paper discusses the modelling of biofilters]

Grady, C. P. L., Daigger, G.T., Lim, H.C. (1999). Biological Wastewater Treatment. New York, Marcel Dekker, Inc. [this is a good reference book on biological wastewater treatment]

Graham, N., Collins, R., (1996). Advances in Slow Sand and Alternative Biological Filtration. Chichester, John Wiley & Sons. [this is a good reference book on filtration processes for wastewater treatment]

Hozalski, R. M. (1996). Removal of Biodegradable Organic Matter in Drinking Water Biofilter: Experimental Studies and Model Development. Maryland, Johns Hopkins. [this discusses experiments and modelling of biofilters used in removing organic matter in water treatment]

Hozalski, R. M. and Bouwer, E., (1998). Deposition and Retention of Bacteria in Backwashed Filters. J. AWWA, 90(1), 71(1998). [this paper discusses the effect of various operating parameters on the performance of sand filters used in water treatment]

Huck, P. M., Zhang, S., Price, M.L. (1994). Removal during Biological Treatment: A First order Model. American Water Works Association, 86(6): 61. [this paper discusses modelling of biofilters used in treatment of wastewater]

Ikemoto, R. Y., Komori, T., (2003). Effects of C/N, C/S and S/N Ratios on TOC and Nitrogen Removal in the Sulfate Reduction-Sulfur Denitrification Process. Journal of Water & Environment Technology 1(1): 7-12. [this paper discuses how the nature of the influent affects biofilter operations]

Krasner, S. W., Sclimenti, M. J., Coffey B.M., (1993). Testing Biologically Active Filters for Removing Aldehydes Formed during Ozonation. American Water Works Association 85(5): 62-71. [this paper discusses the performance of biofilters under different operating conditions]

Lazarova, V. and J.Manem (1995). Biofilm Characterization and Activity analysis in Water and Wastewater Treatment. Water Research 29(10): 2227-2245. [this paper gives detail information of the characteristics of biofilms used in treatment of wastewater]

LeChevallier, M. W., W. C. Becker, Schorr, P., Lee, R.G. (1992). Evaluating the Performance of Biologically Active Rapid Sand Filters. American Water Works Association 84(4): 136. [this paper gives detailed information on the performance of biofilters used in treatment of wastewater]

Liu, X., P. Huck, Slawson R.M. (2001). Factors Affecting Drinking Water Biofiltration. American Water Works Association 93(12). [this paper gives detailed information on the performance of biofilters used in treatment of wastewater]

Loosdrecht, M. C. M., Lyklema, J., Norde, W., Zehnder, A.J.B. (1990). Influence of Interfaces on Microbial Activity. Microbiological Reviews 54: 75-87. [this paper gives information on the development of biofilms used in treatment of wastewater]

Machdar, I., H. Harada, A. Ohashi, Sekiguchi, Y., Okui, H., Ueki, K. (1997). A Novel and Cost-effective Sewage Treatment System Consisting of UASB Pre-treatment and Aerobic Post-treatment Units for Developing Countries. Water Science and Technology 36(12): 189-197. [this paper details the use of sponge as a biofilter media in sewage treatment]

Mattson, J.S. and Mark, H.B. (1971). Activated carbon: surface chemistry and adsorption from solution, M. Dekker, New York. [this book details adsorption processes using activated carbon]

McKay, G. (1996). Use of Adsorbents for the Removal of Pollutants from Wastewater. Boca Raton, CRC Press. [this book details adsorption processes for wastewater treatment]

Ocik, J. (1982). Adsorption. Ellis Horwood, Chichester, PWN, Warsaw. [this book details adsorption processes]

Percival, S. L., Walker, J. T., Hunter, P.R., (2000). Microbiological Aspects of Biofilms and Drinking Water. Boca Raton, CRC press. [this is a good reference book on biofiltration processes used for water treatment]

Prevost, M., Coallier, J., Mailly, J., Desjardins, R., Duchesne, D., (1992). Comparison of Biodegradable Organic Carbon Techniques for Process Control. J. Water SRT-A qua, 41(3), 141 (1992). [this paper gives results of removal of organic carbon with biofiltration for different operating conditions]

Rachwal, A. J., Bauer, M. J., Chipps, M. J., Colbourne, J. S., Foster, D. M., (1996). Comparisons Between Slow Sand and High Rate Biofiltration, Advances in Slow Sand and Alternative Biological Filtration, John Wiley & Sons, Inc. [this paper indicates the amount of microbial activity with biofilters operated under for different conditions]

Servais, P., Billen, O. and Bouillot, P., (1994). Biological Colonization of Granular Activated Carbon Filters in Drinking-Water Treatment, J. Environ. Eng., 120(4), 888 (1994). [this paper discusses how empty bed contact time (EBCT) and hydraulic loading rate affects the removal rate of biofilters]

Slejko, F. L. (1985). Adsorption technology. Marcel Dekker, New York. [this book details adsorption processes]

Smith, M. (2003), Biological Filters for Aquaculture, L. S. Enterprises [this book details the use of biofilters in treatment of aquaculture effluent]

Smith, H. L. (2005). Bacterial Growth. Arizona. [this book details the use of biofilters in wastewater treatment processes]

Snoeyink, V.L., Weber, W.J. (1967). Surface Chemistry of Active Carbon, A discussion of structure and surface functional groups, Environment Science Technology, 1, (1967) pp. 228-234. 9. [this paper is useful in understanding adsorption processes]

Suzuki, M. (1990). Adsorption engineering. Elsevier, Amsterdam. [this book details adsorption processes]

Tchobanoglous, G., F. Burton, Eds. (1991). Wastewater Engineering Treatment, Disposal and Reuse. McGraw Hill Series in Water Resources Environmental Engineering, Metcalf & Eddy Inc. [this book details wastewater treatment and reuse processes]

Urfer, D., P. M. Huck, Gagnon, G.A., Mutti, D., Smith, F. (1997). Biological Filtration for BOM and Particle Removal: a Critical Review. American Water Works Association 89: 83-98. [a good review paper on biofiltration]

Uhl, W., Gimbel, R., (1996). Investigations on the Performance of Fast-rate Biological Filters in Drinking Water Treatment. In Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [this chapter is a good review on the use of biofiltration for treating drinking water]

Vahala, R. (2002). Two-step Granular Activated Carbon Filtration in Drinking Water Treatment. Civil and Environmental Engineering. Helsinki, Helsinki University of Technology: 81. [this report details the effect of various influent feed in the performance of GAC filters]

VanDerHoek, J. P., Bonne, P.A.C., (1996). Slow Sand Filtration: Effect of Grain Size and Filtration Rate on Operation and Performance. In Advances in Slow Sand and Alternative Biological Filtration. N. Graham and R. Collins. Chichester, John Wiley & Sons. [this chapter discusses how the performance of biofilters is affected under various operating conditions]

Van der Plas, T. (1968). The Surface Chemistry of Carbon, Bronder-offset, Rotterdam, Netherlands. [this book is useful in understanding adsorption processes]

Wang, J. W, Summers, R. C., Mlltner, R. J., (1995a). 'Biofiltration Performance: Part 1, Relationship to Biomass:' J. AWWA, 87(12), 55. [this is a detailed paper on various aspect of biofiltration technology]

Wang, J. Z, Summers, R. S., Miltner, R. J., (1995b). 'Biofiltration Peroformance: Part 2, Effect of Backwashing' J. AWWA, 87(12), 64. [this is a detailed paper on various aspect of biofiltration technology]

Wang, J.Z., Summers, R. S., (1996). Biodegradation Behavior of Ozonated Natural Organic Matter in Sand Filters. Rev. Sci. Eau. 9(1):3-16. [this is a detailed paper on various aspect of biofiltration technology]

Wheaton F.W., Hochheimer J. N., Kiser G. E., Malone R. F., Krones M. J., Libey G.S. & Easter C. C., (1994). Nitrification Filter Principles, Aquaculture water Reuse Systems: Engineering Design and Management, 3rd ed, Elsevier [this book details the use of biofilters in treatment of aquaculture effluent]

Wilcox, D. P., E. Chang, Dickson, K.L., Johansson, K.R. (1983). Microbial Growth Associated with Granular Activated Carbon in a Pilot Water Treatment Facility. Applied and Environmental Microbiology 46(2): 406-416. [this paper details the microbial activity in a pilot scale biofilters used for water treatment]

Wuertz, S., P. Bishop, et al. (2003). Biofilms in Wastewater Treatment. An Interdisciplinary Approach. London, IWA Publishing. [this book details biofilters in wastewater treatment processes]

Biographical Sketches

Dr S. Vigneswaran has been working on water and wastewater treatment and reuse related research since 1976. During the last twenty years, he has made significant contributions in physico-chemical water treatment related processes such as filtration, flocculation, membrane-filtration and adsorption. His research activities both on new processes development and mathematical modeling are well documented in reputed international journals such as Water Research, American Institute of Chemical Engineers Journal, Chemical Engineering Science, Journal of American Society of Civil Engineers, and Journal of Membrane Science. He has also been involved in a number of consulting activities in this field in Australia, Indonesia, France, Korea, and Thailand through various national and international agencies. He has authored two books in this field at the invitation of CRC press, USA, and has published more than 230 papers in journals and conference's proceedings. Currently a Professor of the Environmental Engineering Group at the University of Technology, Sydney, he was the founding Head of and the founding Co-ordinator of the University Key Research Strength Program in Water and Waste Management. He is coordinating the Urban Water Cycle and Water and Environmental Management of the newly established Research Institutes on Water and Environmental Resources Management and Nano-scale Technology respectively.

Ms T. T. L. Hoang undertook research in partial fulfillment of her Master of Engineering at the University of Technology, Sydney. Her research was on the use of biofilters for treating wastewater.

Dr J. Kandasamy is Senior Lecturer in the Faculty of Engineering University of Technology, Sydney, Australia. He obtained his PhD from University of Auckland., New Zealand where is also obtained his Bachelor in Civil Engineering and Masters in Civil Engineering. He has worked in the New South Wales Government as a Senior Engineer for 15 years and has wide industry knowledge.

Dr D. N. S Chaudhary is a senior engineer at Maunsell AECOM, a firm of consulting engineers. He obtained his PhD from University Technology, Sydney. He has made significant contributions to the understanding of wastewater treatment using the adsorption and biofilter processes.