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Innovative Biological Treatment Processes for Wastewater in Canada

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Biological treatment of wastewater has been employed successfully for many types of industries. Aerobic processes have been used extensively. Production of large amounts of sludge is the main problem and methods such as biofilters and membrane bioreactors are being developed to combat this phenomenon. Anaerobic waste treatment has undergone significant developments and is now reliable with low retention times. The UASB, the original high rate anaerobic reactor, is now becoming less popular than the EGSB reactor. New developments such as the Annamox process are highly promising for nitrogen removal. For metal removal, processes such as biosorption and biosurfactants combined with ultrafiltration membranes are under development. Biosurfactants have also shown promise as dispersing agents for oil spills. If space is available, wetlands can be used to reduce biological oxygen demand (BOD), total suspended solids (TSS), nutrients and heavy metals. These innovative processes are described in this paper in terms of applications, the stage of development, and future research needs particular to Canada.

Key words: **biofilter, membrane bioreactor, heavy metal removal, wetlands, Annamox, biosurfactants**

Introduction

Biological treatment is commonly used as a secondary treatment. The major biological treatment processes for wastewater include activated sludge processes, aerated lagoons or stabilization ponds, trickling filters or fixed-film reactors, and anaerobic processes. The major groups of biological processes include aerobic, anaerobic and a combination of both. The systems are divided into suspended or attached growth processes for the removal of BOD, nitrification, denitrification, stabilization and phosphorus removal. Aerobic processes including activated sludge, trickling filters, aerated lagoons and rotating biological contactors have been used extensively. However, the supply of air is expensive in addition to the large amounts of sludge that must be sent for disposal. Recently, significant developments have been made in the area of anaerobic waste treatment. Each technology has advantages and disadvan-

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tages that must be considered when choosing an appropriate technology for the water treatment. The aim of this paper is to review recent developments in biological wastewater treatment, with emphasis on applications in Canada. Their applicability, state of development and research requirements will be discussed.

Aerobic Biological Treatment

Aerobic Systems in Canada

A recent survey was performed by CWWA for a range of facilities serving populations of various sizes (CWWA 2001). The results for the types of treatment processes are summarized in Table 1. A large number of facilities have biological systems. Activated sludge systems are the most popular followed by extended aeration. A significant number have aerobic lagoons. Overall approximately 65% of facilities responding and serving up to 5000 in population have one or more lagoons. Clearly, aerobic systems are popular in Canada for water treatment. Other treatments include primary sedimentation and chemical flocculation. This is mainly due to the significant experience of engineers in this area. This does not mean research is complete but significant improvements in aeration techniques, mixing, and sludge reduction are required. However, there are other more innovative biological wastewater treatment processes that are being developed including biofilters and membrane bioreactors. These will be discussed here.

Table 1. Survey of wastewater treatment systems in Canada (adapted from CWWA 2001)

	Population						
Type of system	<1000	>1000	>5000	>25,000	>100,000	Not given	Total
Activated sludge	13	59	53	30	16	15	186
Extended aeration	21	62	26	3	1	6	119
Oxidation ditch	1	10	2	3	0	3	19
RBC	13	5	8	2	2	1	31
SBR	1	5	6	2	0	4	18
Trickling filter	3	3	3	6	2	1	18
Aerobic lagoons	31	117	44	5	1	12	210
Anaerobic lagoons	46	50	9	1	0	11	117
Facultative lagoons	59	52	30	6	0	5	153
Total facilities	178	289	136	55	30	50	738

Biofilters

A biofilter is a new type of trickling filter that uses natural absorbents such as peat or synthetic medium for microbial attachment that can be used for the secondary and tertiary treatment of municipal or communal wastewater, restaurants, hotels, individual domestic sewage, landfill leachate (Jowett et al. 1997), food-processing wastewater and some farm animal wastewater applications. The medium (about the size of a fist) is chosen to obtain high biomass retention times, optimal microbial attachment, high porosity and separate paths for air and water. Other media such as vitrified clay called biolite was developed in France and is sold in North America in systems called the biological aerated filter.

A sprinkler system distributes the liquid over the media. Loading rates are in the range of 50 to 80 cm/day which can be compared to sand filters which typically handle around 4.7 cm/day. Typical removal rates are 95% TSS, 90 to 95% BOD, 20 to 50% total nitrogen and 90 to 99% coliform bacteria. Although housings are used for cold climates, these types of reactors are mainly installed in the southern part of Canada. There are currently thousands installed in Canada, U.S.A. and Europe.

Membrane Bioreactor

Another variation of the activated sludge process is the incorporation of ultrafiltration membranes with a biological reactor to increase sludge retention while decreasing hydraulic retention times. In the process, wastewater enters the reactor for biological treatment. The water is then passed to the ultrafiltration step where the biomass and high molecular weight soluble components are separated from the treated water. The retained components are then recycled to the bioreactor. The process can nitrify or denitrify the wastewater when an anoxic reactor is added. Oxygen transfer rates are reduced due to fouling of the membranes. It reduces construction costs, land area, operator labour, sludge volumes, odour and chemical costs. In a typical sewage treatment plant, the sludge would be removed by the membranes, thus eliminating the need for clarifiers and sludge digestion.

Organic loading rates for municipal wastewaters are typically 1 to 4 kg COD/m^3-day for VSS concentrations of 15 to 25 kg/m^3. However, loading rates have ranged from 0.05 to 0.66 kg BOD/m^3-day with 90 to 99.8% removal efficiencies (Stephenson et al. 2000). For industrial applications, COD concentrations in the influent have been 68,000 mg/L for breweries (Kempen et al. 1997) and 29,430 mg/L for oily wastes (Zaloum et al. 1994). Sludge ages for industrial and municipal wastewaters vary between 6 to 300 days while HRTs are in the order of days for industrial wastewater and hours for municipal systems.

Inert solids can accumulate in the system and thus a bleed should be incorporated into the system to remove these solids. The only drawback is that the solids are difficult to remove. Efforts are needed to enhance oxygen transfer. These membrane bioreactors are ideal for high salt concentrations where aggregation is difficult and for high concentrations of components that do not degrade anaerobically. More information is also required on the relationship of membranes and colloid retention.

Membrane reactors can be used for many types of wastewater ranging from oily wastewater, metal finishing wastes, landfill leachates, alcohol-based cleaning solution, detergents, aqueous paint-stripping wastes, deicing fluids, soil washing effluents, contaminated groundwater to high strength and variable feed wastewater. According to Stephenson et al. (2000), 27% of membrane bioreactors have been used for industrial wastewaters, 27% for domestic wastewater, 24% for in-building, 12% for municipal and 9% for landfill leachates. There are more than 500 full-scale units installed world-wide. Most are aerobic (98%) and the rest are anaerobic. Two types of systems are utilized, the membrane external to the reactor (45%) (Fig. 1) and the membrane within the bioreactor (55%). Two other types of membrane bioreactors, membrane aeration bioreactors to enhance oxygen transfer and extractive membrane bioreactors for toxic effluents, have been developed to pilot scale only. Research and development of these units is underway.

Installations of membrane bioreactors are now occurring in Canada and the United States. Three municipal installations have been commissioned since 1996 in British Columbia (capacities of 380, 1130, and 3800 m^3/day) and one in Ontario (1000 m^3/day) (Stephenson et al. 2000). More than 15 plants in North America have been installed for the treatment of wastewater up to 9500 m^3/day. More than 15 installations have been installed for the treatment of synthetic oil and grease metal industry wastewater (up to 750 m^3/day) (Coté and Thompson 2000).

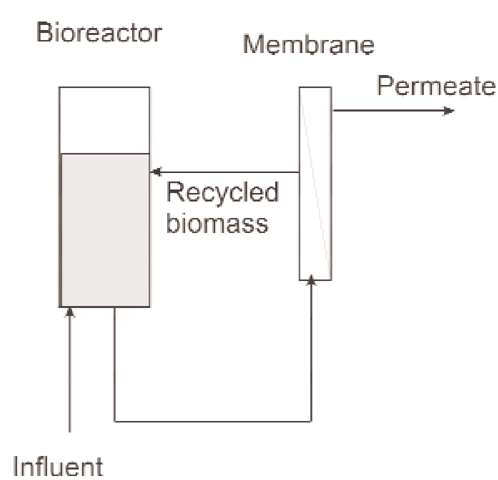

Fig. 1. Schematic of a membrane bioreactor.

More than 50 membrane bioreactors have been installed for residential and office developments, shopping centres, schools, hotels and resorts with flows from 10 to 200 m^3/day (Coté and Thompson 2000). For example, a membrane bioreactor was chosen as a resort wastewater treatment system in central Ontario (Kent 2001). An immersed hollow fibre system was used for the water generated by up to 600 guests. The system is modular and includes disinfection by UV before discharge into a lake. Sludge settling tanks are not required. Membrane surfaces are kept clean by introduction of air bubbles, flows are periodically reversed and the membranes are removed a couple of times a year and dipped in a cleaning solution. Fouling is the main concern with membrane systems and developments are still needed in this area. Other limitations include increased capital costs and maintenance over traditional activated sludge systems.

Anaerobic Processes

Anaerobic processes have become popular since 1980 when the Dutch upflow anaerobic sludge blanket (UASB) system was introduced. They have several advantages over aerobic processes including lower electricity costs, high efficiencies, low construction and operating costs, low rates of sludge production, high organic loading rates production of biogas which can be used as a fuel and the aerobic microbes do not have the enzymes to remove chlorine from chlorinated compounds. Anaerobic biomass does not have to be fed continuously. Complete degradation of chlorinated compounds can be accomplished by anaerobic followed by aerobic processes. Anaerobic processes do not require oxygen and produce methane, carbon dioxide and low molecular weight end products. Methane production, once it is handled with care, can be useful for heating purposes. Sludge production is much less than for aerobic processes (5 to 20% of aerobic), reducing disposal problems and costs. All these aspects seem to potentially meet the NRC (1995) criteria for sustainable development. Degradation times may be longer, however, since anaerobic metabolism is a slower process but loading rates are higher.

Anaerobic processes can transform some compounds better than aerobic ones. Chlorinated compounds in the pulp and paper industry can be dehalogenated (Parker et al. 1993) and formaldehyde can be removed (Omil et al. 1999). Macarie (1999) reviewed many recent applications that included anaerobic treatment of effluents with maleic acid, carboxymethyl-cellulose, synthetic resins and petrochemicals. Since anaerobic sludges can remain inactive for several months, seasonal wastewaters such as the fish processing or sugar refining industries, can be treated anaerobically (Omil et al. 1996). Other components that can be degraded include nitroaromatic compounds, N-substituted aromatics, alkylphenols and azo dyes (Donlon et al. 1996; Razo-Flores et al. 1996, 1997).

There have been advances in high temperature treatment (van Lier 1995). Growth rates increase but granular sludge formation can be a problem. Even at low temperatures (10 to 12°C), anaerobic treatment can be achieved for acidified wastewater at loads up to 10 kg COD/m^3-day (Rebac 1998). Acidification is required since the acidifying bacteria are affected at this temperature. An overview of the newer developments in anaerobic technologies follows.

Upflow Anaerobic Sludge Blanket (UASB) Reactor

A variation of the anaerobic contact process is the sludge blanket process (UASB) which is a biological tank with upflow and a settling tank developed in The Netherlands (Lettinga et al. 1980). Granules are produced during the degradation of the easily degradable organic matter and consist of high concentrations of biomass (Fig. 2). They are permanently formed and remain in the reactor. The wastewater enters the bottom of the reactor and passes through the granules. The organic matter is converted to methane and carbon dioxide and leads to the formation of gas bubbles which can provide adequate mixing and wastewater/biomass contact. The granules rise in the reactor due to the bubbles, however they will settle in the tank since their settling velocities are greater than the upflow velocity (typically 1 m/h). An adequate settling zone is provided (van Haandel and Lettinga 1994). Since the concentrations of sludge can be up to 5 to 15 kg VSS/m^3, generally twice that of contact processes, recycling is not required. They are the most common type of high rate process in the world today because they can perform at higher efficiencies than anaerobic fixed film and continuous flow aerobic (Latkar and Chakrabarti 1994).

Bacterial sensitivity to pH, temperature and toxic compounds, long start-up and production of odorous compounds have been cited as disadvantages for these processes. However, although chemical addition may be necessary for industrial effluent treatment, it is not usually the case for domestic wastewater and sewage (van Haandel and Lettinga 1994). The bacteria adapt well to low temperatures and can tolerate some toxicants such as aliphatic hydrocarbons and chlorinated alcohols even better than aerobic bacteria (Blum and Speece 1991). UASB reactors have been used to degrade pentachlorophenol (PCP) with up to 99% efficiency (Hendricksen et al. 1992). They have also been used for nitroaromatic compounds (Donlon 1996). Other applications include sugarbeets, fatty acids, piggery, slaughterhouse, potato starch, pulp and paper, alcohols and milk fat (McCarty 2001). Start-up times can be reduced by using adequate inoculum such as digested sludge or biomass from operating anaerobic reactors, particularly if lower operating temperatures are used (Singh et al. 1997). Toxic compounds can lead to biomass that does not settle well and subsequent biomass washout.

UASB reactors are suitable for organic loads of 0.5 to 20 kg COD/m^3-day which is higher than aerobic processes (Kato 1994). This reduces reactor volume and space requirements. UASB reactors can be used for high-strength wastewaters with VSS:COD ratios less than 1 and with COD concentrations between 500 and 20,000 mg/L. The HRT can be less than 24 h.

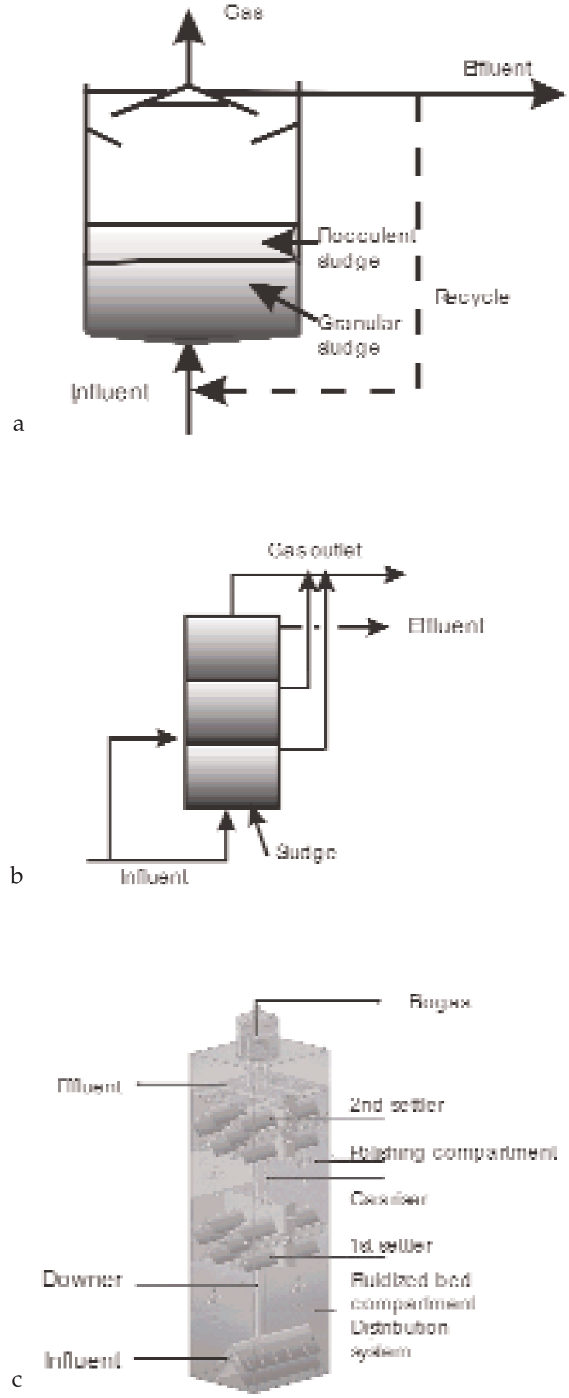

Fig. 2. Anaerobic reactors including (a) UASB, (b) Multiplate and (c) IC reactor.

Cases where lower strength wastewaters with less than 1000 mg COD/L have not been frequently reported. In Kanpur, India, a full-scale UASB reactor has been treating 5000 m^3 of raw sewage per day since 1989 (Draaijer et al. 1992). Another unit to treat 36,000 m^3/day in the same town was subsequently built (Haskoning Consulting Engineers and Architects 1996a). Average loadings were 2.5 kg COD/m^3-day with COD, BOD and TSS removals of 50 to 70%, 50 to 65% and 45 to 60%, respectively. Based on these results a pond with a one-day retention was added for installation in another Indian town (Mirzapur) (Haskoning Consulting Engineers and Architects 1996b). With loading rates of 0.95 kg COD/m^3-day on the UASB reactor and 0.13 kg COD/m^3-day for the polishing ponds, the final effluent conditions of 30 mg COD/L and TSS of 10 mg/L could be achieved. Temperatures were between 18 and 32°C. Overall COD, BOD, TSS removal rates were 81, 86 and 89%, respectively.

In Canada, a full-scale UASB system is operating at Roger's Sugar (Taber, Alberta) for the treatment of beet sugar mill wastewater in 1999. An aerobic activated sludge reactor follows the UASB. The capacity of the system is 35,545 kg COD/day. There are numerous other applications as can be seen in Table 2. It has also been postulated that UASB reactors can be used to treat municipal wastewater in Canada, in particular for remote areas such as Indian Reserves (Singh and Viraraghavan 2000).

Expanded Granular Sludge Blanket (EGSB) Reactors

For treating sewage at lower temperatures (4 to 20°C), it was determined in pilot tests that the UASB reactors did not provide adequate influent distribution. The expanded granular sludge bed (EGSB) reactor was developed to incorporate higher superficial velocities (greater than 4 m/h) from the fluidized bed reactors without the need for carriers. This was accomplished by higher height to diameter ratios and the use of effluent recirculation. The higher upflow velocities expand the bed, and eliminate dead zones and lead to better wastewater/biomass contact (van der Last and Lettinga 1992). Soluble pollutants are efficiently treated by these reactors but not suspended solids or colloidal matter. A 205 m^3 unit was operated in The Netherlands for approximately 33 months at temperatures between 16 and 19°C with HRT between 1.5 and 5.8 hours. COD and BOD removal rates were 30 and 40%, respectively, with no TSS removal (van der Last and Lettinga 1992). Low strength wastewaters (Kato et al. 1994) and high strength wastewaters which are diluted due to the recirculation stream are treated efficiently in these reactors. For the low strength wastewaters such as sewage, recirculation is not necessary. UASB reactors behave like static beds whereas the EGSB reactors are similar to mixed tanks (Rinzema 1988). This phenomenon increases the organic loading that can be handled by the latter type of reactor. Space requirements for the reactor are small while loading rates are high. Pumping costs, however, are increased due to the recirculation.

Table 2. Anaerobic UASB plants installed in Canada in the last 10 years (Biothane 2002)

Installation	Type of wastewater	Volume of reactor and loading	Year of start-up
Fleishmann's yeast	Yeast Flow: 17 m^3/h COD load: 7173 kg/day	Reactor of 500 m^3 COD loading rate: 14.3 $kg/m^3 \cdot day$	1993
A. Lassonde. Inc.	Flow: 42 m^3/h COD load: 10,900 kg/day	Reactor of 800 m^3 COD loading rate: 13.6 $kg/m^3 \cdot day$	1994
Canning operation	Flow: 21 m^3/h COD load: 4545 kg/day	Reactor of 400 m^3 COD loading rate: 11.4 $kg/m^3 \cdot day$	1994
Commercial alcohol	Alcohol Flow: 42 m^3/h COD load: 7680 kg/day	Reactor of 500 m^3 COD loading rate: 15.4 $kg/m^3 \cdot day$	1997
3M	Chemical Flow: 0.4 m^3/h COD load: 300 kg/day	Reactor of 50 m^3 COD loading rate: 12.0 $kg/m^3 \cdot day$	1998

The internal circulation (IC) reactor technology is a type of EGSB reactor. It consists of two UASB reactors, one on top of the other (Fig. 2). One is for high loads while the second is for low loads. The gas from the first stage drives a gas lift and internal circulation. The biogas is collected in the top of the reactor. The four basic processes in the reactor are the mixing section, expanded bed section, the polishing section and the recirculation system.

The Biobed system, another type of EGSB reactor, has been completed at Robin Hood Multi-Foods near St. Catherine and is under construction at McCain Foods in Grand Falls, N.B., and will be used as a pretreatment at Inter-Quisa in Montreal. More than 40 systems are operating or are under construction throughout the world. Therefore, activity in Canada has been strong. Applications are for the brewery, chemical, fermentation and pharmaceutical industries.

The Multiplate Reactor

The multiplate reactor technology was constructed in 1991 at a dairy plant in the province of Quebec (Canada) (Mulligan et al. 1996). The reactor is comprised of a shell, plates, parallel feed entrances and lateral gas exits (Fig. 2). Typical total COD removal rates of greater than 93% and soluble COD removal rates of 98% are achieved. Other effluents have also been pilot tested with this reactor for volatile organic compounds (VOCs), aircraft deicing agents, brewery and potato processing wastewater (Mulligan et al. 1997). Its potential at the laboratory scale for the degradation of chlorinated solvents is being investigated. More full-scale demonstrations of this unit are required.

Anaerobic Sequencing Batch Reactor

The Anaerobic Sequencing Batch Reactor (ASBR) is an anaerobic version of the conventional SBR technology. It is applicable for high strength wastewaters and can remove 75 to 94% COD with hydraulic retention times of 8 to 24 hours. The age of the biomass is 60 to 70 days. The four cycles of fill, react, settle and decant operate on three- to twelve-hour cycles. Operation is based on timing. Due to the batch-fed operation, short-circuiting does not occur. The biomass is highly granulated and contains many bacterial species and fungi with mineral deposits. These granules settle rapidly at a rate of a metre per minute. Organic loading rates of 4 kg COD/m^3-day are used (Beun et al. 1999). Dilution of toxic materials does not occur. This type of reactor appears to still be under development due to a lack of full-scale systems. A semi-commercial system has been developed by Agriculture and Agri-Food Canada for swine manure slurries and has been pilot tested at 30°C for the treatment of slaughterhouse wastewater (Massé and Masse 2000).

Annamox Process

Recently, an innovative process, known as Anammox (anaerobic ammonium oxidation), has been discovered (Strous et al. 1999). Up to

2.6 kg total N/m^3 reactor-day can be achieved compared to 0.1 kg total N/m^3 reactor-day for activated sludge processes (Jetten et al. 1999; STOWA 1996). SBR and fluidized bed reactors can be used. This process can convert ammonium in the wastewater to nitrogen gas under anoxic conditions with nitrite as the electron acceptor and ammonium as the electron donor with sludge production. Sludge generation in this process is very low. This reaction is very promising but insufficient work has been done to take advantage of this process. The main disadvantage is the slow doubling time of Annamox bacteria (11 days). The ratio of ammonium to nitrite should be 1:1.3 and has been accomplished by partially treating the wastewater with the Sharon reactor (1 day HRT at 35°C).

In our research (Mulligan and Chan 2001), the feasibility of ammonium removal from wastewater at the same time as COD removal by nitrite addition has been examined at room temperature. Further experiments will also be needed to determine the ratio of nitrite to ammonia required for the Anammox process to take place. Using continuous reactors may favour their development. Development of this technology will be highly important for the anaerobic treatment of municipal and other industrial wastewaters where nitrogen removal is essential.

Analysis of Anaerobic Technologies

Full-scale anaerobic systems have been quite successful. There are many misconceptions about anaerobic treatment that limit its use. These problems have arisen due to poor designs before the 1950s and a lack of understanding of anaerobic processes. A major advantage for anaerobic processes over aerobic is the decreased rate of sludge production. Sludge production can be between three and twenty times less than for aerobic processes (Rittmann and Baskin 1985). The costs of disposal of large amounts of sludge can be substantial. In addition, the processing of the sludge before disposal is energy intensive unless gravity or flotation thickening is feasible. Overall, proper reactor design and operation can overcome any disadvantages of anaerobic treatment.

Since anaerobic treatment processes often lead to effluents that are greater than regulatory requirements, further treatment is often necessary. Aerobic polishing can be used. This maintains the advantages of anaerobic treatment with an effluent that meets requirements for discharge into streams or rivers. The solids from the aerobic treatment can be treated in the anaerobic system.

An analysis of full-scale anaerobic technologies was performed by Frankin (2001). He showed that there were approximately 1215 plants in 65 countries. A breakdown of the processes is shown in Table 3. Although UASB systems are still the most common, the growth of the EGSB in the last few years is particularly noteworthy. The average design loading rates are also shown which clearly indicate that the EGSB design is twice that of the UASB, thus leading to smaller reactors. This would also indicate why the UASB reactors are gradually being replaced by the EGSB. In terms of applications, food wastewaters are the most treated by anaerobic

Table 3. Distribution of full-scale anaerobic technologies and their average organic loads (Frankin 2001)

Process	% of Total plants in database	% of Total plants built from 1990 to 1996	% of Plants built from 1997 to 2000	Average load (kg COD $m^3 \cdot$ day)
Low rate	15	12	8	2
UASB	56	68	34	10
Fixed bed	4	4	3	unknown
Fluidized bed	1	2	1	unknown
Hybrid	1	1	2	7.5
EGSB	16	8	50	20
Unknown	5	6	3	unknown

reactors, followed by breweries and beverages and then distilleries and fermentation (Fig. 3). The newest development of anaerobic systems is for municipal wastewater. Until now, applications at low temperatures have been limited due to low treatment rates. The hydrolysis step will need to be improved, however. Costs are more competitive than activated sludge treatment when sewage temperatures are above 15°C and the land cost is above $23/m^2 (Hulshoff Pol et al. 1998).

The same trend as for other countries has held in Canada where the pulp and paper and the food industries are the most common applications for anaerobic treatment. Japan, Germany, The Netherlands and the United States are leading countries in implementing anaerobic reactors for wastewater treatment. Canada is tenth as a country in applying anaerobic technologies for wastewater treatment at 0.8 reactors per million habitants (Hulshoff Pol et al. 1998). There are no plants that use anaerobic treatment for municipal wastewater treatment in Canada, despite the potential benefits in this area.

The most appropriate anaerobic technology should be selected based on bench or pilot tests with the actual wastewater, particularly if the wastewater contains toxic components. The result of the tests depends on retaining an active microbial population. Process conditions should be designed and operated for the optimal performance of the microorganisms. More development is needed in modelling and in the control of anaerobic reactors and the use of biosensors in the presence of high solids contents (Aubrun et al. 2001). Choice of the inoculum sludge is very important, in addition to the training of the operators. The main factors for consideration are easy construction, reliability over a variety of wastewater characteristics, easy restart, low operating costs and high efficiency. UASB and contact processes are generally more simple to operate and maintain while EGSB, IC and fluidized bed reactors are more complex. Developments in the treatment of recalcitrant compounds and the use of low temperature processes will enable wider adoption of anaerobic technologies.

Wetland Systems

Natural wetlands are areas of land with the water surface near that of the land, thus maintaining saturated soil conditions and vegetation including plants, peat, wildlife, microbial cultures and vegetation including cattails (*Typha* spp.), reeds (*Phragmites* spp.), sedges (*Carex* spp.), bulrushes (*Scirpus* spp.), rushes (*Juncus* spp.), water hyacinths (*Eichhornia crassipes*), duckweeds (*Lemna* spp.), grasses and others detailed by Mitsch and Gosselink (1992). Constructed wetlands have been specifically designed to include these species for the removal of BOD, SS, nutrients and heavy metals for optimal performance. Denitrification also occurs due to the anaerobic conditions in the water. It was reported by Reed et al. (1995), that 1000 managed wetlands are in operation throughout the world.

The wetland systems can be designed either as surface flow with a free water surface or as a subsurface flow (Fig. 4) where the water must enter after passing through a permeable medium. Both types of wetland systems can be applied to commercial and industrial wastewaters. High strength wastewaters are usually treated anaerobically first. Both types of wetlands have been used for wastewater from food processing, pulp and paper processing, chemical production and oil refineries. Pilot tests may be preferable if inadequate treatment data exists. Wetlands have also been used for the removal of sediments from urban stormwater from landscapes, streets and parking lots. They also have some benefit for BOD, nitrate, phosphate and trace metal removal. The basis of these systems is a combination of shallow marshes and deep ponds to which wet meadows and shrub areas can be added.

In a partial list of the wetlands in the North American Wetland Treatment System Database, 154 were for the treatment of municipal wastewater, nine for industrial, six for agricultural wastewater and seven

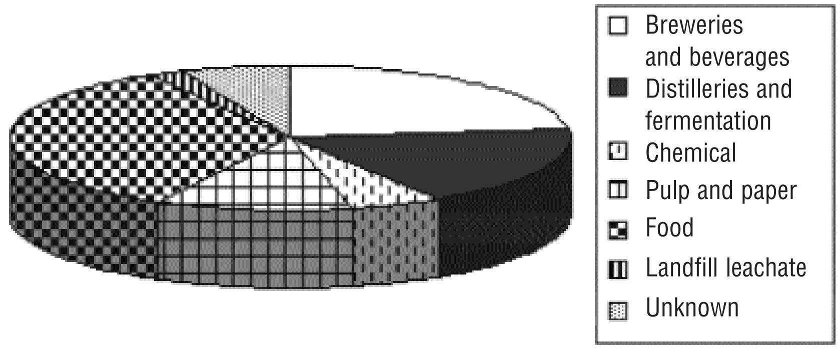

Fig. 3. Breakdown of applications for anaerobic treatment.

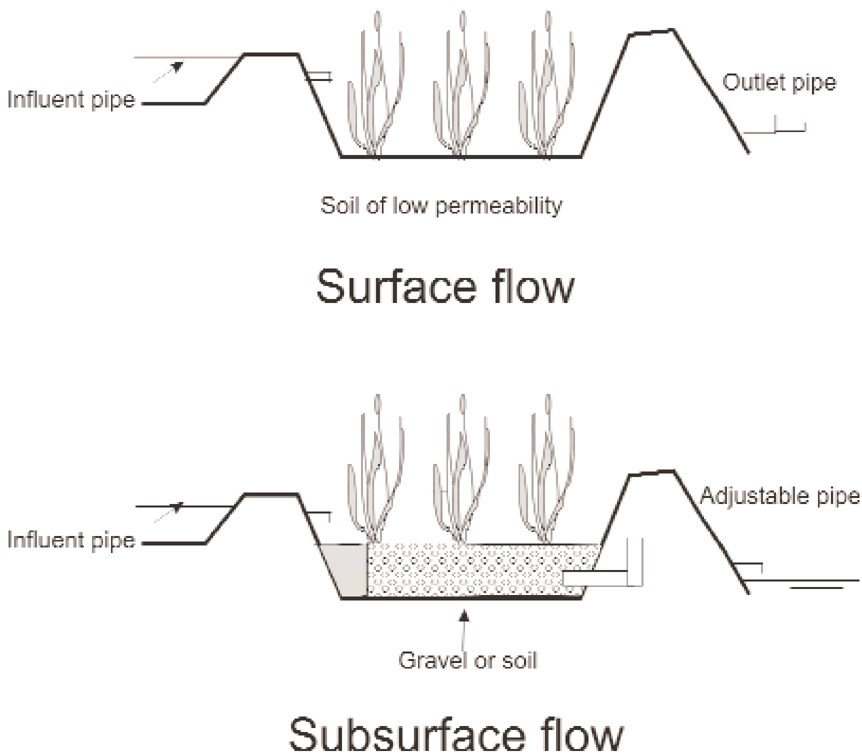

Fig. 4. Schematic of wetland systems including surface flow and subsurface flow.

were for stormwater (Kadlec and Knight 1996). These systems treat more than 190 m^3/day. Of these, 120 are surface flow systems and 48 are subsurface systems, while 8 are both. Wetland treatment systems are, thus, becoming more and more accepted for municipal, agricultural and industrial wastewaters, as well as for stormwater management.

Wetlands are becoming more accepted for stormwater quality management in Canada (Warner and Li 2000). Two wetlands were constructed in Nova Scotia for domestic wastewater treatment and as a wildlife habitat. Rates of removal for BOD, suspended solids, fecal coliform bacteria, total phosphorus and total nitrogen were 90% from 1996 to 1998 (Hanson and McCullough 2002). In general, average removal efficiencies are 50 to 80% as shown in Table 4 (API 1998). Phenols can be reduced by 70% in the petroleum industry and VOCs up to 95%. Even 50% metal removal efficiencies have been achieved for aluminum, cadmium, copper, iron, lead, mercury, nickel, silver and zinc. This is due to growing confidence in the performance of these systems and the shortage of affordable technologies (Kadlec and Knight 1996).

For treatment of acid mine drainage, constructed wetlands could be used in Canada (MEND 1999). Design will need to be optimized and

Table 4. Summary of the performance of North American wetland treatment systems[a]

	Concentration (mg/L)		
Parameter	In	Out	Efficiency (%)
BOD	29.8	8.1	73
TSS	46.0	13.0	72
NH_4-N	4.97	2.41	52
Total N	9.67	4.53	53
Total P	3.8	1.68	56

[a]Adapted from Kadlec and Knight (1996) and API (1998).

many parameters will need to be understood including biological reaction and metal retention in the wetlands. The effect of freezing temperatures and variable flows will need to be addressed. The wetlands will most likely be applied where winters are short and mild and where flow rates are constant. If operation during the winter is not possible, large retention ponds will be required during this period. Capital costs have been estimated at \$8 to 48/m^2 of wetland with \$85,000 in operating costs for a 60 L/min wetland (MEND 1999).

In the Biosphere in Montreal, Quebec, wastewater has been treated since 1995 with a pilot wetland system part of the year (Environment Canada 2002). It consists of three ponds with an area of 800 m^2. Total retention time is 2 weeks. The system is working well and is an example for future housing projects. More intensive monitoring of the system will be taking place.

A more recent approach which could be applied in Canada was developed in France for communities with less than 1000 inhabitants (Betts 2002). It uses chrysanthemum plants for aerobic wetland treatment of the wastewater. Ammonia can be easily treated within 72 hours. Nitrogen and phosphorus removal was 40 to 80%, BOD removal was 91% and 95% of the suspended solids were removed. Heavy metal removal is unknown at this point and more data is required to determine the effects of cold weather that may freeze the plants.

For the use of wetlands to develop, more collaboration will be required between engineers and scientists due to the interdisciplinary nature of the technology. More than 100 natural wetlands exist in Canada (Warner and Li 2000). Constructed wetlands will enable engineers to design systems with more control and obtain regulatory approval. Capital costs are low, with low operation and maintenance requirements. This technology is emerging and its advantages make it attractive. It will need everyone (engineers and scientists) to share the knowledge to improve know-how. An approach similar to the U.S. may be necessary where interdisciplinary groups help to develop guidelines (Cole 1998). Currently, no accepted methodology exists for wetland design. Depths of 1.5 m and length to width ratios of 3:1 with surface loadings of up to 220 kg BOD/ha-day usually provide good BOD and SS removal results (Rittmann and McCarty 2001). This is a sustainable and green technology for purifying water with numerous benefits for the future.

Metal Treatment Processes

Biosorption

Biosorption involves the removal of metals from wastewater via adsorption on living or dead biomass. The biomass can include bacteria (*Bacillus subtilis*, *Bacillus licheniformis*), yeast (*Candida tropicalis*), fungus (*Aspergillus niger*, *Penicillium chryosogenum*, *Rhizopus arrhizus*), algae (*Sargassum natans*, *Ascophyllum rodosum*, *Fucus vesiculosus*) and plant material (peat moss, wood chips and pine cones). Algal biomass (*Sargassum natans*) can uptake metals up to almost 40% of its dry weight. Many metals can be adsorbed such as silver, gold, cadmium, chromium, copper, iron, mercury, nickel, lead, zinc and radioactive metals. Various types of materials have been used for immobilization including alginate, polyacrylamide, polysulfone, silica gel, cellulose and glutaraldehyde. For commercial systems, biosorption processes can take place in batch or continuous-stirred tanks, fixed packed beds, and fluidized beds (Volesky 1990).

Biosorbent use depends on biosorption capacity, availability of the biosorbent, cost, ease of regeneration and use in various reactor configurations. Eluents such as dilute acids or carbonate can be used to desorb the adsorbed contaminants. *Aspergillus*, *Penicillium* and *Saccharomyces* can withstand 10 cycles of regeneration without decreased adsorption capacity. However, more research is needed in this area. Other biosorbents such as anaerobic sludge is currently being evaluated for the removal of Cd, Cu, Pb and Ni (in batch and continuous systems (Alhawari and Mulligan 2002).

Biosorption can be useful for radionuclides from dilute streams such as mine leachates. *Aspergillus niger* can adsorb between 31 to 214 mg/g of uranium, *Rhizopus arrhizus* can adsorb about 200 mg/g and *Saccharomyces cerevisiae* can adsorb 150 mg/g. This can be compared to traditional adsorbers such as ion exchange resin IRA-400 (79 mg/g) and Activated Carbon F-400 (145 mg/g). Only a few biosorbents have been commercialized.

Potential applications of these biosorbents include industrial effluent polishing and metal removal from dilute effluents. The advantages of using biosorbents include versatility and flexibility, robustness, selectivity of heavy metals over alkaline earth metals, ability to reduce metal concentrations to drinking water standards, and cost-effectiveness (Garnham et al. 1992). Current constraints are the competition with ion exchange resins, the low capacity of metal fixation in terms of mg of metal adsorbed per gram of sorbent, the selectivity and the ability to regenerate these materials. Engineers, in general, prefer more established processes such as ion exchange as they have a lack of knowledge concerning biosorbents. A greater understanding of these biological-based systems may help their commercialization potential in the future.

There have been a few studies related to acid mine drainage and biosorption. The use of living biomass is not likely to be feasible in the winter. Dead biomass systems appear more promising. Biosorption could also be used as a secondary treatment process (MEND 1999).

Metal Precipitation and Sulfur Removal

Sulfate-reducing bacteria include *Desulfovibrio*, *Desulfotamachulum*, *Desulfobacter*, *Desulfococcus*, *Desulfonema* and *Desulfosarcina*. They can remove metals by hydrogen sulfide production which subsequently precipitates metals. Sulfur-oxidizing bacteria include *Thiobacillus thioxidans*, *T. thioplaus* and *T. denitrificans*. Reactors have been developed to take advantage of these processes. For example, for heavy metal and sulfate removal, metal precipitates are formed. In a second reactor, the sulfide is converted to sulfur. Metal reuse is possible if only one metal is used such as zinc. These biological processes have been operated in the treatment of electronic component and electro-plating wastewaters.

In the past, sulfur effluents have been treated with lime which forms gypsum that has to be landfilled. Although lime addition is simple, the sludge is not easy to dewater and frequently sulfate concentration below 1500 mg/L cannot be achieved. The final sulfur product contains 60% solids with a purity of 95% and can be used for sulfuric acid production or as soil amendments.

An example of a full-scale installation is at a synthetic fiber production plant (Emmen, The Netherlands) where 40 m^3/h of wastewater containing 2 g/L sulfate has been treated since 1995. Approximately 75% of the sulfate is converted to sulfur. Currently through oxidative or reductive processes, full-scale reactors up to 2000 m^3 have been constructed. More than 24 commercial plants have been constructed for desulphurization and six combine metal and sulfur removal. In the future, developments will be required for removal of mercaptan and other organic sulfur compounds (Kuenen and Lens 2001).

Reactor systems for sulfate-reducing bacteria have been pilot tested for treatment of acid mine drainage in Canada and appear feasible for low flow rates (MEND 1999). Longer term studies at flow rates higher than 1 L/min will be required. The choice of carbon source will be the key to the success of the reactor. Open reactors can only be used where the winter is not exceedingly cold. Closed reactors, however, could be used in all climates. It has been estimated that small open systems of 50 to 60 L/min could cost approximately $34,000 and closed systems (75 to 100 L/min) approximately $56,000 (MEND 1999). Recently, the BioSulphide/Thiopaq process (Fig. 5), the result of a Canadian-Netherlands agreement enabled a commercial plant to be designed, constructed and commissioned at the Caribou Mine in Bathurst, New Brunswick, for the treatment of acid water and selected metals including copper, zinc, cadmium and lead (BioteQ 2002).

Use of Biosurfactants

Biosurfactants, surface active agents produced by bacteria or yeast, are potentially useful in wastewater treatment, particularly due to their anionic nature, low toxicity, biodegradability and excellent surface active properties. Recently, their feasibility for enhancing metal removal has been demonstrated (Mulligan et al. 2001). Copper and zinc (10 mg/L) were rejected by ultrafiltration membranes and with membranes of molecular weight cutoffs of 50,000 amu for surfactin and 10,000 amu for rhamnolipid. Concentrations of greater than 0.1% for both surfactants showed the highest metal rejection ratios (greater than 80%). This phenomenon is due to metal complexation with the biosurfactants. Further experiments are now being performed with hollow fiber membranes.

Another recent development is the feasibility of biosurfactants for dispersing oil slicks (Holakoo and Mulligan 2001). At 25°C and a salinity of 35‰, a solution of 2% rhamnolipids diluted in saline water and applied at a dispersant to oil ratio (DOR) of 1:2, could immediately disperse 65% of a Brut crude oil. Co-addition of 60% ethanol and 32% octanol with 8% rhamnolipids applied at a DOR of 1:8 improved dispersion to 82%. Dispersion efficiency decreased in fresh water and at lower temperatures but altering the formulation could improve efficiencies. Comparison of the dispersion behaviour to Corexit showed that the rhamnolipids had excellent potential as non-toxic oil dispersing agents.

Future Developments

Many types of wastewater can be treated biologically with proper analysis and environmental control. Changes in the environment must allow the organisms to adapt or the effects may be highly detrimental. In the future, research must focus on the development of systems that can increase the rate of the treatment process to decrease retention times and subsequently reactor volumes. There is usually resistance by engineers, and waste treatment plant operators, among others, to biological augmentation (addition of specific microorganisms). Experts in design, operation and biological processes will need to combine their efforts to enhance system performance, particularly for the treatment of recalcitrant compounds. Because experience is fairly limited in the biological treatment of toxic compounds, it is difficult to predict their fate and effect in bioreactors. More developments are required for thermophilic anaerobic

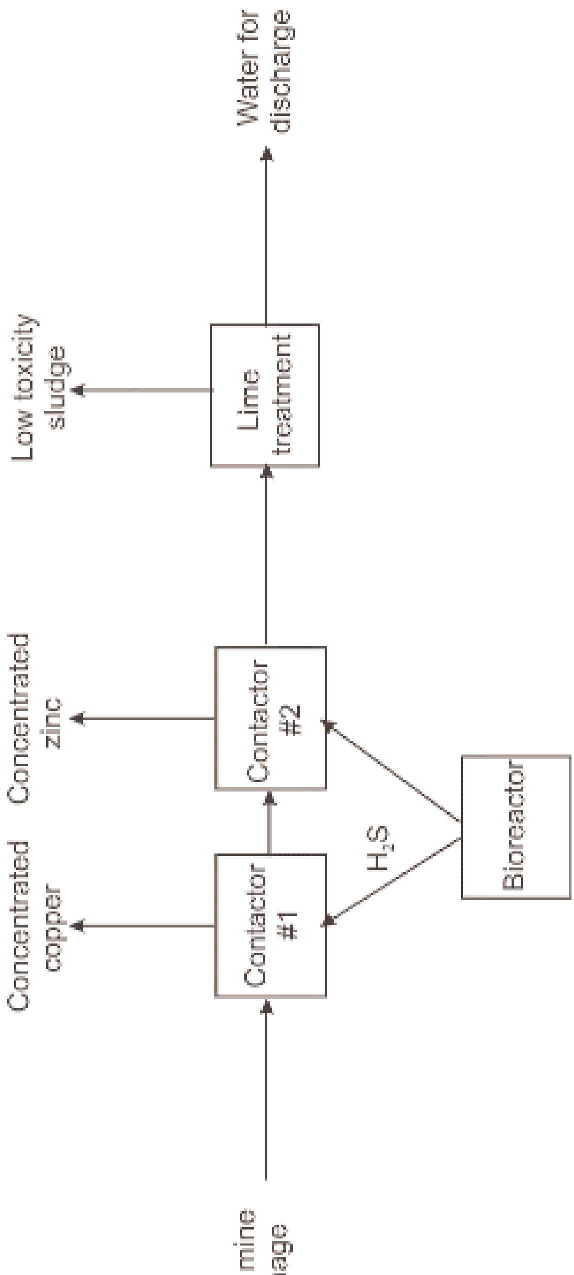

Fig. 5. Reactor for removal of sulfur.

reactors, granular SBR and membrane reactors, in addition to odour control for anaerobic reactors, and improving efficiencies of refractory organic degradation. Systems such as wetlands are highly complex and research is needed to determine specific mechanisms for toxicity reduction. Due to the success of sulfate and metal removal in the Netherlands, installations will be expected in Canada. Engineers will need to have a better understanding of biological processes through working with multidisciplinary teams.

For the future, anaerobic treatment and other biological treatment processes such as constructed wetlands should play an important role in the sustainable development of water resources. Fresh water is depleting rapidly in countries such as India, China and even the U.S. and Canada. Rivers are drying up and water table levels are decreasing. Therefore, we must protect the quality of the water that we have by treating the water in the most appropriate manner before discharge. These processes will need to be efficient and cost-effective and must not generate further waste problems. In summary, the increasing population is leading to fewer waste management options, environmental destruction, and increased disasters due to global warming. Environmental management and technological development of biological processes should clearly be a priority.

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