Biological Drinking Water Treatment: Benefiting from Bacteria

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While the use of microbial biomass for the degradation of contaminants, nutrients, and organics has been commonly used in the *wastewater* field since the early 1900s, the biological treatment of drinking water has been limited, particularly in the United States. However, recent developments in the drinking water treatment field are beginning to broaden the applicability, feasibility, and favorability of biological drinking water treatment technologies. These developments include 1) the increasing costs and complexities of handling water treatment residuals (e.g., membrane concentrate), 2) the emergence of new contaminants that are particularly amenable to biological degradation (e.g., perchlorate), 3) the push for green technologies (i.e., processes that efficiently destroy contaminants instead of concentrating them), 4) regulations limiting the formation of disinfection by-products (DBPs), and 5) the emergence of membrane-based treatment systems, which are highly susceptible to biological fouling.

Process Fundamentals

Bacteria gain energy and reproduce by mediating the transfer electrons from reduced compounds (i.e., compounds that readily donate electrons) to oxidized compounds (i.e., compounds that readily accept electrons). Once donated by the reduced compound, electrons travel back and forth across a cell's mitochondrial membrane in a series of internal oxidation-reduction reactions; the electrons are ultimately donated to the terminal electron accepting compound. This series of reactions, which is cumulatively known as the electron transport chain, creates a chemical and electrical gradient across the cell membrane, which the bacteria ultimately use to generate adenosine triphosphate (ATP), also known as energy (Madigan, et al., 1997). As compounds gain or lose electrons, they are converted to different, often innocuous forms that are thermodynamically more stable than the original compounds. The example below illustrates the microbially-mediated oxidation-reduction reaction between acetate (electron donor) and two environmental electron acceptors (dissolved oxygen and nitrate). Notice that nitrate, a common drinking water contaminant, is converted to innocuous nitrogen gas. The Gibb's free energy values for the overall reaction are listed to the right of the equations (Rikken et al., 1996). The more negative the Gibb's free energy value, the more thermodynamically unstable a reaction, the greater the energy yield for bacteria mediating the reaction. Electron transfer is seen in the overall reaction only by evaluating the oxidation states of individual atoms.

- $CH_3COO^- + 2O_2 \rightarrow 2HCO_3^- + H^+$; $\Delta G^{o\prime} = -844$ KJ/mol acetate
- $CH_3COO^- + {}^{3}/_{5}NO_3^- + {}^{13}/_{5}H+ \rightarrow 2HCO_3^- + {}^{4}/_{5}H_20 + {}^{4}/_{5} N_2$; $\Delta G^{o\prime} = -792$ KJ/mol acetate

Biological drinking water treatment processes are based on the growth of bacterial communities that are capable of mediating oxidation-reduction reactions involving at least one target contaminant. Heterotrophic biological processes utilize an organic electron donor (e.g., acetic acid) while autotrophic biological processes utilize an inorganic electron donor (e.g., hydrogen).

Contaminant Applications

The applicability of biological drinking water treatment includes surface and ground water and covers a wide range of organic and inorganic contaminants, as illustrated in Table 1.

Table 1 Contaminants amenable to biological treatment[1]

Contaminant Category	Removal Application	Description
Natural Organic Matter (NOM)	• Regrowth substrate • DBP precursors • Color • Membrane foulants	• The biological oxidation of carbonaceous organic matter to CO_2 can minimize distribution system regrowth potential, decrease the production of DBPs, remove color, and improve transmembrane fluxes without chemical addition. Ozone is often used ahead of a biological process to enhance NOM removal.
Trace Organics	• 2-methyl-isoborneol (MIB) • Geosmin • Algal toxins • Endocrine disruptors & pharmaceutically active compunds • Pesticides	• Biological oxidation to CO_2; often degraded as a secondary electron donor (i.e., does not yield the requisite energy to support cell maintenance and growth), thus requires the presence of a primary substrate such as NOM
	• Methyl tertiary-butyl ether (MTBE)	• Biological oxidation to CO_2.
Halogenated Organics	• Perchloroethylene (PCE) • Trichloroethylene (TCE) • Dibromochloropropane (DBCP) • Chloroform	• Biological reductive dechlorination produces innocuous ethane or CO_2.

Inorganics	• Perchlorate • Chlorate • Nitrate • Nitrite • Bromate	• Biological reduction produces innocuous end-products (Cl^-, N_2, Br^-, H_2O), thus eliminating the generation of a contaminated concentrate stream.
	• Selenate • Chromate	• Biological reduction produces insoluble species that are readily filtered or settled out of water, thus eliminating the need for chemical reduction methods.
	• Ammonia	• Biological oxidation of ammonia to nitrate provides an alternative to chemically-intensive breakpoint chlorination.
	• Iron • Manganese	• Biological oxidation of soluble species (Fe^{2+}, Mn^{2+}) to insoluble species (Fe^{3+}, Mn^{4+}) eliminates the need for chemical oxidation prior to filtration or settling.

[1] Table was generated from various references plus personal experience. References include: Bouwer and Crowe,1988; Brown, 2006; Brown et al., 2005, Dahab and Woodbury, 1998; Herman and Frankenberger, Jr.,1999; Kirisits et al., 2002; Lauderdale et al., 2007)

Technology Configurations

There are numerous forms and configurations of biological drinking water treatment processes. Most are operated as fixed biofilm systems, meaning that the process includes a biogrowth support medium on which bacterial communities attach and grow (e.g., granular media). A smaller number of technologies operate in a suspended growth mode, where free-floating bacteria are hydraulically maintained within a reactor. Biological reactors can be inoculated with an enriched bacterial community or can simply be acclimated by the organisms indigenous to the water source being treated. Examples of different biologically drinking water treatment configurations are listed below.

Fixed-Bed

Fixed-bed (FXB) biological processes utilize a stationary bed of media such as sand, plastic, or granular activated carbon on which biofilms develop. The granular media bed can be contained in pressure vessels or open basins. In pressure vessel systems, water is pumped up-flow or down-flow across the biological bed, while open basin systems require up-flow pumping or down-flow by gravity. As water is treated, the growth of biofilms restricts flow and generates increasing head loss across the bed. If the head loss increases unchecked, it will eventually exceed the available driving pressure or cause short-circuiting through the bed. To avoid these complications, FXB systems are routinely taken off line and backwashed to remove excess biomass from the system (Brown et al., 2005; Kim and Logan, 2000). Fixed-bed biological treatment is often coupled with pre-ozonation for improved organic removal, which helps utilities reduce disinfection by-product formation and regrowth potential in distribution systems.

Fluidized-Bed

Fluidized bed reactors (FBRs) also use granular media for biogrowth support. Contaminated water is pumped up-flow through the reactor at a high rate to fluidize the granular media bed and reduce resistance to flow. Typically, the fluidization rate is controlled to maintain a 25 to 30 percent bed expansion over the resting bed height. Feed flow is supplemented with recycle flow to provide the appropriate up-flow velocity for fluidization (Guarini and Webster, 2004; Green and Pitre, 1999). Excess biomass is removed from FBR systems by 1) shear forces generated by the high feed pumping rates, and/or 2) in-line mechanical shearing devices. Thus, while FBRs require higher feed flow capacity, they do not require an off-line backwashing step.

Membrane Bioreactors

Membranes are also being coupled with biological systems for enhanced drinking water treatment. In one approach, ultrafiltration membranes are submerged in a reactor basin, which contains suspended biomass. The reactor basin provides the detention time required to achieve the target biological treatment objective. Treated water is drawn through the membranes by vacuum and is pumped out to down-stream processing by permeate pumps. Airflow is introduced at the bottom of the reactor basin creates turbulence that scrubs and cleans the outside of the membranes. This reduces the solids accumulation on the membrane surface, thereby allowing the membrane to operate for extended periods at high permeate fluxes. The air also has the beneficial side effect of oxidizing iron and other organic compounds that may be present. It also provides mixing within the process tank to maintain solids in suspension. The membranes may be periodically backwashed which consists of passing permeate through the membranes in the reverse direction to dislodge solids from the membrane surface.

A different approach to the "conventional" MBR concept uses hollow fiber membranes to deliver hydrogen gas (electron donor) to the biofilms that grows on the outside of the hollow-fibers. The hollow fiber membranes are submerged in a reactor vessel through which contaminated water passes. Contaminants diffuse from the bulk water into the biofilms and are degraded (Nerenburg, et al., 2002). Occasionally, the membranes are chemically cleaned to remove excess biomass.

Yet another MBR approach involves the use of two treatment chambers separated by an ion-exchange membrane. One chamber contains suspended biomass plus nutrients, the other chamber contains raw water. As raw water enters the system and moves through one chamber, ionic contaminants diffuse across the membrane into the biological treatment chamber where they are degraded. The objective of this approach is to separate the active biomass from the raw and treated water (Liu and Batista, 2000).

Bank Filtration

Drilled near rivers and lakes, bank filtration (BF) wells draw surface water through soil and aquifer material, which serves as a passive treatment reactor. As the surface water moves through the aquifer, it is subjected to filtration, dilution, sorption, and biodegradation processes (Gollnitz et al., 2003; Weiss et al., 2003a; Weiss et al. 2003b Ray et al., 2002). BF has been used for over 100 years in Europe and is now gaining interest and application globally as an effective process for reducing organic and particulate loads to drinking water treatment systems.

Summary

The use of bacteria to help produce potable water goes somewhat against conventional wisdom, given that one key objective of drinking water treatment is the inactivation or removal of microorganisms from raw water. However, biological drinking water treatment processes utilize indigenous, non-pathogenic bacteria and are always followed by downstream processes such as final disinfection. Thus, well-designed biological treatment systems pose no significant inherent threat to the health or safety of distributed water. Instead, they often offer an alternative to conventional processes that has several potential advantages, including the following:

- Operating costs can be low
- Water recoveries are high
- Contaminants are destroyed instead of sequestered and concentrated

- Multiple contaminants can be removed simultaneously
- Sludge production is minimal
- Hazardous waste streams are not generated
- Minimal to no chemical addition is required
- Processes can be robust over a wide range of operating conditions and water qualities

These characteristics make biological treatment highly efficient and environmentally sustainable. As green treatment philosophies gain traction and as regulatory and residuals handling constraints continue to tighten, it is likely that the application of biological drinking water treatment technologies and processes will continue to expand around the globe.

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