9

Bioremediation

9.1 What Is Bioremediation?

- **Biodegradation** – the use of living organisms such as bacteria, fungi, and plants to degrade chemical compounds

- **Bioremediation** – process of cleaning up environmental sites contaminated with chemical pollutants by using living organisms to degrade hazardous materials into less toxic substances

9.1 What Is Bioremediation?

- Why use bioremediation?
  - Most approaches convert harmful pollutants into relatively harmless materials such as carbon dioxide, chloride, water, and simple organic molecules
  - Processes are generally cleaner
  - Can be conducted at the site of pollution

9.2 Bioremediation Basics

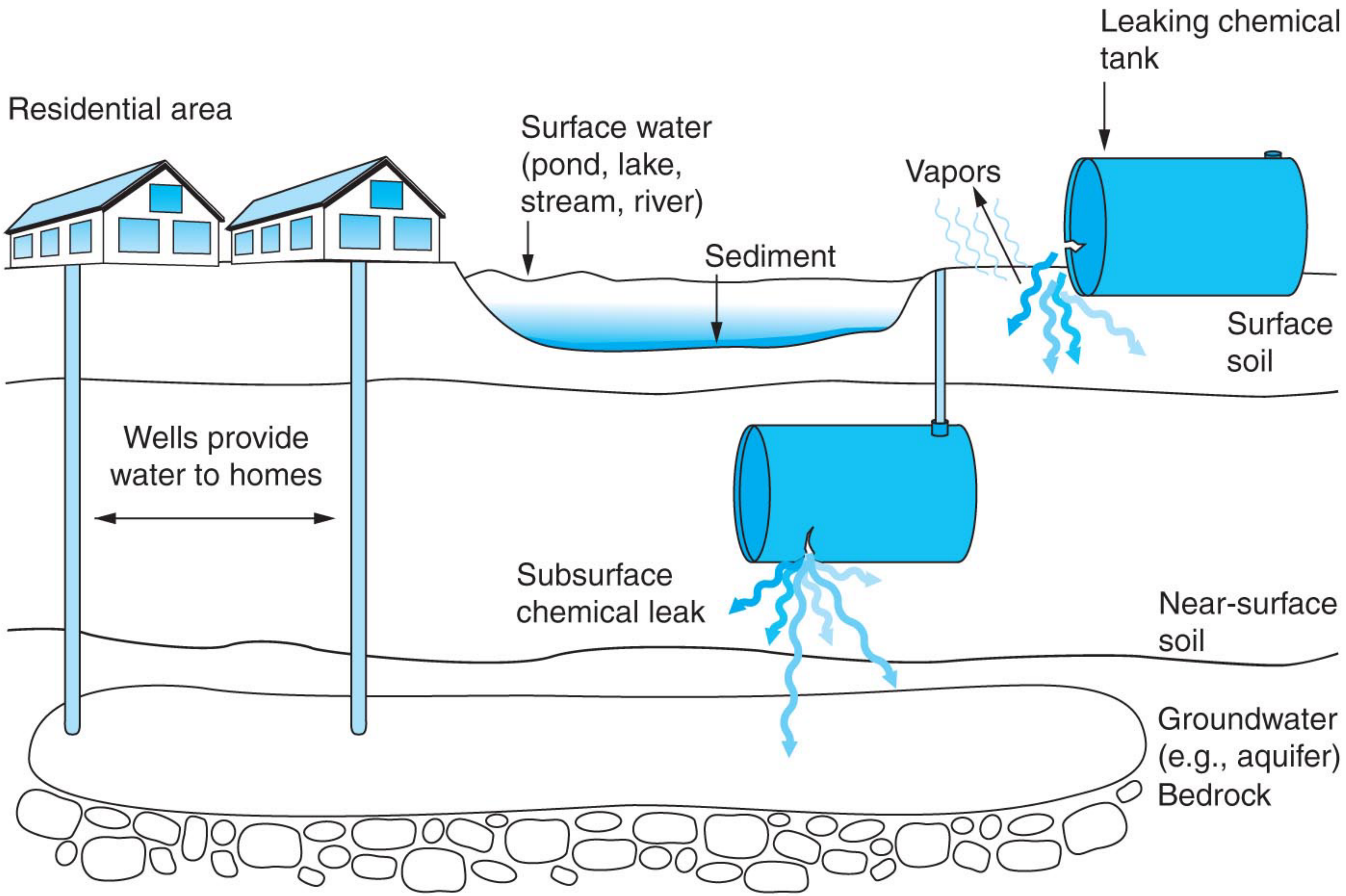
- What needs to be cleaned up?

  - Almost everything
    - Oil, water, air, and sediment are most common

  - Each presents its own complexities for cleanup because the type of bioremediation approach used depends on site conditions

9.2 Bioremediation Basics

- Pollutants enter the environment in many different ways
  - Tanker spill, truck accident, ruptured chemical tank at industrial site, release of pollutants into air
- Location of accident, the amount of chemicals released, and the duration of the spill impacts the parts of the environment affected



Leaking chemical tank
Residential area
Surface water (pond, lake, stream, river)
Vapors
Sediment
Surface soil
Wells provide water to homes
Subsurface chemical leak
Near-surface soil
Groundwater (e.g., aquifer)
Bedrock

9.2 Bioremediation Basics

- Chemicals in the Environment
  - Carcinogens
  - Compounds that cause cancer
  - Mutagens
  - Cause skin rashes, birth defects
  - Poison plant and animal life

TABLE 9.1 TWENTY OF THE MOST COMMON CHEMICAL POLLUTANTS IN THE ENVIRONMENT

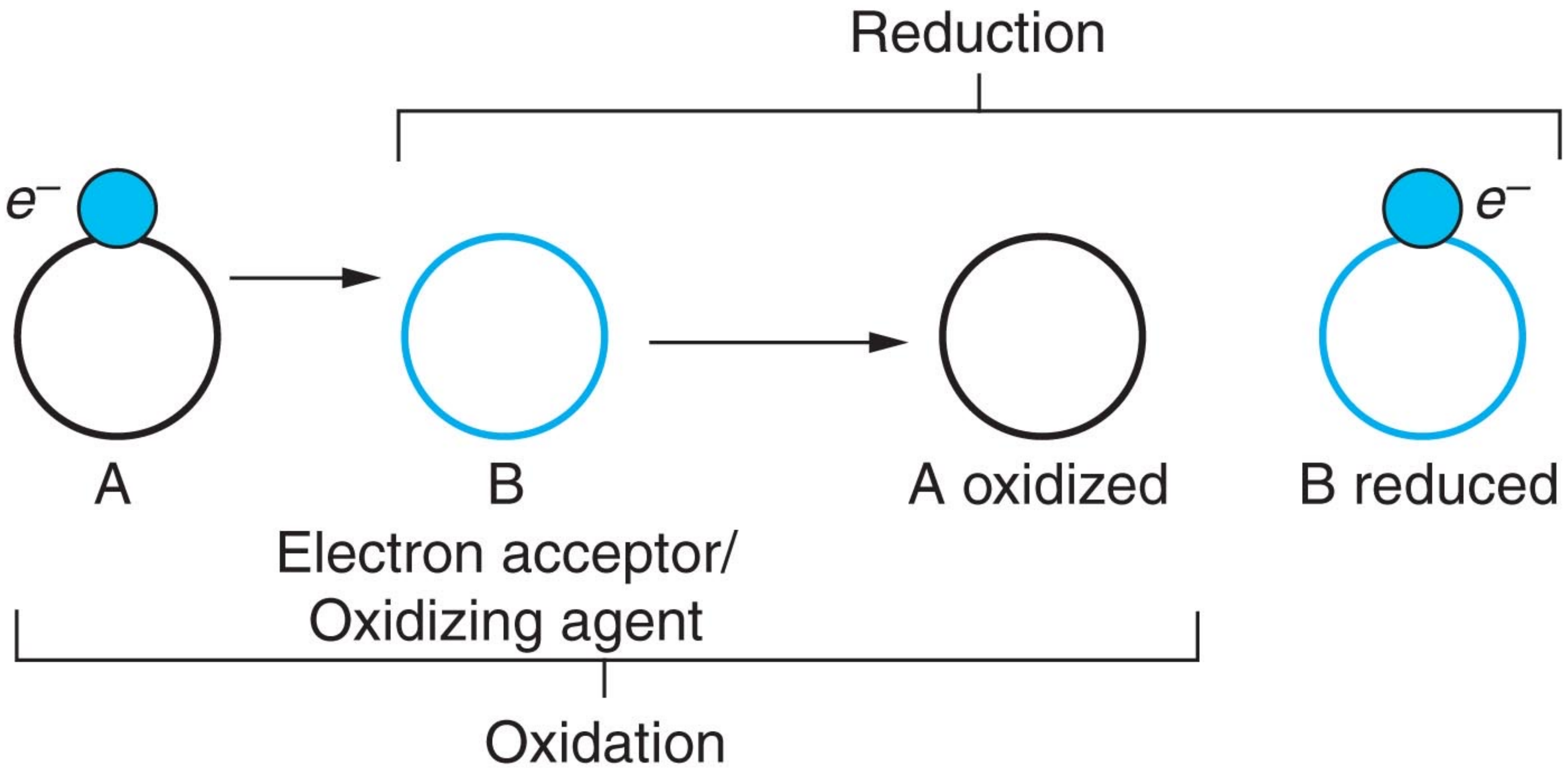
Chemical Pollutant	Source
Benzene	Petroleum products used to make plastics, nylon, resins, rubber, detergents, and many other materials
Chromium	Electroplating, leather tanning, corrosion protection
Creosote	Wood preservative to prevent rotting
Cyanide	Mining processes and manufacturing of plastics and metals
Dioxin	Pulp and paper bleaching, waste incineration, and chemical manufacturing processes
Methyl t-butyl ether (MTBE)	Fuel additive, automobile exhaust, boat engines, leaking gasoline tanks
Naphthalene	Product of crude oil and petroleum
Nitriles	Rubber compounds, plastics, and oils
Perchloroethylene/ tetrachloroethylene (PCE), trichloroethene (TCE), and trichloroethane (TCA)	Dry cleaning chemicals and degreasing agents TCE is present in some 34% of U.S. water supplies and 60% of Superfund sites
Pesticides (atrazine, carbamates, chlordane, DDT) and herbicides	Chemicals used to kill insects (pesticides) and weeds (herbicides)
Phenol and related compounds (chlorophenols)	Wood preservatives, paints, glues, textiles
Polychlorinated biphenyls (PCBs)	Electrical transistors, cooling and insulating systems
Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated hydrocarbons	Incineration of wastes, automobile exhaust, oil refineries, and leaking oil from cars
Polyvinylchloride	Plastic manufacturing
Radioactive compounds	Research and medical institutions and nuclear power plants
Surfactants (detergents)	Manufacturing of paints, textiles, concrete, paper
Synthetic estrogens (ethinyl estradiol)	Female hormone (estrogen)-related compounds created by a variety of industrial manufacturing processes
Toluene	Petroleum component present in adhesive, inks, paints, cleaners, and glues
Trace metals (arsenic, cadmium, chromium, copper, lead, mercury, silver)	Car batteries and metal manufacturing processes
Trinitrotoluene (TNT)	Explosive used in building and construction industries

9.2 Bioremediation Basics

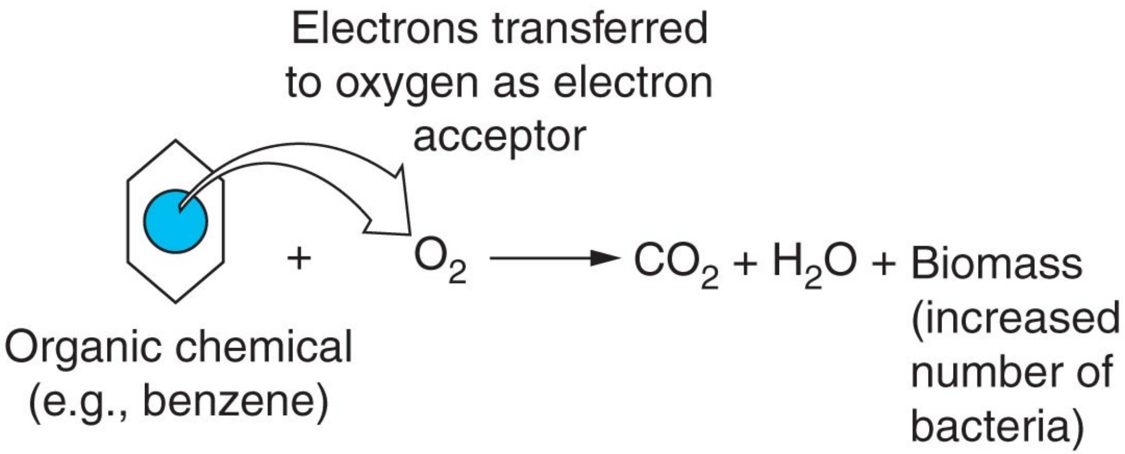
- Fundamentals of Cleanup Reactions

  - Microbes convert chemicals into harmless substances by either:
    - **Aerobic metabolism** (require oxygen) or **anaerobic metabolism** (do not require oxygen)

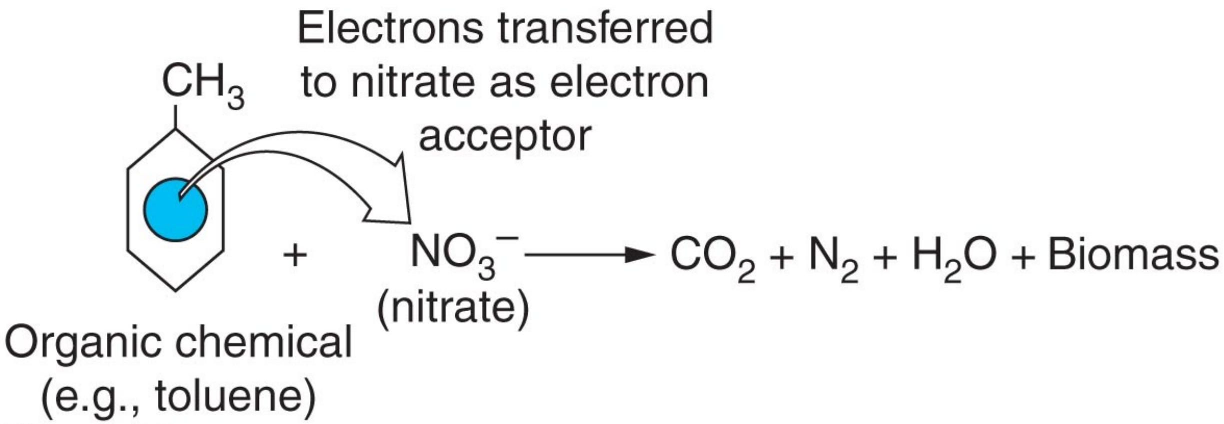
  - Both processes involve **oxidation** and **reduction reactions**
    - Oxidation – removal of one or more electrons from an atom or molecule
    - Reduction – addition of one or more electrons to an atom or molecule


Reduction
e⁻
e⁻
A
B
A oxidized
B reduced
Electron acceptor/
Oxidizing agent
Oxidation

Aerobic biodegradation

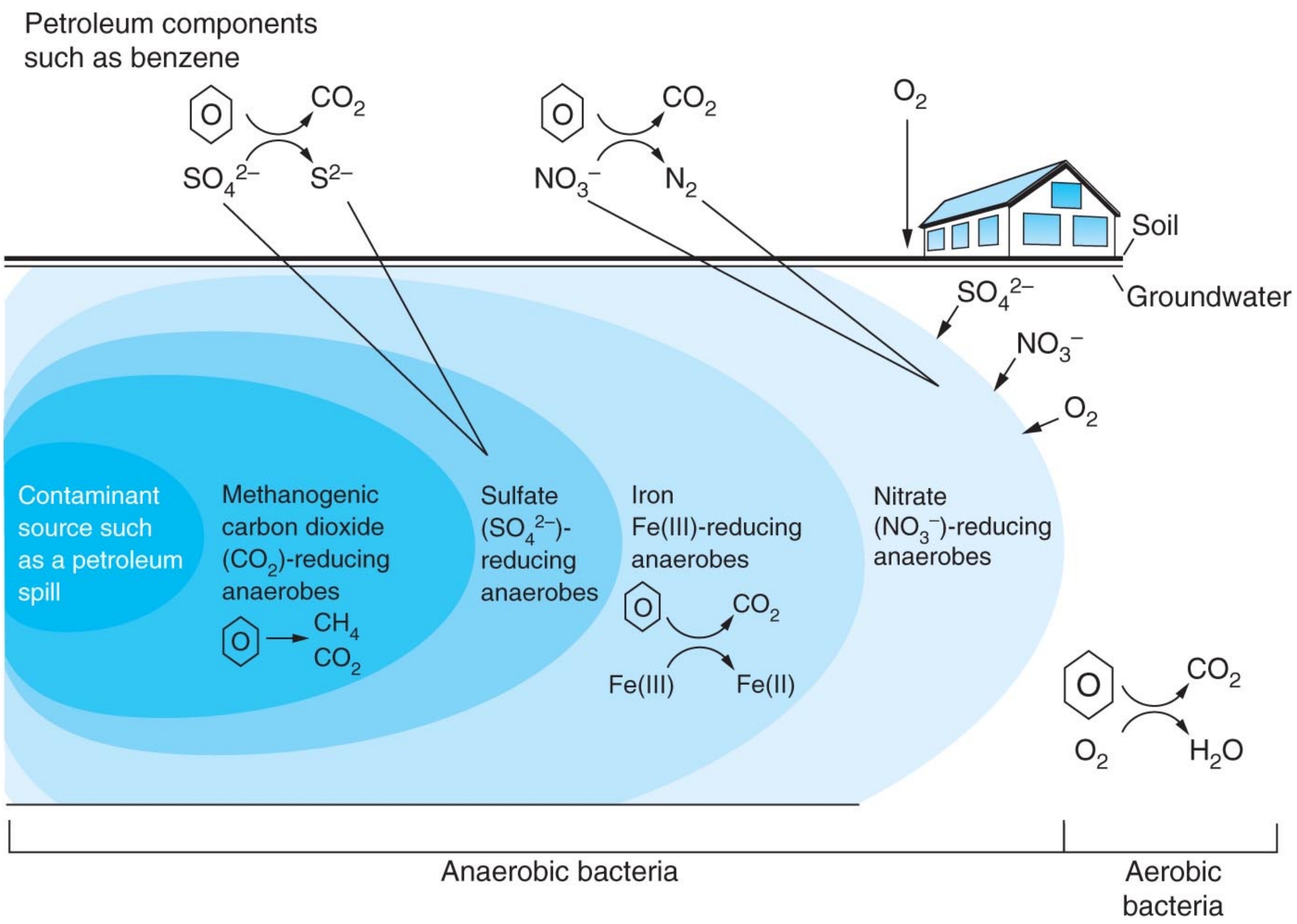


Anaerobic biodegradation



9.2 Bioremediation Basics

- **The Players: Metabolizing Microbes**
  - Scientists use microbes, especially bacteria, as tools to clean up the environment
  - May involve combined action of both aerobic and anaerobic bacteria to fully decontaminate


Petroleum components such as benzene
CO_2
SO_4^{2-}
S^{2-}
CO_2
NO_3^-
N_2
O_2
Soil
Groundwater
SO_4^{2-}
NO_3^-
O_2
Contaminant source such as a petroleum spill
Methanogenic carbon dioxide (CO_2)-reducing anaerobes
CH_4
CO_2
Sulfate (SO_4^{2-})-reducing anaerobes
Iron Fe(III)-reducing anaerobes
CO_2
Fe(III)
Fe(II)
Nitrate (NO_3^-)-reducing anaerobes
CO_2
O_2
H_2O
Anaerobic bacteria
Aerobic bacteria

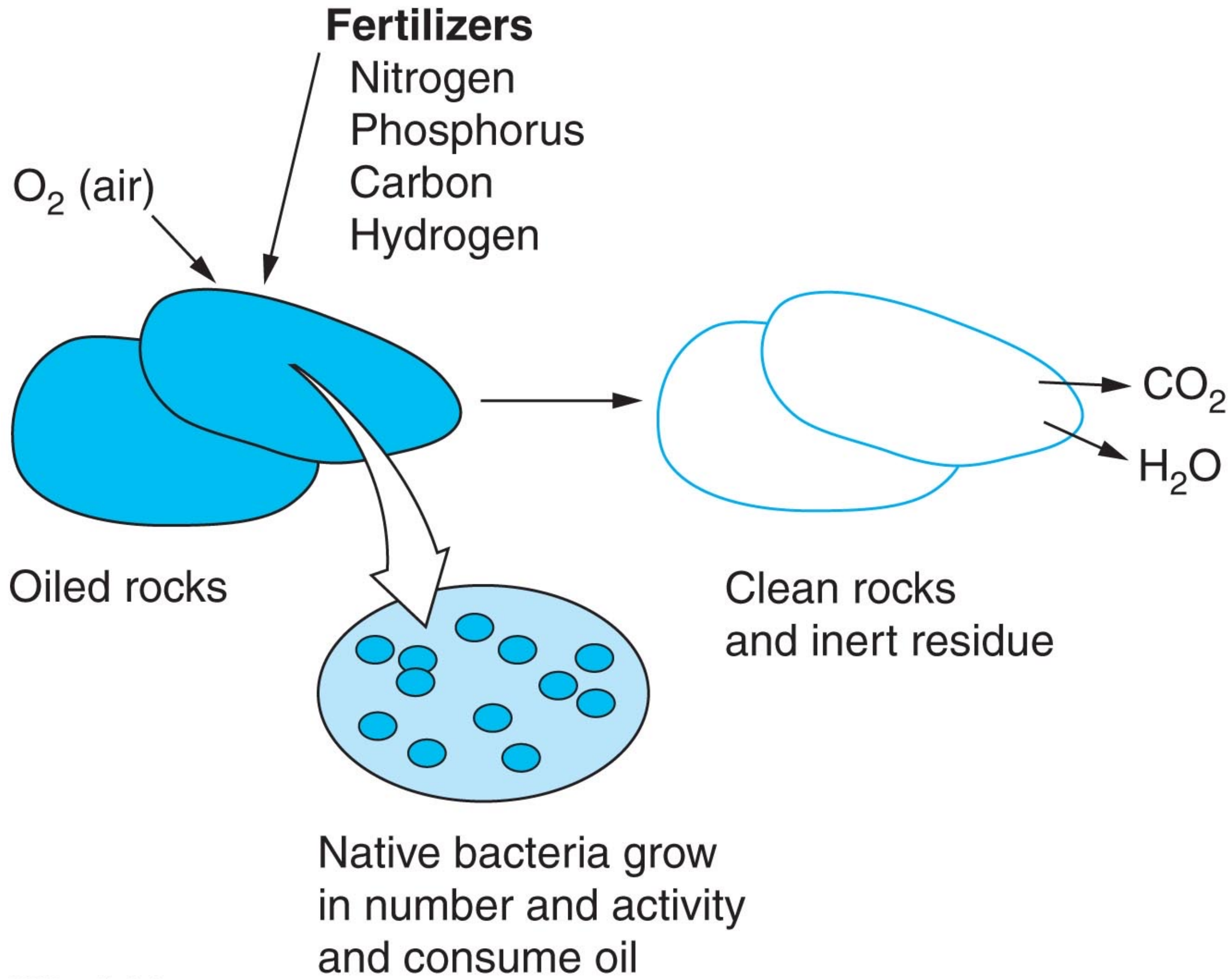
9.2 Bioremediation Basics

- **Indigenous microbes** – those found naturally at a polluted site are often isolated, grown and studied in a lab and then released back into treatment environments in large numbers
  - For example, the bacteria *Pseudomonas* and *E.coli*

- The quest for new metabolizing microbes is an active area of bioremediation research
  - In 2010, US Geological Survey identified a bacterium from California's Mono Lake which may metabolize arsenic and incorporates it into biomolecules such as DNA

9.2 Bioremediation Basics

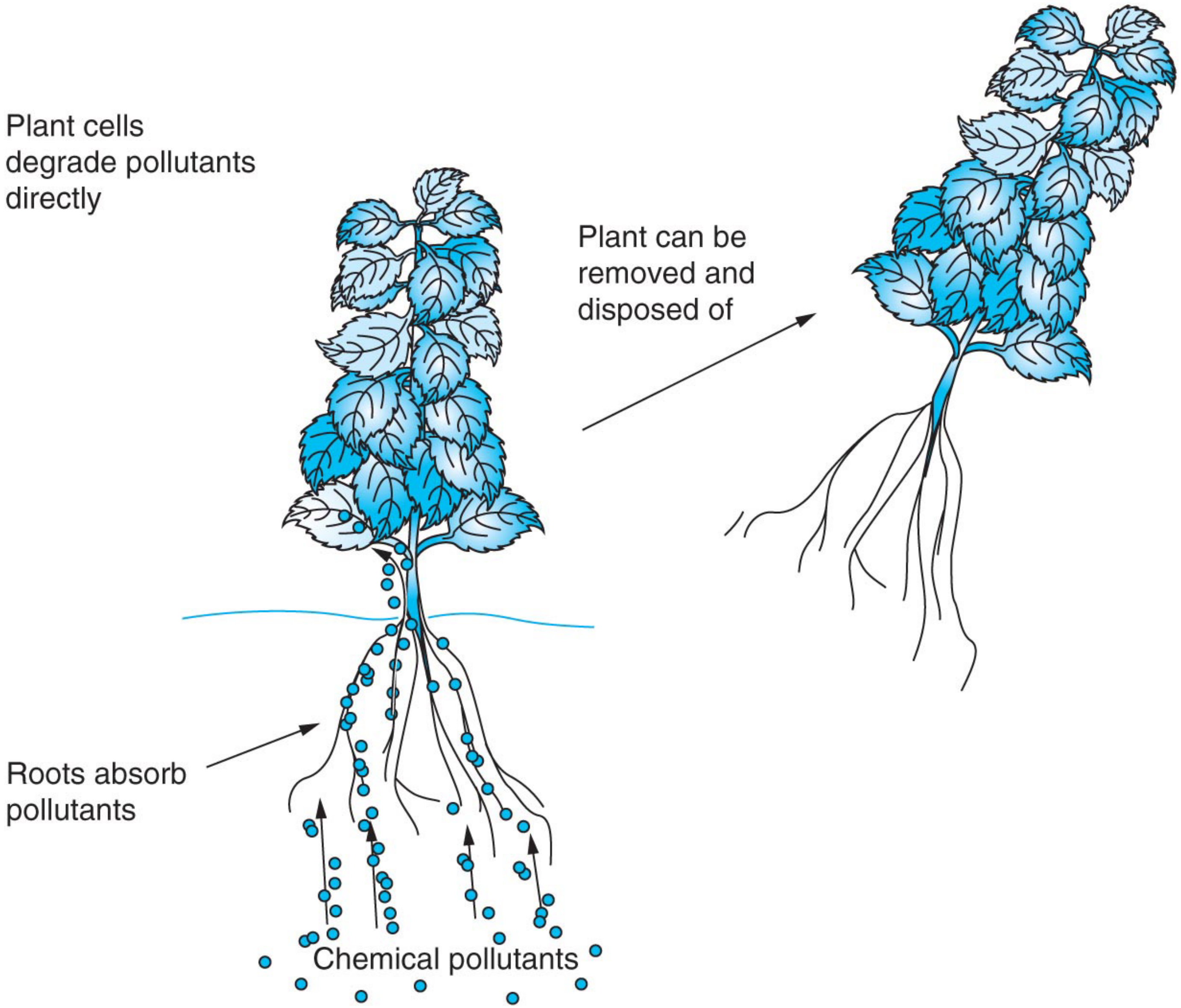
- Bioremediation Genomics Programs
  - Scientists are studying the genomes of organisms that are currently used or may be used for bioremediation (remember the Microbial Genome Program)
  - Possible to identify novel genes and metabolic pathways used to detoxify chemicals
  - Could help develop improved strains through genetic engineering



Fertilizers
Nitrogen
Phosphorus
Carbon
Hydrogen
O_2 (air)
CO_2
H_2O
Oiled rocks
Clean rocks
and inert residue
Native bacteria grow
in number and activity
and consume oil

9.2 Bioremediation Basics

- **Phytoremediation**
  - Utilizing plants to clean up chemicals in the soil, water and air
  - An estimated 350 plant species naturally take up toxic materials. The following have been successfully used:
    - Polar and juniper trees, certain grasses and alfalfa
    - Sunflower plants removed radioactive cesium and strontium at the Chernobyl nuclear power plant in Ukraine
    - Water hyacinths removed arsenic from water supplies in Bangladesh and India


Plant cells
degrade pollutants
directly
Plant can be
removed and
disposed of
Roots absorb
pollutants
Chemical pollutants

9.2 Bioremediation Basics

- Phytoremediation
  - Chemical pollutants are taken in through the roots of the plant as they absorb contaminated water from the ground
  - After toxic chemicals enter the plant, the plant cells may use enzymes to degrade the chemicals
  - In other cases, chemicals can be concentrated in the plant cells
    - The entire plant serves as 'sponge'
    - Contaminated plants treated as wasted
  - High concentrations of chemicals kill most plants, so works best where amount of contamination is low

9.2 Bioremediation Basics

- Phytoremediation can be an effective, low-cost, low-maintenance, and eye-appealing strategy
- Two drawbacks are that only surface layers (to around 50 cm deep) can be treated and cleanup typically takes several years

9.3 Cleanup Sites and Strategies

- Soil Cleanup
  - *Ex situ* bioremediation – removing chemical materials from contaminated area to another location for treatment
  - *In situ* bioremediation – leaves contaminated materials in place
    - Preferred because less expensive and larger contaminated areas can be treated at one time
    - Stimulates microorganisms in the contaminated soil or water

9.3 Cleanup Sites and Strategies

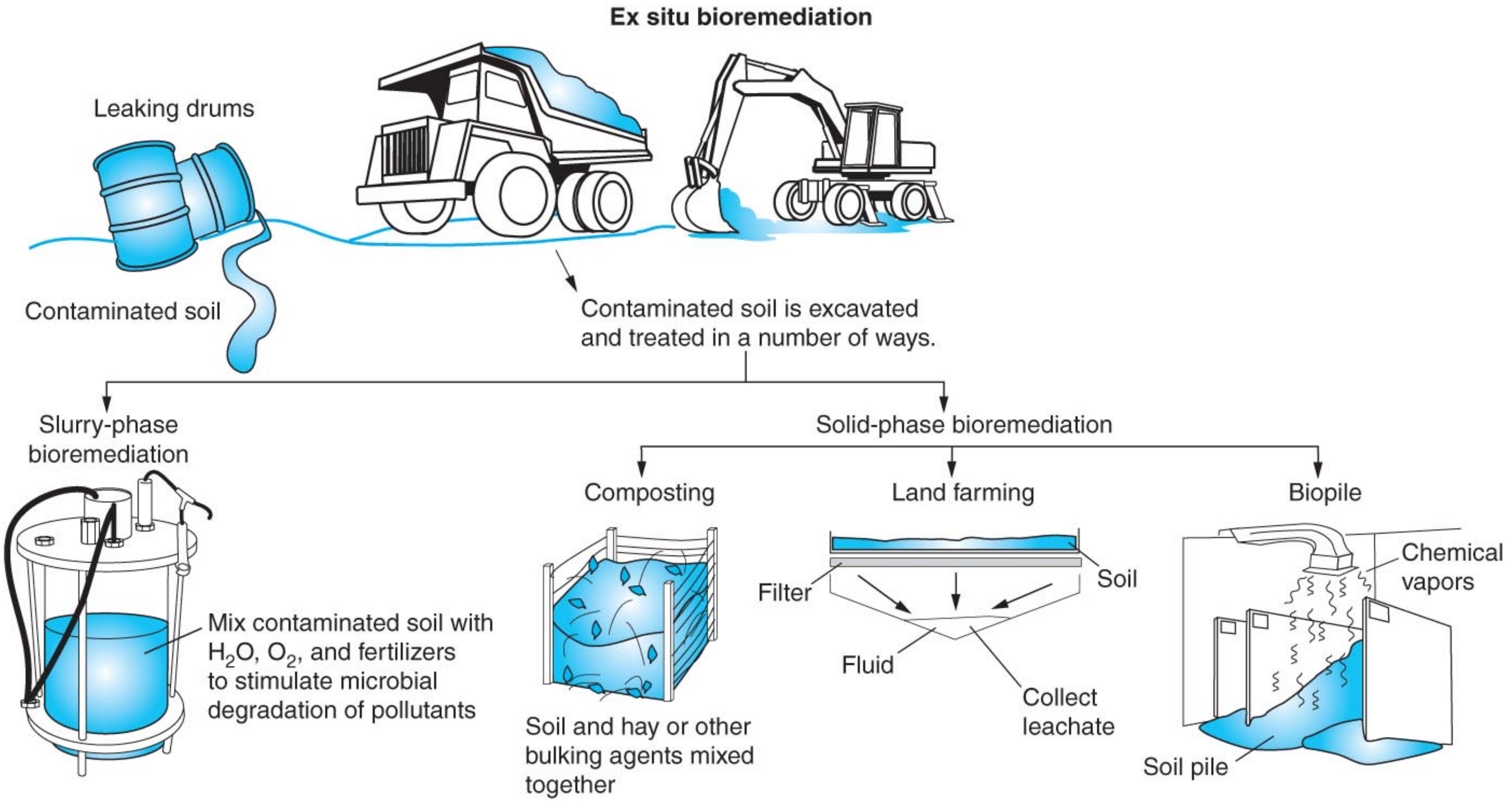
- *In situ* bioremediation

  - Approaches that require aerobic degradation methods often involve **bioventing**
    - Pumping air or H_2O_2 into the contaminated soil
    - May be uses to add fertilizers to stimulate growth and degrading activities of indigenous bacteria

  - Not always the best solution
    - Most effective in sandy soils which allow microorganisms and fertilizing materials to spread rapidly
    - Solid clay and dense rocky soils not typically good
    - Contamination with chemicals that persist for long periods can take years to clean up

9.3 Cleanup Sites and Strategies

- *Ex situ* bioremediation – can be faster and more effective
  - Slurry phase bioremediation
    - Moving to another site, then mixing the soil with water, fertilizers, etc. in large bioreactors
    - Good for smaller amounts of well known contaminants
  - Solid phase bioremediation
    - Composting – degrades food and garden waste
    - Land farming
    - Biopiles


Ex situ bioremediation
Leaking drums
Contaminated soil
Contaminated soil is excavated and treated in a number of ways.
Slurry-phase bioremediation
Mix contaminated soil with H_2O, O_2, and fertilizers to stimulate microbial degradation of pollutants
Solid-phase bioremediation
Composting
Soil and hay or other bulking agents mixed together
Land farming
Soil
Filter
Fluid
Collect leachate
Biopile
Chemical vapors
Soil pile

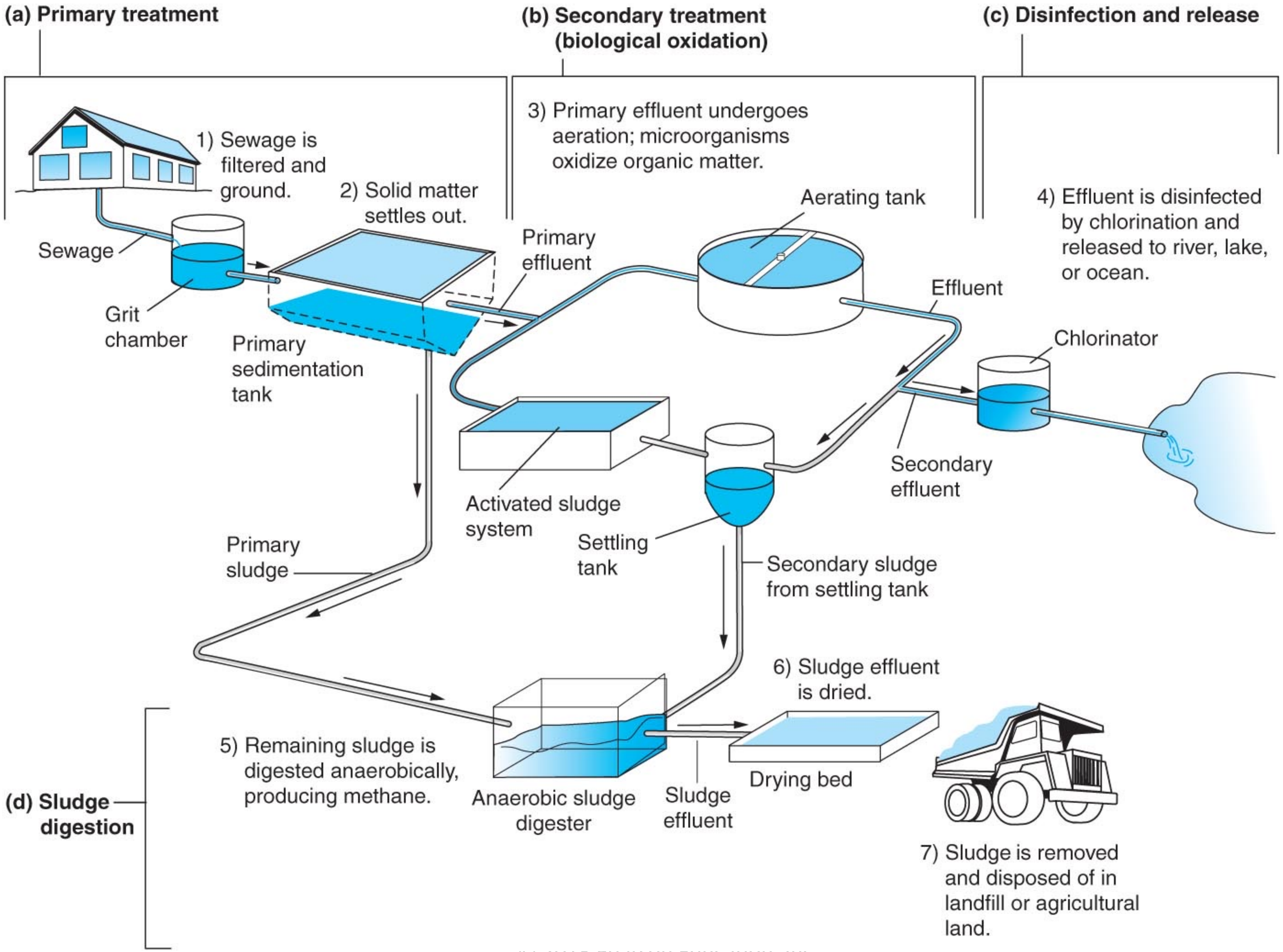
9.3 Cleanup Sites and Strategies

- Biopiles

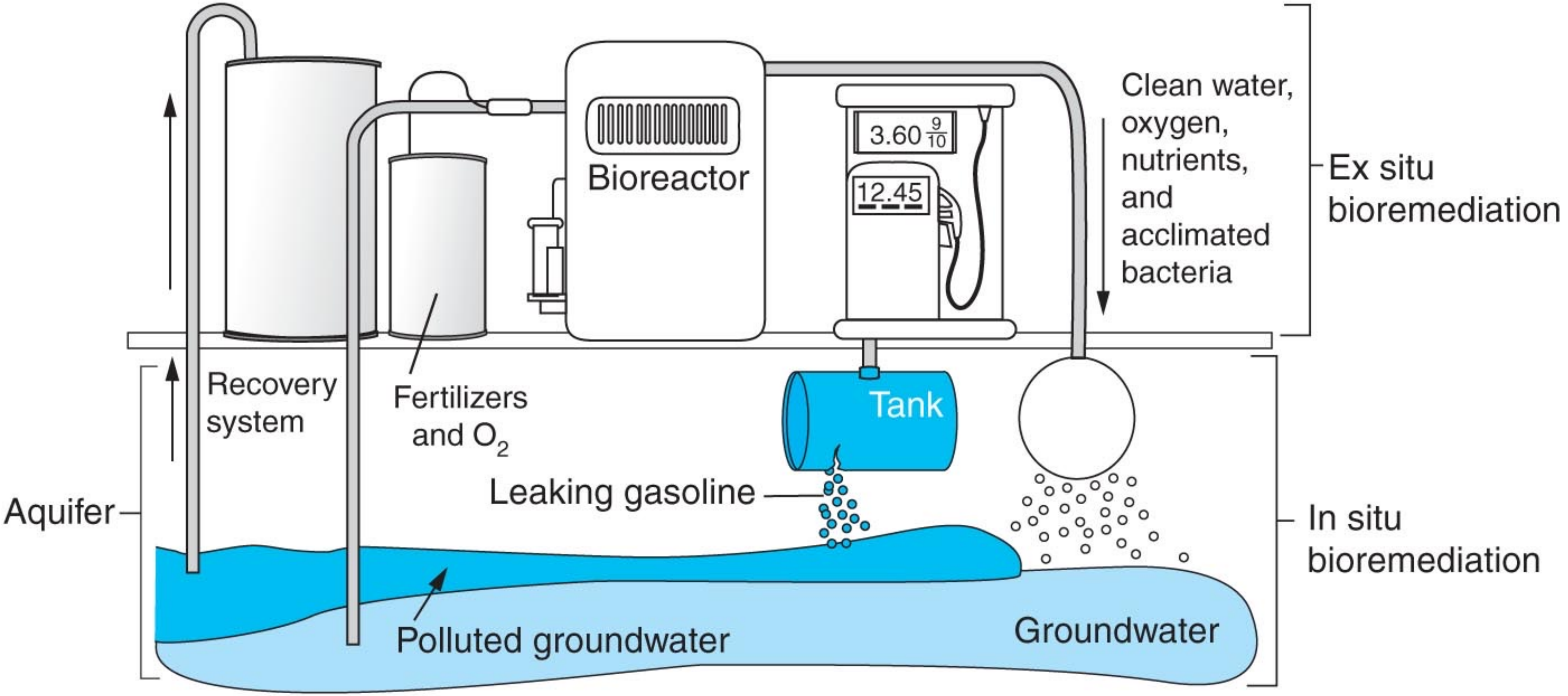
- Septic Tank Additives

9.3 Cleanup Sites and Strategies

- Bioremediation of Water
  - Wastewater treatment
  - Groundwater cleanup

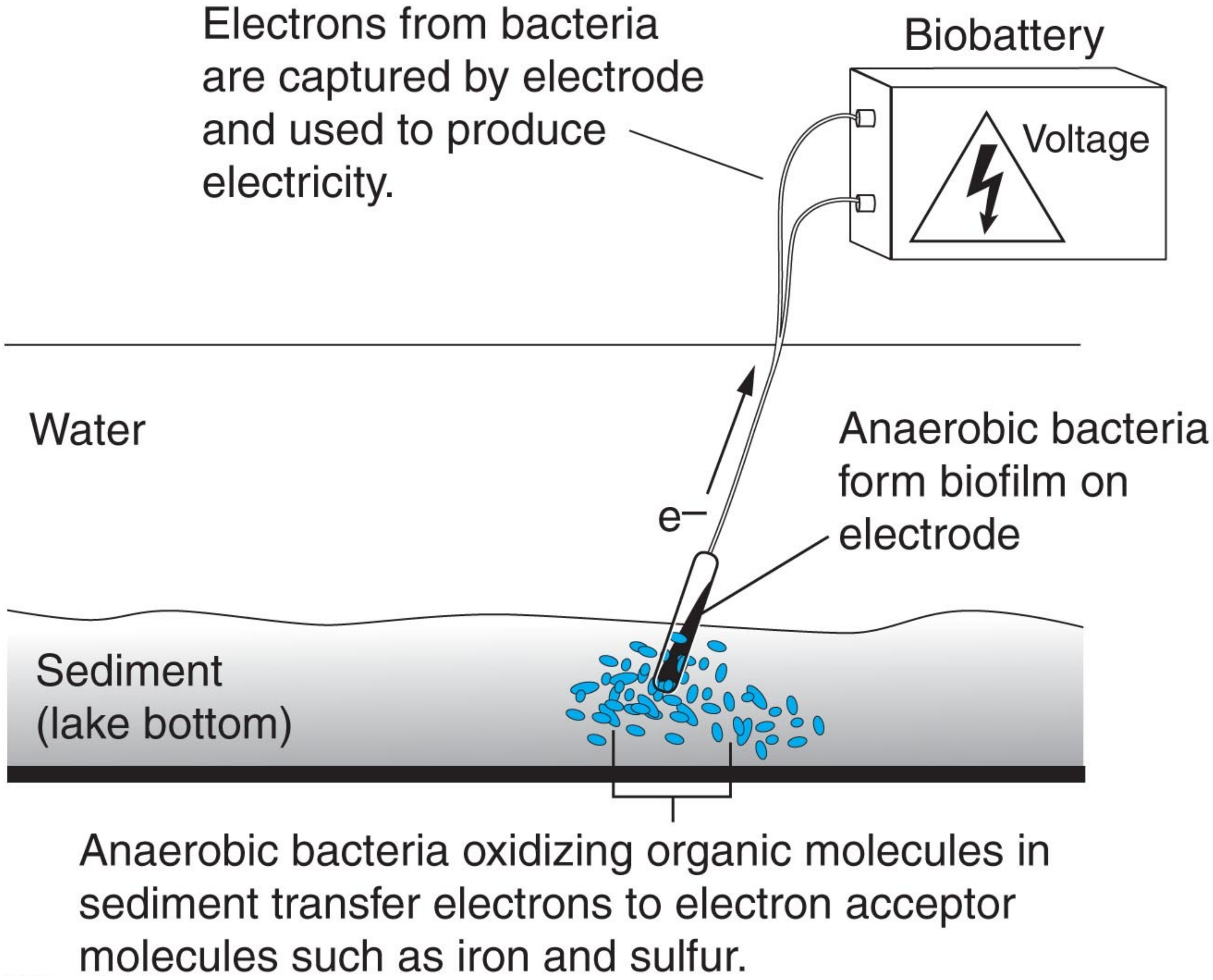

(a) Primary treatment
(b) Secondary treatment (biological oxidation)
(c) Disinfection and release
1) Sewage is filtered and ground.
2) Solid matter settles out.
3) Primary effluent undergoes aeration; microorganisms oxidize organic matter.
Aerating tank
4) Effluent is disinfected by chlorination and released to river, lake, or ocean.
Sewage
Grit chamber
Primary sedimentation tank
Primary effluent
Effluent
Chlorinator
Activated sludge system
Settling tank
Secondary effluent
Primary sludge
Secondary sludge from settling tank
6) Sludge effluent is dried.
5) Remaining sludge is digested anaerobically, producing methane.
(d) Sludge digestion
Anaerobic sludge digester
Sludge effluent
Drying bed
7) Sludge is removed and disposed of in landfill or agricultural land.

9.3 Cleanup Sites and Strategies



9.3 Cleanup Sites and Strategies

- Turning Wastes into Energy
  - Methane gas used to produce electricity
  - Soil nutrients can be sold commercially as fertilizers
  - Anaerobes in sediment that use organic molecules to generate energy
    - **Electrigens** – electricity-generating microbes


Electrons from bacteria are captured by electrode and used to produce electricity.
Biobattery
Voltage
Water
e−
Anaerobic bacteria form biofilm on electrode
Sediment (lake bottom)
Anaerobic bacteria oxidizing organic molecules in sediment transfer electrons to electron acceptor molecules such as iron and sulfur.

9.4 Applying Genetically Engineered Strains to Clean Up the Environment

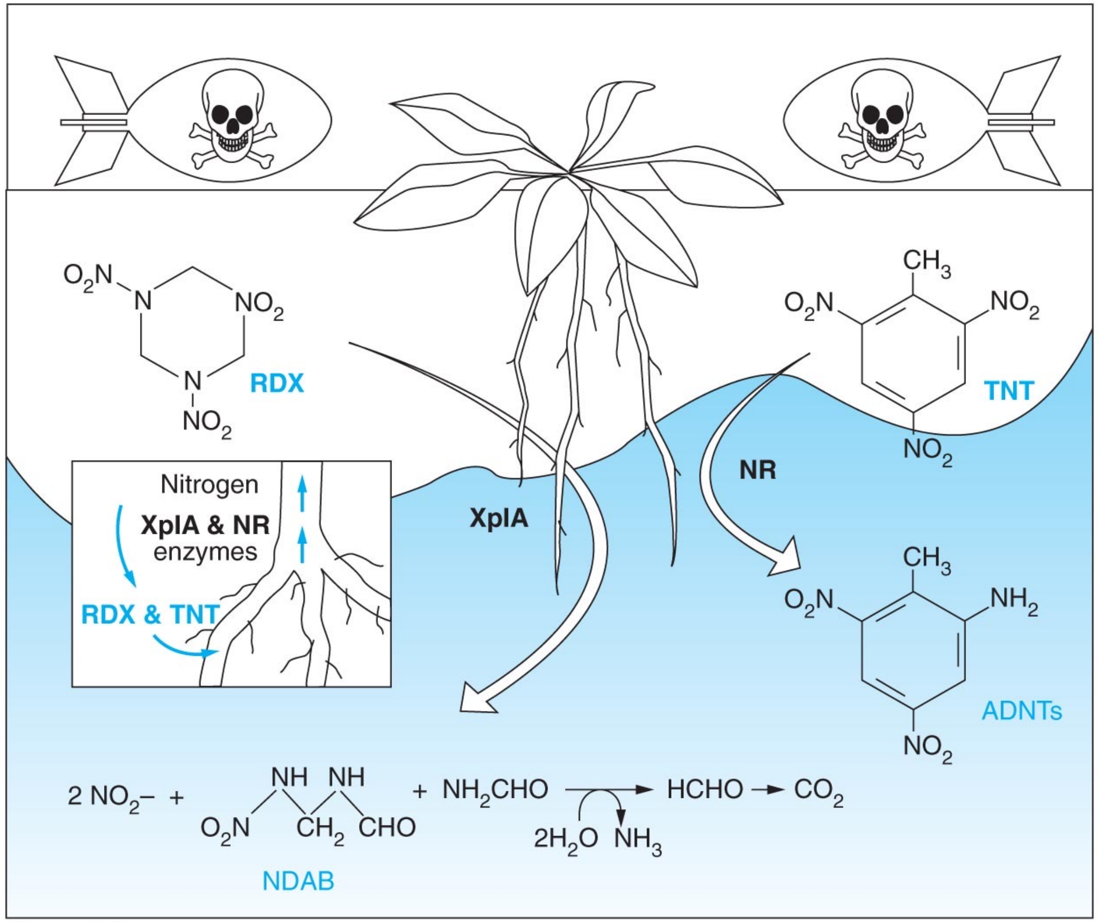
- Many indigenous bacteria cannot degrade certain types of chemicals, especially very toxic chemicals.
  - Organic chemicals produced during the manufacture of plastics and resins
  - Radioactive compounds
- Recombinant DNA technology has enabled creation of GM organisms with the potential to improve bioremediation
- Petroleum-Eating Bacteria
  - Created in 1970s
  - Isolated strains of *pseudomonas* from contaminated soils
  - Contained plasmids that encoded genes for breaking down the pollutants

9.4 Applying Genetically Engineered Strains to Clean Up the Environment

- *E. coli* to clean up heavy metals
  - Copper, lead, cadmium, chromium, and mercury
- Biosensors – bacteria capable of detecting a variety of environmental pollutants
- Genetically Modified Plants and Phytoremediation
  - Plants that can remove RDX and TNT

9.4 Applying Genetically Engineered Strains to Clean Up the Environment

- Phytoremediation of Toxic Explosives Using Transgenic Plants



9.4 Applying Genetically Engineered Strains to Clean Up the Environment

- Recovering Valuable Metals
  - Copper, nickel, boron, gold
- Many microbes can convert metal products into metal oxides or ores
- Useful for recovery of metals from waste solutions from industrial manufacturing processes
- May be used to harvest precious metals

9.4 Applying Genetically Engineered Strains to Clean Up the Environment

- Bioremediation of Radioactive Wastes
  - The US Department of Energy has identified over 100 sites contaminated by weapons production or nuclear reactor development
  - Most radioactive materials kill microbes, but some strains have demonstrated a potential for degrading radioactive chemicals
  - No bacterium has been identified that can completely metabolize radioactive elements into harmless products