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Solid and Hazardous Wastes

Reuters/Str/Landov

Obsolete computer equipment. The computers at this Texas electronic recycler are being disassembled. Functional tubes will be exported to Thailand, where they will be used to manufacture inexpensive televisions. Broken tubes will be recycled or disposed of in the United States.

In the United States, Canada, and other highly developed countries, the average computer is replaced every 18 to 24 months, not because it is broken but because rapid technological developments and new generations of software make it obsolete. Old computers may still be in working order, but they have no resale value and are even difficult to give away. As a result, they sit in warehouses, garages, and basements—or are frequently thrown away with the trash and end up in landfills or incinerators. U.S. residents generate an average of 30 kg per person annually of such electronic waste, or *e-waste*.

This disposal represents a huge waste of the high-quality plastics and metals (e.g., aluminum, copper, tin, nickel, palladium, silver, and gold) that make up computers. Computers also contain toxic heavy metals—lead, cadmium, mercury, and chromium—which could potentially leach from landfills into soil and groundwater. Twenty-five states have passed legislation requiring businesses and residents to *ecycle* consumer electronics—that is, recycle PCs, monitors, cell phones, and televisions.

E-waste has provided business opportunity for certain companies, which disassemble old computers, monitors, fax machines, printers, and other electronic equipment that they obtain from businesses and individuals (see photograph). These ecycling businesses reclaim the glass from monitors, plastics from casings, and metal from wires and circuit boards and ship the components to manufacturers that *upcycle* the materials. (Upcycling is a type of recycling that takes discarded materials and makes a new product with a value higher than that of the original materials.)

Environmentally minded consumers are increasingly purchasing electronic equipment that is recyclable. Some electronics manufacturers, for example, take back their e-waste and recycle it into new products; other manufacturers take back obsolete electronic devices for ecycling by another company. Responsibility for disposition and reutilization of a product after it is obsolete is known as *cradle-to-cradle accounting*.

Although many U.S. companies handle obsolete computers, millions of old U.S. computers are shipped overseas to developing countries such as India, Pakistan, and China. There the computers are disassembled, often by methods potentially dangerous to the workers taking them apart. For example, circuit boards are often burned to obtain the small amount of gold in them, and burning releases hazardous fumes into the air.

Like it or not, humans produce solid waste, and it is our responsibility to deal with our waste in safe, cost-effective, and environmentally sensitive ways. Using a systems perspective, for example, we could design computers to allow more reuse, particularly of the cabinets that house the computer components. No single solution exists to the challenge of solid waste disposal today. A combination of waste reduction, reuse, recycling, composting, burning, and burying in sanitary landfills is currently the optimal way to manage solid waste. In this chapter you will examine the problems and the opportunities associated with the management of solid waste. You will then consider hazardous waste, which contains toxic materials and requires special disposal.

In Your Own Backyard . . .

What are the major sources of solid waste that you produce, and how could you produce fewer solid wastes?

Solid Waste

LEARNING OBJECTIVES

- Distinguish between municipal solid waste and nonmunicipal solid waste.
- Describe the features of modern sanitary landfills and explain some of the problems associated with them.
- Describe the features of a mass burn incinerator and explain some of the problems associated with incinerators.

The United States generates more solid waste, per capita, than any other country. (Canada is a close second.) Each person in the United States produces an average of 1.99 kg (4.38 lb) of solid waste per day. This amount corresponded to a total of 251 million tons in 2012, a slight increase over previous years.

The solid waste problem was made abundantly clear by several highly publicized instances of garbage barges wandering from port to port and from country to country, trying to find someone willing to accept their cargo. One example is the tugboat *Break of Dawn*, which in 1987 towed a garbage barge from New York to North Carolina. When North Carolina refused to accept the solid waste, the *Break of Dawn* set off on a journey of many months. In total, six states and three countries rejected the waste, which was eventually returned to New York to be incinerated.

Waste generation is an unavoidable consequence of prosperous, high-technology, industrial economies. It is a problem not only in the United States but also in Canada and other highly developed countries. Many products that could be repaired, reused, or recycled are simply thrown away. Others, including paper napkins and disposable diapers, are intended to be used once and then discarded. Packaging—which not only makes a product more attractive and more likely to sell but also protects it, keeps it sanitary, and deters theft—contributes to waste. Nobody likes to think about solid waste, but the fact is that it is a concern of modern society—we keep producing it, and places to dispose of it safely are limited.

TYPES OF SOLID WASTE

Municipal solid waste (MSW) is a heterogeneous mixture composed primarily of paper and paperboard; yard waste; plastics; food waste; metals; materials such as rubber, leather, and textiles; wood; and glass (**Figure 23.1**). The proportions of the major types of solid waste in this mixture change over time. Today's solid waste contains more paper and plastics than in the past, whereas the amounts of glass and steel have declined.

[mun]icipal solid waste [(MSW)] Solid materials [disc]arded by homes, [offic]e buildings, retail [st]ores, restaurants, [s]chools, hospitals, [priso]ns, libraries, and [other] commercial and [insti]tutional facilities.

MSW is a relatively small portion of all the solid waste produced (about 2%). **Nonmunicipal solid waste**, which includes wastes from mining (mostly waste rock, about 75% of the total solid waste production), agriculture (about 13%), and industry (about 10%), is produced in substantially larger amounts than MSW. Thus, most solid waste generated in the United States is from nonmunicipal sources.

[no]nmunicipal solid [w]aste Solid waste [gener]ated by industry, [agricul]ture, and mining.

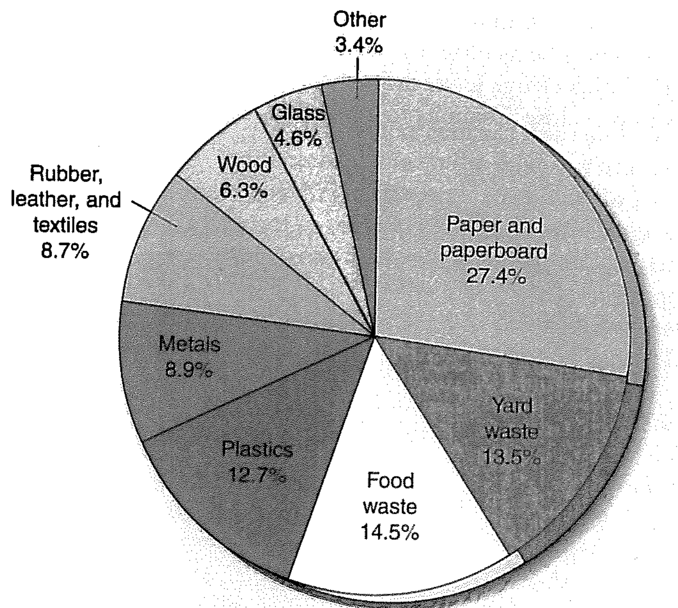


Figure 23.1 Composition of municipal solid waste, 2012. (EPA—Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012)

OPEN DUMPS

Solid waste has traditionally been regarded as material that is no longer useful and that should be disposed of. The four ways to get rid of solid waste are to dump it, bury it, burn it, or compost it. The old method of solid waste disposal was dumping. Open dumps were unsanitary, malodorous places in which disease-carrying vermin such as rats and flies proliferated. Methane gas was released into the surrounding air as microorganisms decomposed the solid waste, and fires polluted the air with acrid smoke. Liquid that oozed and seeped through the solid waste heap ultimately found its way into the soil, surface water, and groundwater. Hazardous materials that were dissolved in this liquid often contaminated soil and water.

SANITARY LANDFILLS

Open dumps have been replaced by **sanitary landfills**, which receive about 54% of the solid waste generated in the United States today (**Figure 23.2**). Sanitary landfills differ from open dumps in that the solid waste is placed in a hole, compacted, and covered with a thin layer of soil every day (**Figure 23.3**). This process reduces the number of rats and other vermin usually associated with solid waste, lessens the danger of fires, and decreases the amount of odor. If a sanitary landfill is operated in accordance with approved guidelines for solid waste management, it does not pollute local surface water and groundwater. Safety is ensured by layers of compacted clay and plastic sheets at the bottom of the landfill, which prevent liquid waste from seeping into groundwater. Newer landfills possess a double-liner system (plastic, clay, plastic, clay) and use sophisticated systems to collect **leachate** (liquid that seeps through the solid waste) and gases that form during decomposition.

sanitary landfill The most common method of disposal of solid waste, by compacting it and burying it under a shallow layer of soil.

Sanitary landfills charge "tipping fees" to accept solid waste. This money helps offset the landfill's operating costs and lets the jurisdiction charge lower property taxes for homes and businesses located in close proximity to the landfill. Tipping fees vary widely from one state to another. Some jurisdictions cannot handle all their waste, so they export their solid waste to nearby states with lower tipping fees. For example, sanitary landfills in Ohio and Indiana accept solid waste from New York and New Jersey.

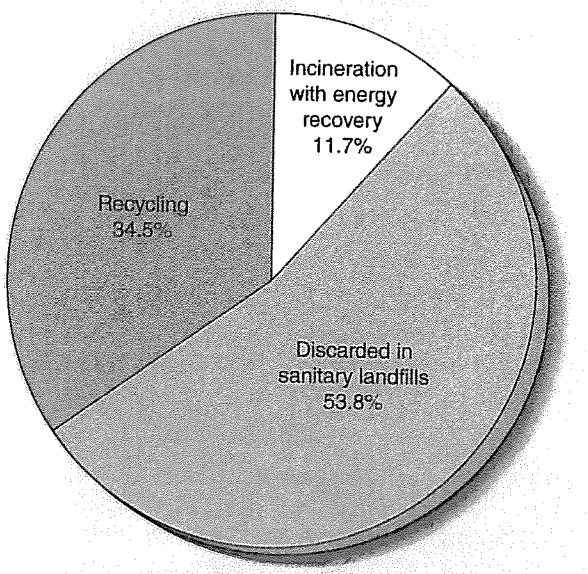


Figure 23.2 U.S. disposal of municipal solid waste in 2012. (EPA—Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012)

The location of an "ideal" sanitary landfill is based on a variety of factors, including the geology of the area, soil drainage properties, and the proximity of nearby bodies of water and wetlands. The landfill should be far enough away from centers of dense population that it is inoffensive but close enough that high transportation costs are not required. Landfill designs should take into account an area's climate, such as rainfall, snowmelt, and the likelihood of flooding.

Problems Associated with Sanitary Landfills Although the operation of sanitary landfills has improved over the years with passage of stricter and stricter guidelines, few landfills are ideal. Most sanitary landfills in operation today do not meet current legal standards for new landfills.

One problem associated with sanitary landfills is the production of methane gas by microorganisms that decompose organic material anaerobically (in the absence of oxygen). This methane may seep through the solid waste and accumulate in underground pockets, creating the possibility of an explosion. It is even possible for methane to seep into basements of nearby homes, which is an extremely dangerous situation. Conventionally, landfills collected the methane and burned it off in flare systems. A growing number of landfills have begun to use the methane for gas-to-energy projects. About 620 U.S. landfills currently use methane gas to generate electricity.

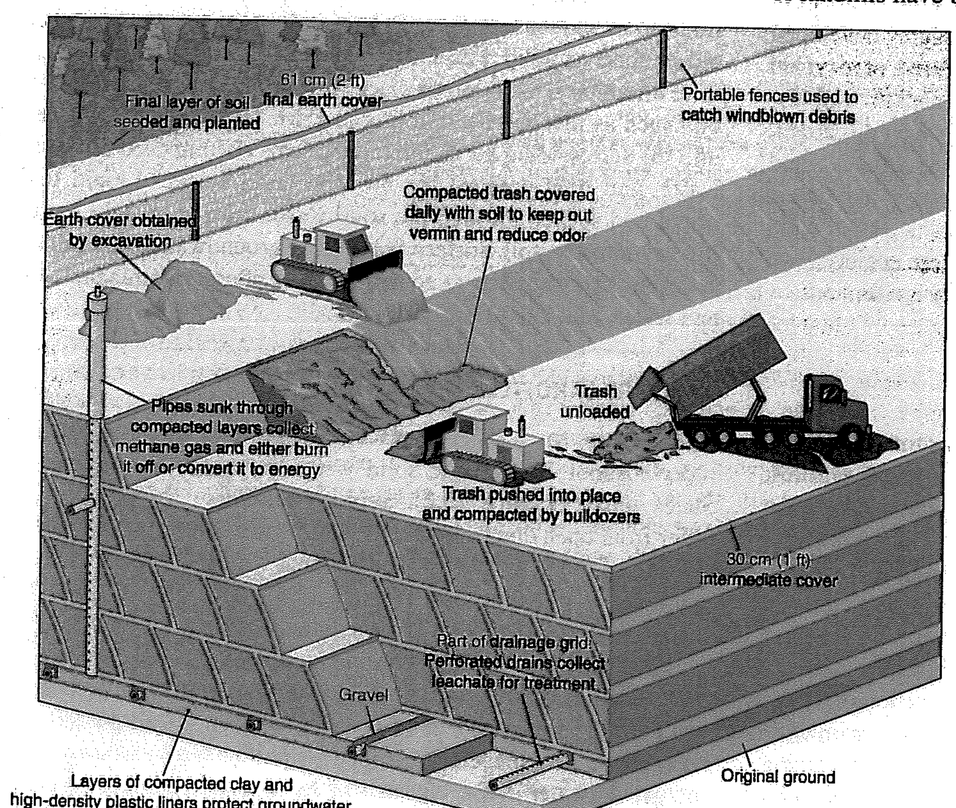


Figure 23.3 Sanitary landfill. Sanitary landfills constructed today have protective liners of compacted clay and high-density plastic and sophisticated leachate collection systems that minimize environmental problems such as contamination of groundwater. Solid waste is spread in a thin layer, compacted into small sections, and covered with soil.

Another problem associated with sanitary landfills is the potential contamination of surface water and groundwater by leachate that seeps from unlined landfills or through cracks in the lining of lined landfills. New York's Fresh Kills landfill, which was the largest in the United States before it closed in 2002, continues to produce an estimated 1 million gallons of leachate each day. Because household trash contains hazardous chemicals such as heavy metals, pesticides, and organic compounds that can seep into groundwater and surface water, the leachate must be collected and treated, even though the sanitary landfill has closed and is now being transformed into a park.

Landfills are not an indefinite remedy for waste disposal because they are filling up. From 1988 to 2009, the number of U.S. landfills in operation decreased from 7924 to 1908. Many of the landfills closed because they had reached their capacity. Other landfills closed because they did not meet state or federal environmental standards.

Fewer new sanitary landfills are being opened to replace the closed ones, although new landfills are generally much larger than in the past. The reasons for opening fewer new landfills are many and complex. Many desirable sites are already taken. Also, people living near a proposed site are usually adamantly opposed to a landfill near their homes. This attitude is partly the result of past problems with landfills, ranging from offensive odors to dangerous contamination of drinking water. It is also caused by the fear that a nearby facility will lower property values.

Once a sanitary landfill is full, closing it involves considerable expense. Because groundwater pollution and gas explosions remain possible for a long time, the Environmental Protection Agency (EPA) currently requires owners to continuously monitor a landfill for 30 years after the landfill is closed. In addition, no homes or other buildings can be built on a closed sanitary landfill for many years.

The Special Problem of Plastic The amount of plastic in our solid waste is growing faster than any other component of MSW. More than half of this plastic is from packaging. Bottled water, for example, is the world's fastest-growing beverage. Plastics are chemical **polymers** composed of chains of repeating carbon compounds. The properties of the many types of plastics—polypropylene, polyethylene, and polystyrene, to name a few—differ on the basis of their chemical compositions.

Most plastics are chemically stable and do not readily break down, or decompose. This characteristic, which is essential in the packaging of certain products, such as food, causes long-term problems. Indeed, most plastic debris disposed of in sanitary landfills will probably last for centuries.

In response to concerns about the volume of plastic waste, some areas have actually banned the use of certain types of plastic, such as the polyvinyl chloride employed in packaging. Special plastics that have the ability to degrade or disintegrate have been developed. Some of these are **photodegradable**; that is, they break down only after being exposed to sunlight, which means they will not break down in a sanitary landfill. Other plastics are **biodegradable**; that is, they are decomposed by microorganisms such as bacteria. Whether biodegradable plastics actually break down under the conditions found in a sanitary landfill is not yet clear, although several studies indicate that they probably do not. Many factors, such as temperature, amount of oxygen present, and composition of the microbial community, affect biodegradation of plastics and other organic materials. (Other waste management options for plastic are discussed later in this chapter.)

The Special Problem of Tires One of the most difficult materials to manage is rubber. Discarded tires—about 300 million each year in the United States—are made of vulcanized rubber, which cannot be melted and reused for tires. Millions of old tires have accumulated in tire dumps, as well as along roadsides and in vacant lots. Disposal of tires in sanitary landfills is a real problem because tires, being relatively large and light, have a tendency to move upward through the accumulated solid waste. After a period, they work their way to the surface of the landfill. These tires are a fire hazard, causing fires that are difficult to extinguish. Old tires also collect rainwater, providing a good breeding place for mosquitoes. Accordingly, most states either ban tires from sanitary landfills or require that they be shredded to save space and prevent water from pooling in them. (Other waste management options for tires are discussed later in the chapter.)

INCINERATION

When solid waste is incinerated, two positive things are accomplished. First, the volume of solid waste is reduced up to 90%. The ash that remains is, of course, much more compact than solid waste that has not been burned. Second, incineration produces heat that can make steam to warm buildings or generate electricity. In 2014, the EPA listed 86 U.S. waste-to-energy incinerators, which burned almost 12% of the nation's solid waste. In comparison, less than 1% of U.S. solid waste was incinerated in 1970. Waste-to-energy incinerators typically produce less carbon dioxide emissions than equivalent power plants that burn coal. (Recall from Chapter 20 that carbon dioxide is a potent greenhouse gas.)

Some materials are best removed from solid waste before incineration occurs. Glass does not burn, and when it melts, it is difficult to remove from the incinerator. Although food waste burns, its high moisture content often decreases the efficiency of incineration, so it is better to remove it before incineration. Removal of batteries, thermostats, and fluorescent lights is desirable because it eliminates most mercury emissions produced during combustion. The best materials for incineration are paper, plastics, and rubber.

Paper is a good candidate for incineration because it burns readily and produces a great amount of heat. Several studies have examined the economic and environmental costs and benefits of various waste paper management options. Many of these studies have concluded that waste-to-energy incineration is better than recycling, which in turn is better than disposal in a sanitary landfill. (The studies do not reach unanimous conclusions because economists do not agree about the cash value that should be applied for environmental benefits and costs. For example, estimates of the environmental cost of emitting 1 kg of carbon dioxide range from $1 to more than $50.) One potential environmental complication associated with burning paper is the presence of hazardous compounds in the ink and paper that might be emitted during incineration. Some types of paper release *dioxins* into the atmosphere when burned; dioxins are discussed later in the chapter.

Plastic produces a lot of heat when it is incinerated. In fact, one kilogram of plastic waste yields almost as much heat as a kilogram of fuel oil. As with paper, the pollutants that might be emitted during the incineration of plastic are of some concern. Polyvinyl chloride, a common component of many plastics, may release dioxins and other hazardous compounds when incinerated.

One of the best ways to dispose of old tires is incineration because burning rubber produces much heat. Some electric utilities in the United States and Canada burn tires instead of or in addition to coal (**Figure 23.4**). Tires produce as much heat as coal and often generate less pollution. About 45% of all tires discarded annually are incinerated.

Types of Incinerators The three types of incinerators are mass burn, modular, and refuse-derived fuel. Most **mass burn incinerators** are large and are designed to recover the energy produced from combustion (**Figure 23.5**). **Modular incinerators** are smaller incinerators that burn all solid waste. They are assembled at factories and so are less expensive to build. In **refuse-derived fuel incinerators**, only the combustible

mass burn incinerator A large furnace that burns all solid waste except for unburnable items such as refrigerators.

portion of solid waste is burned. First, noncombustible materials such as glass and metals are removed by machine or by hand. The remaining solid waste, including plastic and paper, is shredded or shaped into pellets and burned.

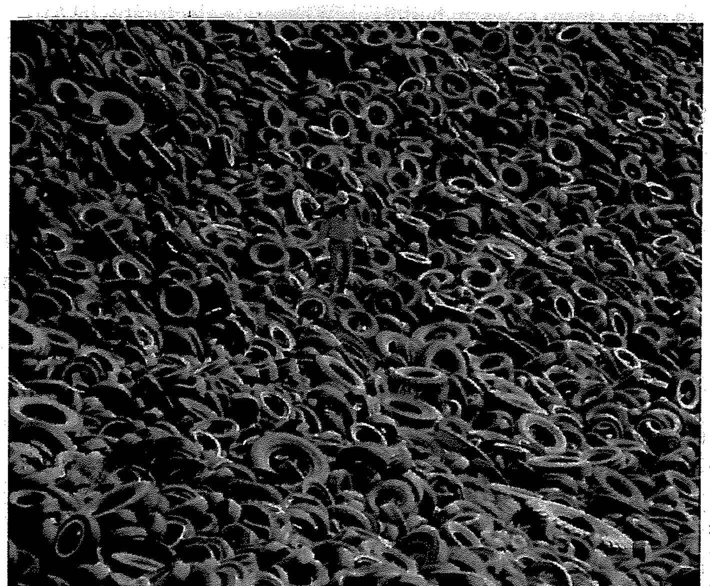

Jose Azel/Aurora Photos

Figure 23.4 Tires that will be burned to generate electricity. This mountain of tires in Westley, California, contains 4 million to 6 million old tires. The power plant that burns them supplies electricity to 3500 homes. (The person wearing red gives a sense of scale.) How would burning more tires affect climate change?

Problems Associated with Incineration The combustion of any fuel, whether it is coal or MSW, yields some air pollution. The possible production of hazardous air pollutants is the main reason people oppose incineration. Incinerators can pollute the air with carbon monoxide, particulates, heavy metals such as mercury, and other hazardous materials, unless air pollution–control devices are used. Such devices include **lime scrubbers**, towers in which a chemical spray neutralizes acidic gases, and **electrostatic precipitators**, which give ash a positive electrical charge so that it adheres to negatively charged plates rather than going out the chimney (see Figure 19.9 for diagrams of a scrubber and an electrostatic precipitator).

Incinerators produce large quantities of bottom ash and fly ash. **Bottom ash**, or slag, is the residual ash left at the bottom of the incinerator when combustion is completed. **Fly ash** is the ash from the flue (chimney) that is trapped by air pollution–control devices. Fly ash usually contains more hazardous materials, including heavy metals and possibly dioxins, than bottom ash.

Currently, both types of incinerator ash are best disposed of in specially licensed hazardous waste landfills (discussed later in this chapter). What happens to the hazardous materials in incinerator ash when it is placed in an average sanitary landfill is unknown; it is possible that the hazardous materials could contaminate groundwater.

As in the case of sanitary landfills, site selection for incinerators is controversial. People may recognize the need for an incinerator, but they do not want it near their homes. Another drawback of incinerators is their high cost. Prices have escalated because costly pollution-control devices are now required.

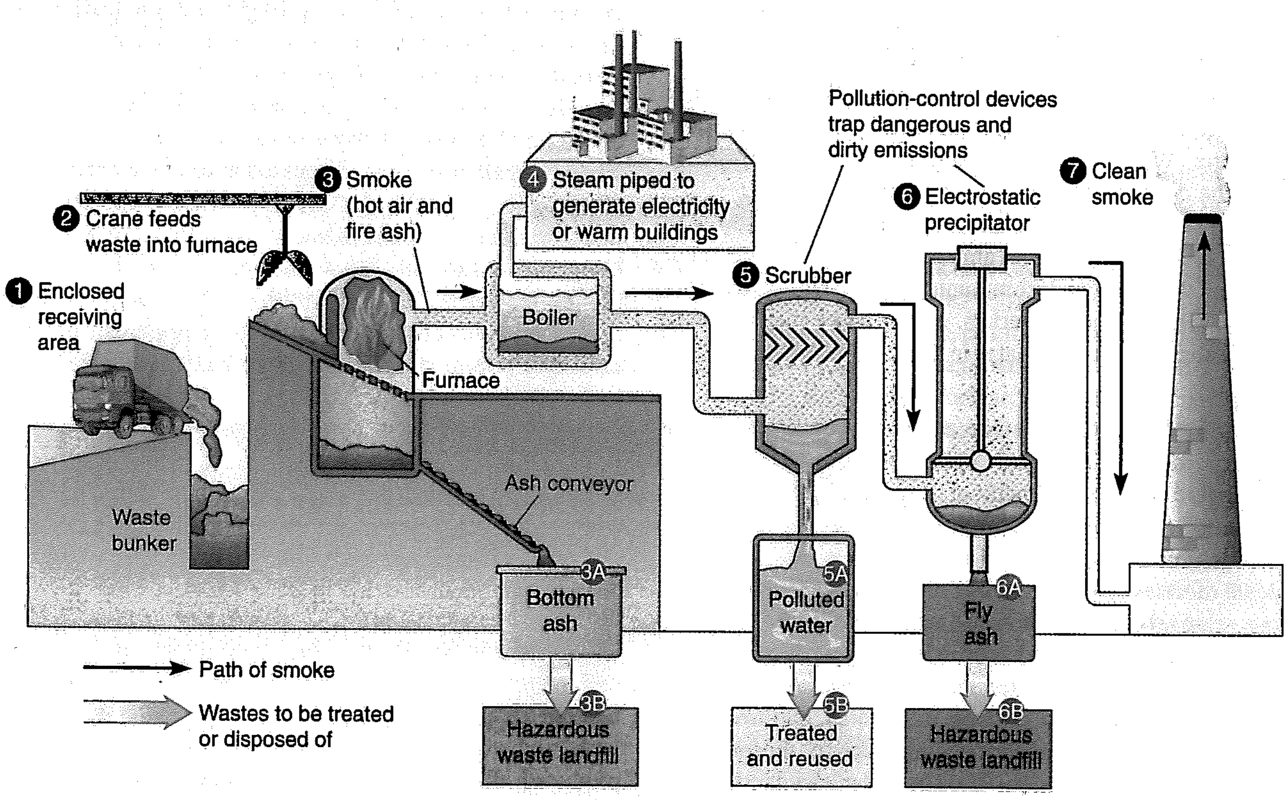


Figure 23.5 Mass burn, waste-to-energy incinerator. Modern incinerators have pollution-control devices such as lime scrubbers and electrostatic precipitators to trap dangerous and dirty emissions. (Begin with step 1 on the left side of the figure.)

COMPOSTING

Yard waste, such as grass clippings, branches, and leaves, is a substantial component of MSW (see Figure 23.1). As space in sanitary landfills becomes more limited, other ways to dispose of yard waste are being implemented. One of the best ways is to convert organic waste into soil conditioners such as compost or mulch (see You Can Make a Difference: Composting and Mulching, in Chapter 14). In 2012, about 58% of yard wastes in the United States were composed or otherwise recycled, per the EPA. Food scraps, sewage sludge, and agricultural manure are other forms of solid waste that can be used to make compost. Compost and mulch are used for landscaping in public parks and playgrounds or as part of the daily soil cover at sanitary landfills. Compost and mulch are also sold to gardeners.

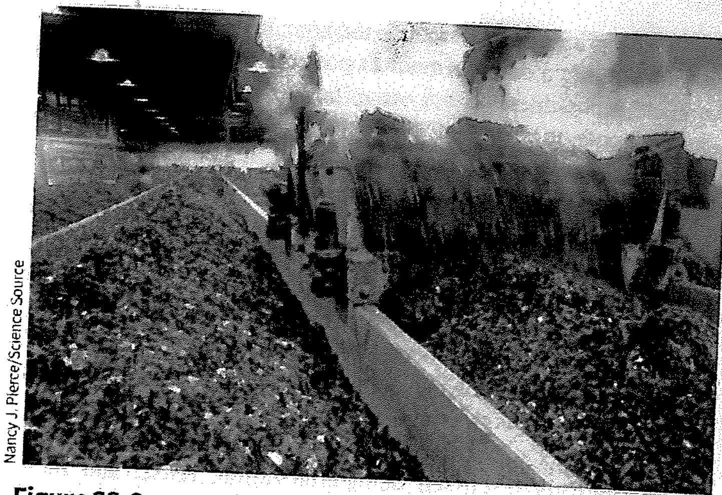
Composting as a way to manage solid waste first became popular in Europe. In 2012, 3120 municipalities in the United States offered composting facilities as part of their comprehensive solid waste management plans, and many states have banned yard waste from sanitary landfills. This trend is likely to continue, making composting even more desirable.

Municipal solid waste composting is the large-scale composting of the entire organic portion of a community's garbage. Because approximately two-thirds of all household garbage is organic (paper, yard wastes, food wastes, and wood), MSW composting substantially reduces demand for sanitary landfills. Numerous city and county governments compost leaves and yard wastes in an effort to reduce the amount of solid waste sent to landfills. Although this endeavor is undeniably beneficial, MSW composting encompasses much more than yard wastes. It involves composting food wastes, paper, and anything else in the solid waste stream that is organic. In 2012, more than 2.4 million U.S. households could participate in food waste composting programs.

Initial composting occurs quickly—in three to four days—because conditions such as moisture and the carbon-nitrogen ratio are continually monitored and adjusted (e.g., by adding water or fertilizer) for maximum decomposition. The decay process is carried out by billions of bacteria and fungi, which convert the organic matter into carbon dioxide, water, and humus. So many decomposers eat, reproduce, and die in the compost heap that the mass heats up, killing off potentially dangerous organisms such as disease-causing bacteria (**Figure 23.6**). When the material emerges, it is placed outside for several months to cure, during which time additional decomposition occurs. Finally, it is sold as compost.

The potential market for compost is huge. Professional nurseries, landscapers, greenhouses, and golf courses use compost. Also, tons of compost could be used to reclaim the 167 million hectares (413 million acres) of badly eroded farmland in the United States. Compost could improve the fertility of badly eroded rangeland, forestland, and strip mines. Should certain technical problems be resolved, composting on a large scale could become economically feasible.

Technical problems include concerns over the presence of pesticide residues and heavy metals in the compost. Pesticides sprayed on urban and suburban landscapes would naturally find their way into compost material on leaves, grass clippings, and other yard wastes. Some herbicides can be highly persistent in compost; many others are decomposed by microbes and high temperatures in the compost heap.



Nancy J. Pierce/Science Source

Figure 23.6 Municipal solid waste composting. In the early stages of composting, a paddlewheel turns MSW at a Minnesota composting facility. Harmful bacteria are killed by the heat generated through decomposition.

More troubling is the concern over heavy metals, such as lead and cadmium. Heavy metals can enter compost from sewage sludge, which may contain industrial wastewater, or from consumer products such as batteries. (Sewage sludge is often added to compost because it is a rich source of nitrogen for the decomposing microorganisms.) Two ways to reduce heavy metal contamination in municipal compost are sorting out heavy metal sources before everything is dumped into the composting drum, and requiring industries to pre-treat their industrial wastewater before it gets to the sewage treatment facility.

REVIEW

1. What is the difference between municipal solid waste and nonmunicipal solid waste?
2. What are three features of a sanitary landfill?
3. What are the main features of a mass burn incinerator?

Waste Prevention

LEARNING OBJECTIVES

- Summarize how source reduction, reuse, and recycling help reduce the volume of solid waste.
- Define *integrated waste management*.

Given the problems associated with sanitary landfills and incinerators, it makes sense to do whatever we can to lessen the need for these waste disposal methods. The three goals of waste prevention, in order of priority, are to reduce the amount of waste as much as possible, reuse products as much as possible, and recycle materials as much as possible.

Reducing the amount of waste includes purchasing products that last longer, are repairable, or have less packaging (**Figure 23.7**). Consumers can also decrease their consumption of products to reduce waste. Before deciding to purchase a product, a consumer should ask, "Do I really *need* this product, or do I merely *want* it?" Many U.S. consumers have participated actively for more than a decade in efforts to convert their throwaway economy into a waste prevention economy. Individual efforts have focused mainly on recycling, however, and much remains to be done in the areas of waste reduction and reuse (see Meeting the Challenge: Reusing and Recycling Old Automobiles).

We already discussed dematerialization, reuse, and recycling in Chapter 15, in the context of conservation of mineral resources. Now let's examine the impact of these practices on solid waste.

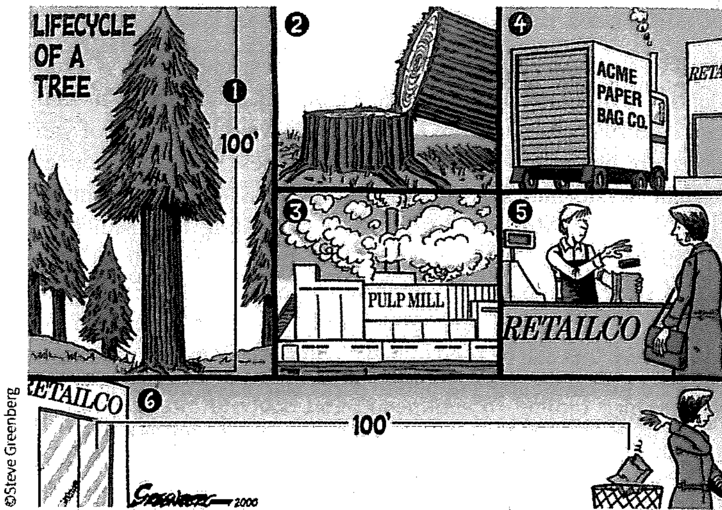


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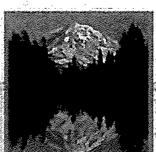
Figure 23.7 The six steps of wasteful packaging. What harmful environmental effects of wasteful packaging are depicted here?

source reduction An aspect of waste management in which products are designed and manufactured in ways that decrease the volume of solid waste and the amount of hazardous waste in the solid waste stream.

REDUCING THE AMOUNT OF WASTE: SOURCE REDUCTION

The most underused aspect of waste management is **source reduction**. Source reduction is accomplished in a variety of ways, such as substituting raw materials that introduce less waste during the manufacturing process and reusing and recycling wastes at the plants where they are generated. Innovations and product modifications can reduce the waste produced after a consumer has used a product. Dry-cell batteries, for example, contain much less mercury today than they did in the early 1980s. The 35% weight reduction in aluminum cans since the 1970s is another example of source reduction.



MEETING THE CHALLENGE

Reusing and Recycling Old Automobiles

In the United States, about 11 million cars and trucks are discarded each year. Although by weight about 75% of a discarded car is easily reused as secondhand parts or recycled as scrap metal, the remaining 25% is not easy to recycle and usually ends up in sanitary landfills. Because automobiles typically contain about 600 materials—glass, metals, plastics, fabrics, rubber, foam, leather, and so on—identifying ways to reuse or recycle old parts is complex. Economics is an important aspect of the problem, for reuse and recycling companies must make money as they sort and process auto components.

How does a car disassembly factory work? Workers typically begin disassembling a used car by draining all fluids—such as antifreeze, gasoline, transmission fluid, oil, and brake fluid—and recycling the fluids or processing them for disposal. Reusable parts and components, such as the engine, tires, and battery, are then removed, cleaned, tested, and inventoried before being sold. Body shops, new and used car dealers, repair shops, and auto and truck fleets are the main buyers of used parts. Some parts are disassembled for their materials. For example, catalytic converters are disassembled because they contain valuable amounts of platinum and rhodium.

An automotive recycling facility then sends the remaining vehicle "shell" to a scrap processor. At the scrap-processing facility, a giant machine shreds the entire automobile into small pieces. Magnets and other machines sort the pieces into piles of steel, iron, copper, aluminum, and "fluff," which consists of the remaining materials, such as plastic, rubber, upholstery, and glass.

About 37% of the iron and steel scrap reprocessed in the United States comes from old automobiles. Recycling iron and steel saves energy and reduces pollution. According to the Environmental Protection Agency, recycling scrap iron and steel produces 86% less air pollution and 76% less water pollution than mining and refining an equivalent amount of iron ore.

Recycling plastic is one of the biggest challenges in auto recycling. Plastic is lightweight, and, as a result, automakers use a lot of plastic to improve fuel efficiency. Because no industry standards for plastic parts currently exist, the kinds and amounts of plastic from which cars are made vary. As many as 15 plastics comprise some dashboards, and because many of these plastics are chemically incompatible, they cannot be melted together for recycling.

Auto manufacturers around the world have begun to address the challenge of reusing and recycling old cars. Japan and the European Union have mandated that by 2015, 95% of each discarded car must be recoverable. Toyota has developed a way to recover urethane foam and other shredded materials to make soundproofing material. Honda, Mercedes-Benz, Peugeot, Toyota, Volkswagen, Volvo, and other auto manufacturers have started to design cars so that each part of an old automobile can be reused or recycled.

The **Pollution Prevention Act** of 1990 was the first U.S. environmental law to focus on the reduced generation of pollutants at their point of origin rather than the reduction of pollutants or repair of damage caused by such substances. The act was written to increase the adoption of cost-effective source reduction measures. It requires the EPA to develop source reduction models, and it requires manufacturing facilities to report to the EPA annually on their source reduction and recycling activities.

Dematerialization, the progressive decrease in the size and weight of a product as a result of technological improvements, is an example of source reduction only if the new product is as durable as the one it replaced. If smaller, lighter products have shorter life spans and must be replaced more often, source reduction is not accomplished.

REUSING PRODUCTS

One example of reuse is refillable glass beverage bottles. Years ago, refillable beverage bottles were used a great deal in the United States. Today they are rarely used. For a glass bottle to be reused, it must be considerably thicker (and heavier) than one-use bottles. Because of the increased weight, transportation costs are higher. In the past, reuse of glass bottles made economic sense because many small bottlers were scattered across the United States, minimizing transportation costs. Today approximately one-tenth as many bottlers exist, making it economically difficult to go back to the days of refillable bottles. The price of beverages might have to increase to absorb increased transportation costs and the energy used to sterilize dirty bottles.

ENVIRONEWS

The U.S.–China Recycling Connection

More than half of recyclable wastes generated by Americans—from scrap metal to old cardboard boxes to used soda bottles—are redeveloped into U.S. products, but the rest are exported, primarily to China. During the early 2000s, China became the biggest importer of America's recyclable materials, collectively called scrap. When the scrap arrives in China, it becomes the raw materials for Chinese factories, paper mills, and steel mills. According to the Institute of Scrap Recycling Industries, scrap is now the third-largest export from the United States to China.

China does not have the natural resource base that countries such as the United States are lucky to possess. To fuel its economic growth, China relies on scrap—used paper for wood pulp and steel scrap to replace its dearth of iron ore. Some of the scrap shipped from the United States to China makes a round trip, returning to the United States as auto parts, polyester shirts, and toys. Because Chinese workers are paid much less than American workers, products made in China are generally less expensive for U.S. consumers than equivalent domestic products. The economic downside of the U.S. scrap–Chinese product cycle is that Chinese imports reduce the number of jobs available in the United States. Environmental disadvantages include degradation to Chinese ecosystems resulting from scrap processing.

Although the quantity of reusable glass bottles in the United States has declined, certain countries still reuse glass. In Japan, almost all beer and sake bottles are reused as many as 20 times. Bottles in Ecuador may remain in use for 10 years or longer. European countries such as Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and Switzerland have passed legislation that promotes the refilling of beverage containers. Parts of Canada and 11 U.S. states also have deposit laws.

RECYCLING MATERIALS

It is possible to collect and reprocess many materials found in solid waste into new products of the same or a different type. Recycling is preferred over landfill disposal because it conserves our natural resources and is more environmentally benign. Every ton of recycled paper saves 17 trees, 7000 gallons of water, 4100 kilowatt-hours of energy, and 3 cubic yards of landfill space. Recycling also has a positive effect on the economy by generating jobs and revenues (from selling the recycled materials). However, recycling does have environmental costs. It uses energy (as does any human activity), and it generates pollution (as does any human activity). For example, the de-inking process in paper recycling requires energy and produces a toxic sludge that contains heavy metals.

The many materials in MSW must be separated from one another before recycling. It is easy to sort materials such as glass bottles and newspapers, but difficult to separate materials in items with complex compositions. Some food containers are composed of thin layers of metal foil, plastic, and paper, and trying to separate these layers is a daunting prospect.

The number of U.S. communities with recycling programs increased remarkably during the 1990s but leveled off somewhat in the early 2000s. Recycling programs, which are tracked by the EPA, include curbside collection, drop-off centers, buy-back programs, and deposit systems. The United States had about 9000 curbside recycling programs in 2009 (latest data available). The annual recycling rate in 2012 of aluminum and steel cans, plastic bottles, glass containers, newspapers, cardboard, and other materials was 189 kg (416 lb) per person.

Recyclables are usually sent to a **materials recovery facility**, where they are either hand-sorted or separated using a variety of technologies, including magnets, screens, and conveyor belts, and prepared for remanufacturing. Currently, the United States recycles 34.5% of its MSW, including composting of yard trimmings; this amount is greater than in other highly developed countries. (Recall, however, that the United States also generates more MSW than any other country.)

Most people think recycling involves merely separating certain materials from the solid waste stream, but that is only the first step. For recycling to work, a market must exist for the recycled goods, and the recycled products must be used in preference to virgin products. Prices paid by processors for old newspapers, used aluminum cans, used glass bottles, and the like vary significantly from one year to the next, depending largely on the demand for recycled products. In some places, recycling—particularly curbside collection—is not economically feasible.

Recycling Paper The United States currently recycles more than 64% of its paper and paperboard. Many highly developed countries have greater paper-recycling rates. Denmark, for example, recycles about 97% of its paper. Part of the reason paper is not recycled more in the United States is that many older paper mills are not equipped to process waste paper. The number of mills that can process waste paper has increased in recent years, in part because of consumer demand. Most new mills in the United States are located near cities to take advantage of a local supply of scrap paper.

Demand is growing for U.S. waste paper in other countries. China, Mexico, Taiwan, and South Korea import large quantities of waste paper and cardboard from the United States.

Recycling Glass Glass is another component of solid waste appropriate for recycling. The United States currently recycles about 34% of its glass containers. Recycled glass costs less than glass made from virgin materials, largely because of the energy savings (**Figure 23.8**). Glass food and beverage containers are crushed to form **cullet**, which glass manufacturers can melt and use to make new products. Cullet is more valuable when glass containers of different colors are separated before being crushed. Cullet made from a mixture of colors has some uses; for example, it is used to make glassphalt, a composite of glass and asphalt that makes an attractive roadway.

Recycling Aluminum and Other Metals The recycling of aluminum is one of the best success stories in U.S. recycling, largely because of economic factors. Making a new aluminum can from a recycled one requires a fraction of the energy it would take to make a new can from raw metal (see Figure 23.8). Because energy costs for new cans are high, a strong economic incentive exists to recycle aluminum. According to the EPA, almost 55% of discarded aluminum beverage cans were recycled in 2012; about 36 barrels (1665 gallons) of gasoline are saved for each ton of recycled aluminum cans.

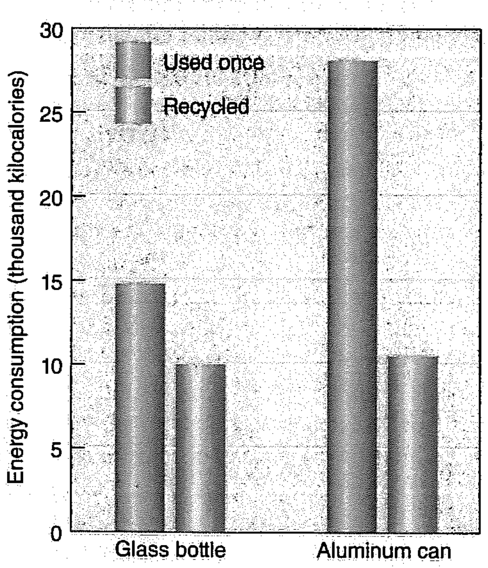


Figure 23.8 Energy savings for recycled bottles and cans. A comparison of the energy required to manufacture 350-mL (12-oz) glass bottles and aluminum cans that are either used once or recycled. (Data from Argonne National Laboratory)

Other recyclable metals include lead, gold, iron and steel, silver, and zinc. One obstacle to recycling metal products discarded in MSW is that their metallic compositions are often unknown. It is also difficult to extract metal from products, such as stoves, that contain other materials besides metal (e.g., plastic, rubber, or glass). In contrast, any waste metal produced at factories is recycled easily because its composition is known.

The economy has a large influence on whether metal is recycled or discarded. Greater recycling generally occurs when the price of metallic ores is more expensive than the price of recycled metals. Thus, although the supply of metal waste is fairly constant, the amount of recycling varies from year to year.

One exception to this generalization is steel. Before the 1970s, almost all steel was produced in large mills that processed raw ores. Starting in the 1970s and continuing to the present, "mini-mills" that produce steel products from up to 100% scrap have become increasingly important. These mills are located near many U.S. cities, so they can process local scrap more profitably (because there is no cost for transporting the scrap long distances). Minimills usually have electric arc furnaces that are energy-efficient and less polluting than the furnaces in old steel mills. According to the Institute of Scrap Recycling Industries, new steel products contain an average of 56% recycled scrap steel.

Recycling Plastic In 2012, about 14% of plastic containers and packaging were recycled. Depending on the economic situation, it is sometimes less expensive to make plastic from raw materials (petroleum and natural gas) than to recycle it. In other words, plastic recycling—indeed, all recycling—is affected by economics. Some local and state governments support or require the recycling of plastic.

Polyethylene terphthalate (PET), the plastic used in bottled water and soda bottles, is recycled more than any other plastic. According to the EPA, 31% of the PET soft drink and water bottles sold annually are recycled to make such diverse products as carpeting, automobile parts, tennis ball felt, and polyester cloth (**Figure 23.9**); it takes about 25 plastic bottles to make one polyester sweater.

Polystyrene (one form of which is Styrofoam) is an example of a plastic that has great recycling potential but is currently not recycled appreciably. Cups, tableware, and packaging materials made of polystyrene can be recycled into a variety of products, such as coat hangers, flowerpots, foam insulation, and toys. Because approximately 2.3 billion kg (5 billion lb) of polystyrene are produced each year, large-scale recycling would make a major dent in the amount of polystyrene that ends up in landfills.

So many kinds of plastic present a challenge in recycling them. About 50 plastics are common in consumer products, and many products contain multiple kinds. A plastic ketchup bottle, for example, may have up to six layers of different plastics bonded together. To allow for effective recycling of high-quality plastic, the different types must be meticulously sorted or separated. If two or more resins are recycled together, the resultant plastic is of lower quality.

Low-quality plastic mixtures are used to make a construction material similar to wood. Because of its durability, this "plastic lumber" is particularly useful for outside products, such as fence posts, planters, highway retaining walls, decks, picnic tables, and park benches.

Courtesy National Association for PET Container Resources (NAPCOR)

Figure 23.9 Recycled plastic. A wide variety of products are made from recycled polyethylene terphthalate (PET), shown, and other plastics.

Recycling Tires Almost 300 million tires are discarded in the United States each year, and 45% of them were recycled in 2012. Relatively few kinds of products are made from old tires: examples include retread tires, playground equipment, trashcans, garden hoses, and rubberized asphalt for pavement. More recently, rubber from old tires has been used to make carpets, roofing materials, and molded products. Research in product development continues, and almost all states now have tire-recycling programs.

INTEGRATED WASTE MANAGEMENT

The most effective way to deal with solid waste is through a combination of techniques. In **integrated waste management**, a variety of options that minimize waste, including the three R's of waste prevention (reduce, reuse, and recycle), are incorporated into an overall waste management plan (**Figure 23.10**). Even on a large scale, recycling and source reduction will not entirely eliminate the need for disposal facilities such as incinerators and landfills. However, recycling and source reduction will substantially reduce the amount of solid waste requiring disposal in incinerators and landfills.

integrated waste management A combination of the best waste management techniques into a consolidated, systems-based program to deal effectively with solid waste.

REVIEW

1. What is source reduction?
2. How do source reduction, reuse, and recycling reduce the volume of solid waste?
3. What is integrated waste management?

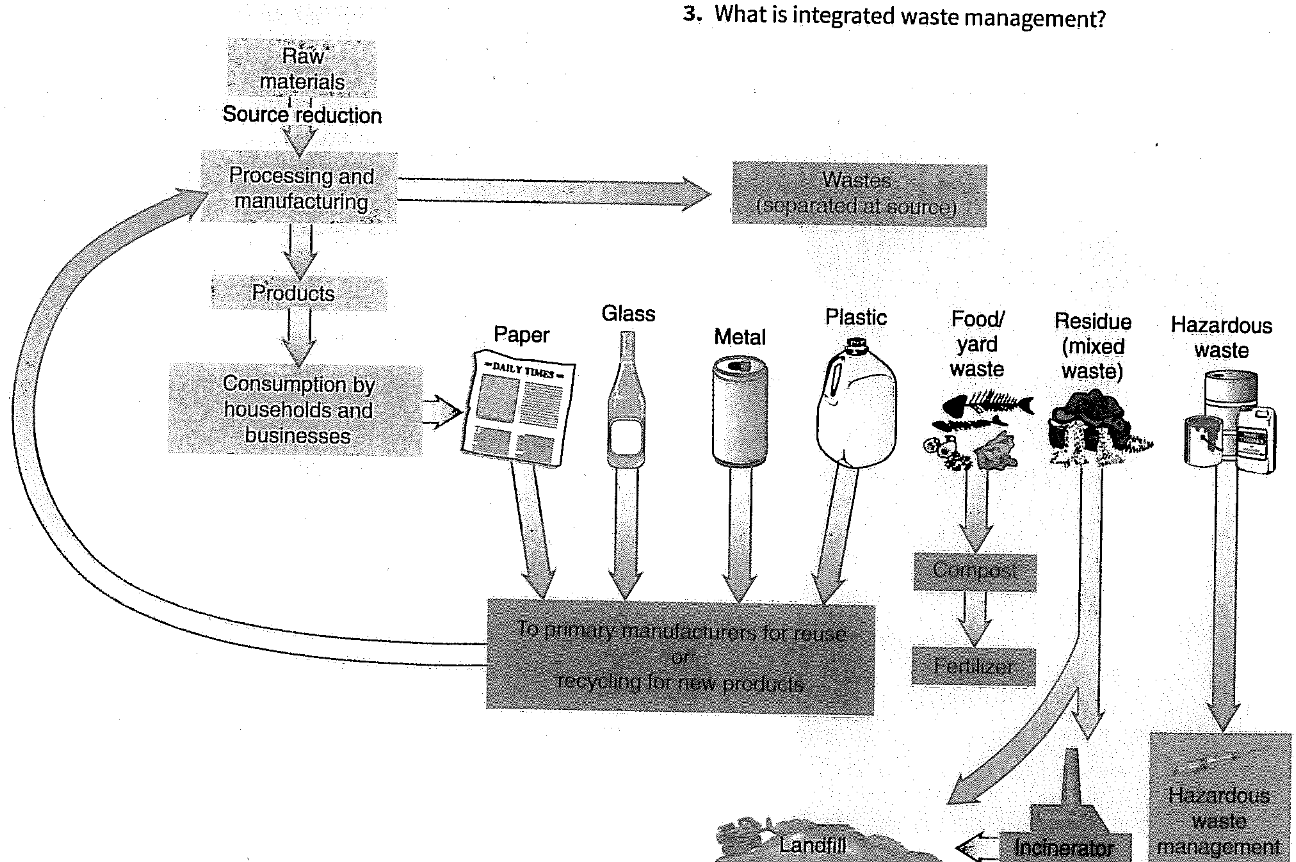


Figure 23.10 Integrated waste management. Source reduction, reuse, recycling, and composting are part of integrated, systems-based waste management, in addition to incineration and disposal in landfills.

Hazardous Waste

LEARNING OBJECTIVES

- Define *hazardous waste* and briefly characterize representative hazardous wastes (dioxins, PCBs, and radioactive wastes).
- Contrast the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act (the Superfund Act).
- Explain how green chemistry is related to source reduction.

hazardous waste Any discarded material that threatens human health or the environment.

Hazardous waste accounts for about 1% of the solid waste stream in the United States. Hazardous waste includes dangerously reactive, corrosive, ignitable, or toxic chemicals. The chemicals may be solids, liquids, or gases.

Hazardous waste has held national attention since 1977, when it was discovered that hazardous waste from an abandoned chemical dump had contaminated homes and possibly people in **Love Canal**, a small neighborhood on the edge of Niagara Falls, New York (**Figure 23.11**). **Lois Gibbs**, a housewife in Love Canal, led a successful crusade to evacuate the area after she discovered what seemed a high number of serious illnesses in the neighborhood, particularly among children. As a result of the publicity, Love Canal became synonymous with chemical pollution caused by negligent hazardous waste management. In 1978, it became the first location ever declared a national emergency disaster area because of hazardous waste; some 700 families were evacuated.

How did the Love Canal disaster come about? From 1942 to 1953, a local industry, Hooker Chemical Company, disposed of about 20,000 metric tons (22,000 tons) of toxic chemical waste in the 914-m-long (3000-ft-long) Love Canal. When the site was filled, Hooker added topsoil and donated the land to the local board of education and apparently provided documentation that wastes were present. A school and houses were built on the site, which began oozing hazardous waste several years later. Over 300 chemicals, many of them carcinogenic, have been identified in Love Canal's hazardous waste.

Andy Levin/Science Source

Figure 23.11 Aerial view of Love Canal toxic waste site in the early 1980s. All the homes shown in this photograph were evacuated and demolished.

Tons of contaminated soil were removed during the cleanup that followed, but because the canal was so huge, the federal government decided to contain the waste and construct drainage trenches to prevent hazardous wastes from leaking from the site. In 1990, after almost 10 years of cleanup, the EPA and the New York Department of Health declared the nearby area safe for resettlement. Today, the canal is a 40-acre mound covered by clay and surrounded by a chain-link fence and warning signs.

Which health problems in residents were caused by the contamination remains unclear, because we know little about the effects of such complex mixtures of toxins. On average, Love Canal residents seem to have had more health problems than the average, from miscarriages and birth defects to psychological disorders.

The Love Canal episode resulted in passage of the federal Superfund law, which held polluters accountable for the cost of cleanups (discussed shortly). Love Canal also generated concern over hazardous waste that has been with us ever since. For example, a 1997 California study reported that women living within a quarter mile of untreated hazardous waste sites (Superfund sites) were at greater risk of having babies with serious birth defects, such as malformed neural tubes and defective hearts.

Other countries have the same problems with hazardous waste management. How should we deal with the bewildering array of hazardous waste continually generated and released in ever-increasing amounts into the environment by mining, industrial processes, incinerators, military activities, and thousands of small businesses? How do we clean up the hazardous materials that have already contaminated our world?

TYPES OF HAZARDOUS WASTE

More than 700,000 chemicals are known to exist. How many are hazardous is unknown because most have never been tested for toxicity, but without a doubt, hazardous substances number in the thousands. According to the EPA report *Chemical Hazard Data Availability Study*, only 7% of the 3000 chemicals used in large quantities (more than 500 tons annually) in U.S. commerce have undergone comprehensive studies of potential health and environmental effects. Hazardous chemicals include a variety of acids, dioxins, abandoned explosives, heavy metals, infectious waste, nerve gas, organic solvents, polychlorinated biphenyls (PCBs), pesticides, and radioactive substances (**Table 23.1**). Many of these chemicals have already been discussed, particularly in Chapters 7, 11, 19, 21, and 22: endocrine disrupters, radioactive waste, air pollution, water pollution, and pesticides. Here we discuss dioxins, PCBs, and radioactive wastes produced during the Cold War.

Dioxins **Dioxins** are a group of 75 similar chemical compounds formed as unwanted by-products during the combustion of chlorine compounds. Some of the known sources of dioxins are medical waste and municipal waste incinerators, iron ore mills, copper smelters, cement kilns, metal recycling, coal combustion, pulp

Table 23.1 Examples of Hazardous Waste

Hazardous Material	*Some Possible Sources*
Acids	Ash from power plants and incinerators; petroleum products
CFCs (chlorofluorocarbons)	Coolant in air conditioners and refrigerators
Cyanide	Metal refining; fumigants in ships, railway cars, and warehouses
Dioxins	Emissions from incinerators and pulp and paper plants
Explosives	Old military installations
Heavy metals:	
Arsenic	Industrial processes, pesticides, additives to glass, paints, electronics discarded in landfills
Cadmium	Rechargeable batteries, incineration, paints, plastics, discarded electronics
Lead	Lead-acid storage batteries, stains and paints, TV picture tubes and electronics discarded in landfills
Mercury	Coal-burning power plants; paints, household cleaners (disinfectants), industrial processes, medicines, seed fungicides, discarded electronics
Infectious waste	Hospitals, research labs
Nerve gas	Old military installations
Organic solvents	Industrial processes; household cleaners, leather, plastics, pet maintenance (soaps), adhesives, cosmetics
PCBs (polychlorinated biphenyls)	Older appliances (built before 1980); electrical transformers and capacitors
Pesticides	Household products
Radioactive waste	Nuclear power plants, hospitals, and weapons production/dismantling facilities

and paper plants that use chlorine for bleaching, and chemical accidents. Incineration of medical and municipal wastes accounts for 70% to 95% of known human emissions of dioxins. In Japan, where nearly 75% of the solid waste is burned in incinerators, the air contains nearly 10 times the amount of dioxins found in other highly developed countries. The more than 6000 hospital waste incinerators in the United States are probably the largest dioxin polluters because they are so numerous, and they generally have unsophisticated pollution controls.

Dioxins are emitted in smoke and then settle on plants, the soil, and bodies of water; from there, they are incorporated into the food web. When humans and other animals ingest dioxins, they are stored and accumulate in fatty tissues (see the discussion of bioaccumulation and biological magnification in Chapter 7). Humans are primarily exposed when they eat contaminated meat, dairy products, and fish. Because dioxins are so widely distributed in the environment, virtually everyone has dioxins in his or her body fat.

Just how dangerous dioxins are to humans is somewhat controversial. Dioxins are known to cause several kinds of cancer in laboratory animals, but the data are conflicting on their cancer-causing ability in humans. A 1997 study of residents of Seveso, Italy, who were exposed to high levels of dioxin after a chemical accident in 1976, revealed a statistically significant increase in cancer deaths. Another study published in 2002 linked high levels of dioxin exposure to an increased incidence of breast cancer in Italian women living near the accident site. According to the EPA, dioxins probably cause several kinds of cancer in humans.

Other concerns center on the effects of dioxins on the human reproductive, immune, and nervous systems. Dioxins may delay fetal development and cause cognitive damage, lead to endometriosis in women (the growth of uterine tissue in abnormal locations in the body), and decreased sperm production in men. Dioxins are also linked to an increased risk of heart disease. Because human milk contains dioxins, nursing infants are considered particularly at risk.

PCBs **Polychlorinated biphenyls (PCBs)** are a group of 209 industrial chemicals composed of carbon, hydrogen, and chlorine. These clear or light-yellow, oily liquids or waxy solids were manufactured in the United States between 1929 and 1979. PCBs were used as cooling fluids in electrical transformers, electrical capacitors, vacuum pumps, and gas-transmission turbines. They were also found in hydraulic fluids, fire retardants, adhesives, lubricants, pesticide extenders, inks, and other materials.

The first evidence that PCBs were dangerous emerged in 1968, when Japanese who ate rice bran oil contaminated with PCBs experienced liver and kidney damage. A similar mass poisoning, also attributed to PCB-contaminated rice oil, occurred in Taiwan in 1979. Since then, toxicity tests conducted on animals indicate that PCBs harm the skin, eyes, reproductive organs, and gastrointestinal system. PCBs are endocrine disrupters because they interfere with hormones released by the thyroid gland. Several studies suggest that children exposed to PCBs before birth have certain intellectual impairments, such as poor reading comprehension, memory problems, and difficulty paying attention. Several studies suggest that PCBs may be carcinogenic.

PCBs are chemically stable and resist chemical and biological degradation. Like dioxins, PCBs accumulate in fatty tissues and are subject to biological magnification in food webs. The general human population is mainly exposed to PCBs by eating food that became contaminated through biological magnification. One way that PCBs enter aquatic food webs is via benthic invertebrates that live in contaminated sediments. (PCBs tend to bind to organic particles in aquatic sediments.) Small fish eat these invertebrates, and as larger fish eat the smaller fish, the PCBs bioaccumulate. Human populations whose diets consist primarily of fish and marine mammals, such as the Inuit of northern Canada, are exposed to large amounts of PCBs.

Prior to the EPA ban in the 1970s, PCBs were dumped in large quantities into landfills, sewers, and fields. Such improper disposal is one of the reasons PCBs are still a threat today. Also, when sealed electrical transformers and capacitors leak or catch fire, PCB contamination of the environment occurs.

High-temperature incineration is one of the most effective ways to destroy PCBs. However, incineration is not practical for the removal of PCBs that have leached into the soil and water because, among other difficulties, the cost of incinerating large quantities of soil is prohibitively high.

Several bacteria can degrade PCBs. However, when PCB-eating bacteria are sprayed on the surface of the soil, they cannot decompose the PCBs that have already leached into the soil or groundwater systems. These microorganisms show promise in removing PCBs from the environment, but additional research is needed to make the biological degradation of PCBs practical. (Additional discussion about using bacteria to break down hazardous waste is found later in this chapter.)

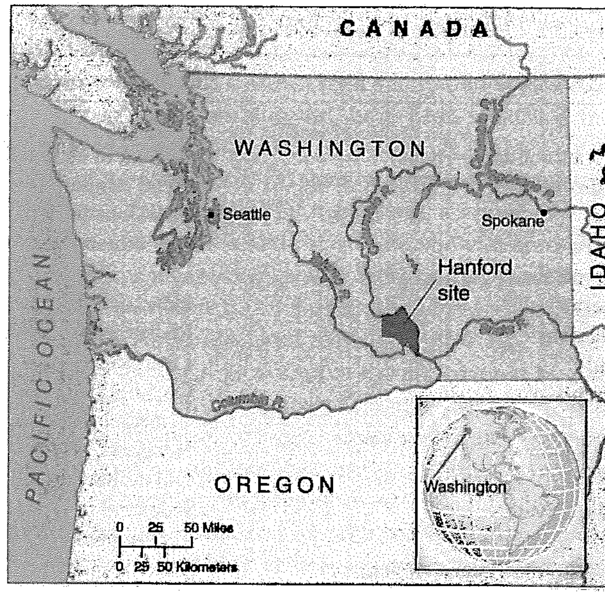
CASE IN POINT

HANFORD NUCLEAR RESERVATION

U.S. nuclear weapons facilities are no longer actively manufacturing nuclear weapons, but they present us with a greater challenge—reducing and managing radioactive and toxic wastes that have accumulated at numerous sites around the United States since the 1940s. Every step in the production of nuclear warheads generated radioactive and chemical wastes. We focus our discussion on the Hanford Nuclear Reservation, a 1400-km^2 (560-mi^2) area on the Columbia River in south-central Washington State (**Figure 23.12**). Hanford, the main production site for plutonium used in nuclear weapons, is the largest, most seriously contaminated site in the U.S. nuclear weapons infrastructure. Cleanup there began with a 1989 agreement between the EPA, the U.S. Department of Energy (DOE), and the State of Washington Department of Ecology.

The immensity of the cleanup task at Hanford has proved daunting. Tons of highly radioactive solid and liquid wastes were stored or dumped into trenches, pits, tanks, ponds, and underground cribs—a total of 1700 waste sites. (These methods of disposal were standard practice at the time.) Two concrete pools of water stored more than 100,000 spent fuel rods. As they corroded, the rods released highly radioactive uranium, plutonium, cesium, and strontium into the water, contaminating soil and groundwater and endangering the Columbia River. The fuel rods have been removed and placed in canister storage until a national or regional spent fuel repository is available (see Chapter 12).

The Columbia River is also threatened by millions of gallons of toxic chemical and radioactive liquid wastes stored in 177 large underground tanks. Liquids in some of these tanks are so reactive that they boiled for years from the heat of their own radioactivity or chemical activity, but most tanks are now covered by semisolid crusts that formed from chemical reactions within the mixtures. Some of the tanks are potentially explosive: Chemical reactions produce hydrogen and other hazardous gases. Vents allow the gas to escape and reduce the danger of ignition. Many of these tanks were designed to last only 10 to 20 years and are now leaking their poisons into the ground.



(a) Location of Hanford along the Columbia River in Washington State.

(b) Suited workers prepare to manage high-level radioactive waste at Hanford.

Figure 23.12 Hanford Nuclear Reservation.

Cleanup of this hazardous waste is complicated because the extent of radioactive pollution and the kinds of hazardous mixtures present are not well known (environmental records of hazardous waste production generally were not kept until the 1970s). Scientists and engineers were required to assess the damage, prioritize the cleanup process, and determine how best to proceed for each type of contamination. The cleanup, which is under the direction of DOE, has cost $30 billion so far and has fallen behind schedule, primarily because of budget restraints. Originally expected to be near completion, cleanup will likely continue for decades and cost tens of billions of dollars more.

The cleanup has sparked legal battles over environmental concerns and workers' health. In fact, cleanup may be a more dangerous occupation than working at Hanford when it was at full operation producing nuclear arms. Some of the cleanup workers have developed serious chronic illnesses because they come into close contact with toxic materials, such as beryllium, that were used to make bombs. Inhalation of beryllium particles can cause an incurable lung disease.

After the cleanup is finished, Hanford will remain hazardous for hundreds or even thousands of years, in part because we do not have the technologies to address the widespread soil contamination. Also, much of the buried radioactive waste may be left where it is because there is no other place to move it. Long-term monitoring will need to be maintained at the site to limit human exposure to remaining hazards.

MANAGEMENT OF HAZARDOUS WASTE

Humans have the technology to manage hazardous waste in an environmentally responsible way, but it is extremely expensive. Although great strides have been made in educating the public about the problems of hazardous waste, we have only begun to address many of the issues of hazardous waste disposal. No country currently has an effective hazardous waste management program, but several European countries have led the way by producing smaller amounts of hazardous waste and using fewer hazardous substances.

Chemical Accidents When a chemical accident occurs in the United States, whether at a factory or during the transport of hazardous chemicals, the National Response Center is notified. Most chemical accidents reported to the National Response Center involve oil, gasoline, or other petroleum spills. The remaining accidents involve more than 1000 other hazardous chemicals, such as ammonia, sulfuric acid, and chlorine.

Chemical safety programs have traditionally stressed accident mitigation and the addition of safety systems to existing procedures. More recently, industry and government agencies have focused on accident prevention through the **principle of inherent safety**, in which industrial processes are redesigned to involve less hazardous materials so that dangerous accidents are prevented. The principle of inherent safety, which is an example of systems thinking, is an important aspect of source reduction.

Current Hazardous Waste Policies Currently, two federal laws dictate how hazardous waste should be managed: (1) the Resource Conservation and Recovery Act, which is concerned with managing hazardous waste being produced now, and (2) the Superfund Act, which provides for the cleanup of abandoned and inactive hazardous waste sites.

The **Resource Conservation and Recovery Act (RCRA)** was passed in 1976 and amended in 1984. Among other things, RCRA instructs the EPA to identify which waste is hazardous and to provide guidelines and standards to states for hazardous waste management programs. RCRA bans hazardous waste from land disposal unless it is treated to meet the EPA's standards of reduced toxicity. In 1992, the EPA initiated a major reform of RCRA to expedite cleanups and streamline the permit system to encourage hazardous waste recycling.

In 1980, the **Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)**, commonly known as the **Superfund Act**, established a program to clean up abandoned and illegal hazardous waste sites across the United States. At many of these sites, hazardous chemicals have migrated deep into the soil and have polluted groundwater. The greatest threat to human health from hazardous waste sites comes from drinking water laced with such contaminants.

Cleaning Up Existing Hazardous Waste: The Superfund Program The federal government estimates that the United States has more than 400,000 hazardous waste sites with leaking chemical storage tanks and drums (both above and below ground), pesticide dumps, and piles of mining waste (**Figure 23.13a**). This estimate does not include the hundreds or thousands of hazardous waste sites at military bases and nuclear weapons facilities.

CERCLA lists an inventory of more than 10,000 hazardous waste sites that the EPA has deemed as qualifying for cleanup. These sites are not identified according to any particular criteria. Some are dumps that local or state officials have known about for years, whereas concerned citizens identify others. The sites in the inventory are evaluated and ranked to identify those with extremely serious hazards, based on data from preliminary assessments, site inspections, and expanded site inspections, which include contamination tests of soil and groundwater and sampling of hazardous waste.

The sites that pose the greatest threat to public health and the environment are placed on the **Superfund National Priorities List**, which means that the federal government will assist in their cleanup (**Figure 23.13b**). As of 2014, a total of 1326 sites were on the National Priorities List. The five states with the greatest number of sites on the National Priorities List as of 2014 are New Jersey (114 sites), California (97 sites), Pennsylvania (95 sites), New York (86 sites), and Michigan (65 sites).

As of 2014, a total of 375 hazardous waste sites had been cleaned up enough to be deleted from the National Priorities List, and 60 other sites were partially corrected. The 1158 sites designated "construction completions" have had extensive cleanups but remain on the Superfund list because of continued problems with groundwater contamination. The average cost of cleaning up a site is $20 million.

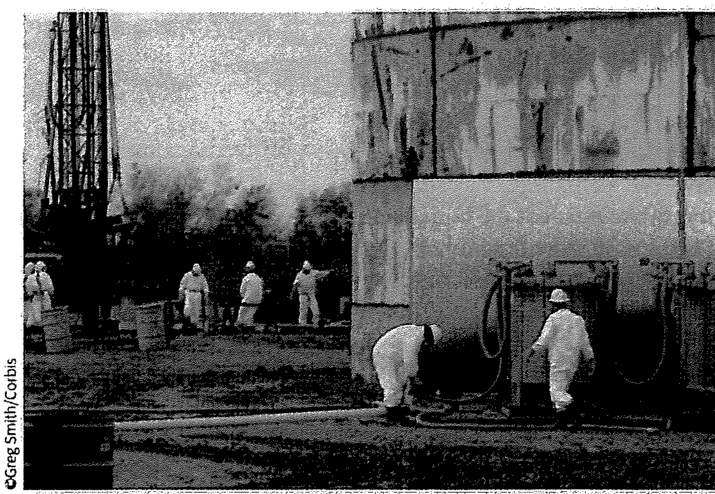
One reason for the urgency in cleaning up sites on the National Priorities List is their locations. Most were originally in rural areas on the outskirts of cities. With the growth of cities and their suburbs, residential developments now surround many of the dumps. One in three Americans lives within 5 km (3 mi) of one or more Superfund sites.

Because the federal government cannot assume major responsibility for cleaning up every old dumping ground in the United States, CERCLA requires that the current landowner, prior owners, and anyone who has dumped waste or has transported waste to a particular site share cleanup costs. For some sites, many parties are considered liable for cleanup costs. The cleanup process has been mired in litigation—mostly by companies charged with polluting, which are suing each other. Despite the urgency of cleaning up sites on the National Priorities List, it will take many years to complete the job.

Although critics decry the slow pace and high cost of cleaning up Superfund sites, the very existence of CERCLA is a deterrent to further polluting. Companies that produce hazardous waste are

Courtesy USDA

(a) Hazardous waste in deteriorating drums at a site near Washington, DC. The metal drums in which much of the waste is stored have corroded and started to leak. Old hazardous waste dumps are commonplace around the United States.



©Greg Smith/Corbis

(b) Cleanup of a Superfund site near Houston, Texas. Removal and destruction of the wastes are complicated by the fact that often nobody knows what chemicals are present.

Figure 23.13 Cleaning up hazardous waste.

now fully aware of the costs of liability and cleanup and are more likely to take steps to dispose of their hazardous wastes in proper fashion.

The Biological Treatment of Hazardous Contaminants A variety of methods are employed to clean up soil contaminated with hazardous waste. Because most of these processes are prohibitively expensive, innovative approaches such as bioremediation and phytoremediation are being developed to deal with hazardous waste. **Bioremediation** is the use of bacteria and other microorganisms to break down hazardous waste into relatively harmless components. **Phytoremediation** is the use of plants to absorb and accumulate hazardous materials from the soil. (The prefix *phyto-* comes from the Greek word meaning "plant.")

More than 1000 species of bacteria and fungi have been demonstrated to clean up various forms of organic pollution. Bioremediation takes a little longer to work than traditional hazardous waste disposal methods, but it accomplishes the cleanup at a fraction of the cost. In bioremediation, the contaminated site is exposed to an army of microorganisms, which gobble up poisons such as petroleum and other hydrocarbons and leave behind harmless substances such as carbon dioxide, water, and chlorides. Bioremediation encourages the natural processes in which bacteria consume organic molecules such as hydrocarbons. During bioremediation, conditions at the hazardous waste site are modified so that the desired bacteria will thrive in large enough numbers to be effective. Environmental engineers might pump air through the soil (to increase its oxygen level) and add a few soil nutrients such as phosphorus or nitrogen. They might install a drainage system to pipe any contaminated water that leaches through the soil back to the surface for another exposure to the bacteria.

In phytoremediation, plant species known to remove specific hazardous materials from the soil are grown at a contaminated site. Phytoremediation refers to several different ways that plants remove pollutants (**Figure 23.14**). In *phytoextraction*, some roots

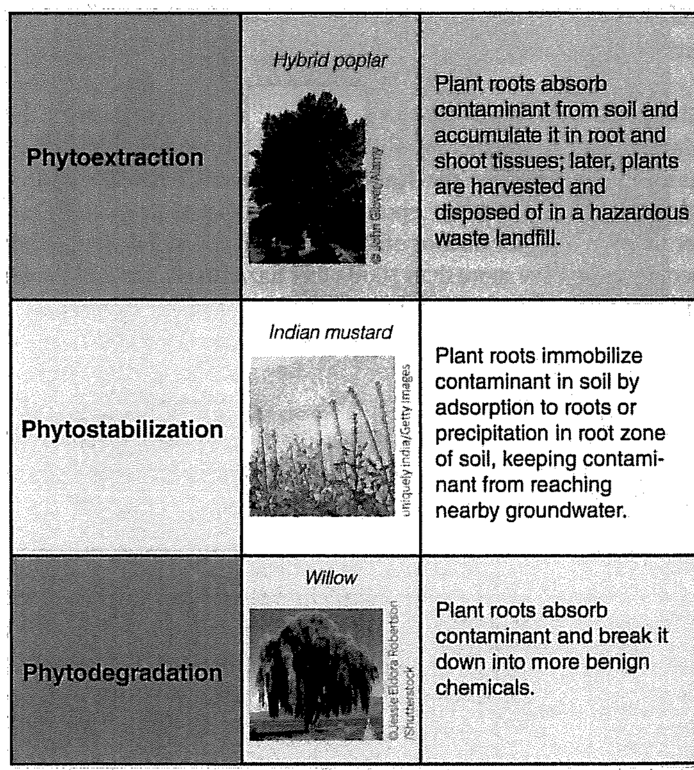


Figure 23.14 Examples of phytoremediation.

selectively absorb toxins from the soil and accumulate them in root and shoot tissues; later, the plants are harvested and disposed of in a hazardous waste landfill. Alternatively, some plants break down a hazardous chemical into more benign chemicals (*phytodegradation*). In *phytostabilization*, some plants immobilize toxins in soil, keeping them from reaching nearby groundwater.

Specific plants are known to remove such hazardous materials as trinitrotoluene (TNT), radioactive strontium and uranium, selenium, lead, and other heavy metals. Hybrid poplars and willows, for example, can remove chlorinated solvents from groundwater; Indian mustard removes heavy metals such as lead from the soil.

Phytoremediation costs less than conventional methods to clean up hazardous waste sites, but it does have limitations. Plants cannot remove contaminants present in the soil deeper than their roots normally grow. Also, insects and other animals might eat the plants, thereby introducing the toxins into the food web.

Managing the Hazardous Waste We Are Producing Now

Many people think, incorrectly, that establishment of the Superfund has eliminated the problem of hazardous waste. The Superfund deals only with hazardous waste produced in the past; it does nothing to eliminate the large amount of hazardous waste produced today. We manage hazardous waste by source reduction, conversion to less hazardous materials, and long-term storage.

As with MSW, the most effective of the three methods is *source reduction*—that is, reducing the amount of hazardous materials used in industrial processes and substituting less hazardous or nonhazardous materials for hazardous ones. Source reduction relies on an increasingly important subdiscipline of chemistry known as **green chemistry** (see Case in Point: Green Chemistry in Chapter 21).

For example, chlorinated solvents are widely used in electronics, dry cleaning, foam insulation, and industrial cleaning. It is sometimes possible to accomplish source reduction by substituting a less hazardous water-based solvent for a chlorinated solvent. Reducing solvent emissions also results in substantial source reduction of chlorinated solvents. Most chlorinated solvent pollution gets into the environment by evaporation during industrial processes. Installing solvent-saving devices benefits the environment and also provides economic gains, because smaller amounts of chlorinated solvents must be purchased. No matter how efficient source reduction becomes, however, it will never entirely eliminate hazardous waste.

The second-best way to deal with hazardous waste is to *reduce its toxicity* by chemical, physical, or biological means, depending on the nature of the hazardous waste. One method to detoxify organic compounds is high-temperature incineration. The high heat of combustion reduces these dangerous compounds, such as pesticides, PCBs, and organic solvents, into safe products such as water and carbon dioxide. The incineration ash, however, is hazardous and must be disposed of in a landfill designed specifically for hazardous materials. One method of reducing this toxic by-product is incineration using a *plasma torch*, which produces such high temperatures (up to 10,000°C, as much as five times hotter than conventional incinerators) that hazardous waste is almost completely converted to mostly harmless gases. (However, CO_2, which alters climate, is a harmful product of the plasma torch.) Hazardous waste that is produced in spite of source reduction and that is not completely detoxified must be placed in *long-term storage*.

Hazardous waste landfills are subject to strict environmental criteria and design features. They are located as far as possible from aquifers, streams, wetlands, and residences. These landfills have many special features, including several layers of compacted clay and high-density plastic liners at the bottom of the landfill to prevent leaching of hazardous substances into surface water and groundwater (**Figure 23.15**). *Leachate* is collected and treated to remove contaminants. The entire facility and nearby groundwater deposits are carefully monitored to make sure no leaking

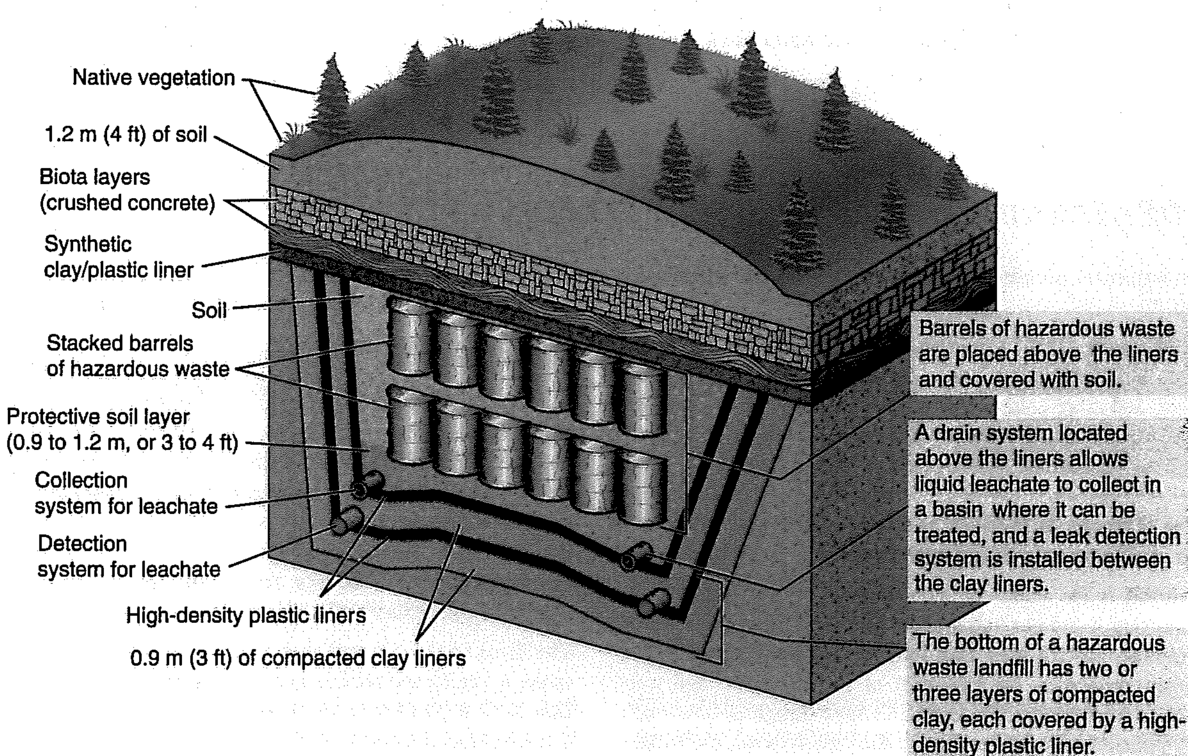


Figure 23.15 Cutaway view through a hazardous waste landfill. (Adapted from Rocky Mountain Arsenal Remediation Venture Office)

occurs. Only solid chemicals (not liquids) that have been treated to detoxify them as much as possible are accepted at hazardous waste landfills. These chemicals are placed in sealed barrels before being stored in the hazardous waste landfill.

Few landfills are certified to handle hazardous waste. Currently, only 23 commercial hazardous waste landfills are open in the United States, although many larger companies are licensed to treat their hazardous waste on-site. As a result, much of our hazardous waste is still placed in sanitary landfills, burned in incinerators that lack the required pollution-control devices, or discharged into sewers.

Some liquid hazardous wastes, such as certain organic compounds, fuels, explosives, and pesticides, are stored in the Earth's crust by **deep well injection**. These wells extend into impermeable rock layers several thousand feet below the surface. The Safe Drinking Water Act and the Underground Injection Control Program regulate the placement and number of such wells, which can be located only where minimal danger of groundwater contamination exists.

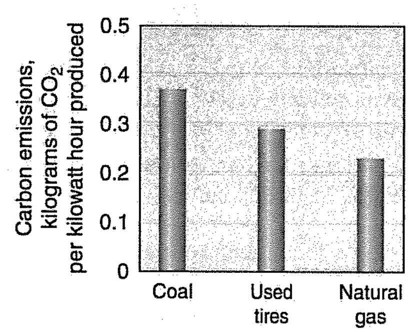
REVIEW

1. What is hazardous waste?
2. How are the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act alike? What is the focus of each?
3. How does green chemistry relate to source reduction?

ENERGY AND CLIMATE CHANGE

Storing, Reusing, or Incinerating Used Tires

As discussed in this chapter, the nearly 300 million used tires discarded each year in the United States present a variety of health and safety concerns. However, storing old tires can also be a form of carbon sequestration; that is, burying them can store the carbon they contain, rather than adding it to the atmosphere (see Chapter 20). Alternatively, old tires can be shredded and used for a variety of purposes, such as replacing some of the asphalt and gravel in roads. Finally, tires can be incinerated, and the energy they contain can be turned into electricity. Burning tires for energy releases about 78% as much carbon as does burning coal, but somewhat more than is produced when burning natural gas (see figure).



Carbon dioxide produced per unit energy produced. Burning used tires for energy produces less CO_2 than does producing the same amount of energy from burning coal, but slightly more than burning natural gas. Do you think we are better off burying used tires, turning them into other products, or burning them for energy? (Source: Energy Information Administration)

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Distinguish between municipal solid waste and nonmunicipal solid waste.**

Municipal solid waste (MSW) consists of solid materials discarded by homes, office buildings, retail stores, restaurants, schools, hospitals, prisons, libraries, and other commercial and institutional facilities. **Nonmunicipal solid waste** consists of solid waste generated by industry, agriculture, and mining.

- **Describe the features of modern sanitary landfills and explain some of the problems associated with them.**

A **sanitary landfill** is the most common method of disposal of solid waste, by compacting it and burying it under a shallow layer of soil. The location of a sanitary landfill must take into account the geology of the area, soil drainage properties, the proximity of surface waters and wetlands, and distance from population centers. Despite design features such as high-density plastic liners and **leachate** collection systems, most sanitary landfills have the potential to contaminate soil, surface water, and groundwater.

- **Describe the features of a mass burn incinerator and explain some of the problems associated with incinerators.**

A **mass burn incinerator** is a large furnace that burns all solid waste except for unburnable items such as refrigerators. Most mass burn incinerators recover the energy produced from combustion. One drawback of incineration is the great expense of installing pollution-control devices on the incinerators. These controls reduce the toxicity of the gaseous emissions from incinerators but make the ash that remains behind more hazardous.

- **Summarize how source reduction, reuse, and recycling help reduce the volume of solid waste.**

The three goals of waste prevention are to reduce the amount of waste, reuse products, and recycle materials as much as possible. **Source reduction** is an aspect of waste management in which products are designed and manufactured in ways that decrease the volume of solid waste and the amount of hazardous waste in the solid waste stream. One example of reuse is refillable glass beverage bottles. Recycling involves collecting and reprocessing materials into new products. Many communities recycle paper, glass, metals, and plastic.

- **Define *integrated waste management*.**

Integrated waste management is a combination of the best waste management techniques into a consolidated, systems-based program to deal effectively with solid waste.

- **Define *hazardous waste* and briefly characterize representative hazardous wastes (dioxins, PCBs, and radioactive wastes).**

Hazardous waste consists of any discarded chemical that threatens human health or the environment. **Dioxins** are hazardous chemicals formed as unwanted by-products during the combustion of many chlorine compounds. **Polychlorinated biphenyls (PCBs)** are hazardous, oily, industrial chemicals composed of carbon, hydrogen, and chlorine. Radioactive and chemical wastes have accumulated at numerous U.S. nuclear weapons facilities around the United States; the largest, most seriously contaminated site is Hanford Nuclear Reservation in Washington State.

- **Contrast the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act (the Superfund Act).**

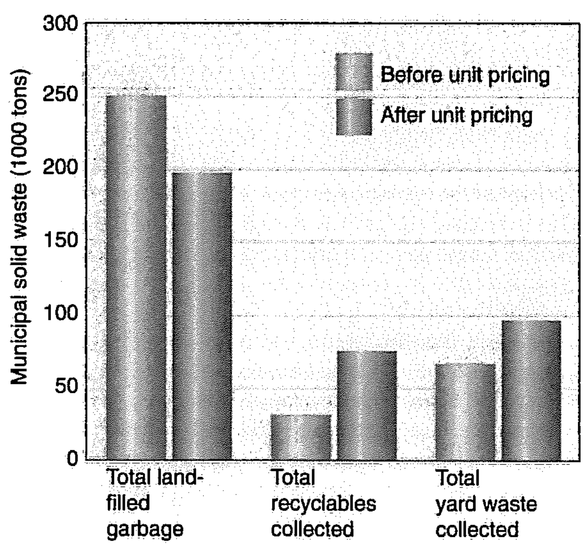
The **Resource Conservation and Recovery Act (RCRA)** instructs the EPA to identify which waste is hazardous and to provide guidelines and standards to states for hazardous waste management programs. The **Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)**, also known as the **Superfund Act**, addresses the challenge of cleaning up abandoned and illegal hazardous waste sites in the United States.

- **Explain how green chemistry is related to source reduction.**

Green chemistry is a subdiscipline of chemistry in which commercially important chemical processes are redesigned to significantly reduce environmental harm. Source reduction is the best way to reduce hazardous waste, so green chemists redesign processes with source reduction in mind.

Critical Thinking and Review Questions

1. What is solid waste?
2. Compare the advantages and disadvantages of disposing of waste in sanitary landfills and by incineration.
3. List what you think are the best ways to treat each of the following types of solid waste, and explain the benefits of the processes you recommend: paper, plastic, glass, metals, food waste, yard waste.
4. What initiatives can (or do) college campuses—or students on them—take to reduce the volume of various solid wastes they generate?
5. Why is creating a demand for recycled materials sometimes referred to as "closing the loop"?
6. How does recycling link the world's largest economy (the United States) to the world's fastest-growing economy (China)?
7. What are dioxins, and how are they produced? What harm do they cause?
8. Suppose hazardous chemicals were suspected to be leaking from an old dump near your home. Outline the steps you would take to (1) have the site evaluated to determine if it is dangerous and (2) mobilize the local community to get the site cleaned up.
9. What are the goals, strengths, and weaknesses of the Superfund program?
10. The Organization for African Unity has vigorously opposed the export of hazardous waste from industrialized nations to developing countries. It calls this practice "toxic terrorism." Explain.
11. What is integrated waste management? Why must a sanitary landfill always be included in any integrated waste management plan?
12. Compare integrated pest management, discussed in Chapter 22, to integrated waste management. How does each reduce potential damage to the environment?
13. How does the system of integrated waste management depicted in Figure 23.10 compare to a natural ecosystem?
14. How do the three R's of waste prevention reduce the release of climate-altering CO_2 into the environment?
15. In an effort to reduce municipal solid waste, some communities require customers to pay for garbage collection according to the amount of garbage they generate, known as unit pricing. The figure shows the effects of unit pricing in San Jose, California, on garbage sent to landfills and on wastes diverted through recycling and separation of yard wastes. How did unit pricing affect the amount of garbage sent to landfills? How did unit pricing affect the quantity of materials recycled? Of yard wastes collected?



Food for Thought

Keep track of the amount of food waste you produce daily, both the food itself and any packaging. What percent of the waste do you throw away? Compost? Recycle? What changes in your purchasing habits could you make to reduce the amount of packaging you discard? What changes in your diet or meal preparation could you make to avoid discarding food? Could you reduce your food waste without diminishing your quality of life? How?