CHAPTER 22

Managing Our Waste

CENTRAL
case study

A Mania for Recycling on Campus

> **An extraterrestrial observer might conclude that conversion of raw materials to wastes is the real purpose of human economic activity.**
> Gary Gardner and Payal Sampat, Worldwatch Institute

> **Recycling is one of the best environmental success stories of the late 20th century.**
> U.S. Environmental Protection Agency

At the time of year when NCAA basketball fever sweeps America's campuses, there's another kind of March Madness now taking hold: a mania for recycling.

It began in 2001, when waste managers at two Ohio campuses got the idea to use their schools' long-standing athletics rivalry to jump-start their recycling programs. Ed Newman of Ohio University, in Athens, and Stacy Edmonds Wheeler of Miami University, across the state in Oxford, challenged each other to see whose campus could recycle more in a 10-week competition. Come April, Miami University had taken the prize, recycling 41.2 pounds per student. Recyclemania was born.

Students at other colleges and universities heard about the event and wanted to get in on the action, and year by year more schools joined. Today, Recyclemania pits several hundred institutions against one another, involving several million students and staff across North America. The event has grown to have a board of directors and major corporate sponsors.

Each year student leaders rouse their campuses to compete in 2 divisions and 11 different categories over 8 weeks in February and March. Every week during the competition, recycling bins are weighed and campuses report their data, which are compiled online at the Recyclemania website as the competition proceeds. The all-around winner gets a funky trophy made of recycled materials (a figure nicknamed "Recycle Dude," whose body is a rusty propane tank)—and, more important, global bragging rights for a year.

In the spring of 2019, some 300 colleges and universities slugged it out. In the end, the battlefield was littered with stories of the victors and the vanquished (**FIGURE 22.1**, p. 620). Loyola Marymount University in Los Angeles, California, took top honors, recycling an impressive 89% of its waste, topping runners-up Berkshire Community College in Massachusetts and Kendall College of Art and Design of Ferris State University in Michigan. Loyola Marymount also took the prize for most recyclables per person, with a hefty 78.7 pounds per student. Rutgers University in New Jersey claimed top honors in the Total Recycling category, which measures total weight of items recycled, topping out at a staggering 2,575,073 pounds. And Knox College in Illinois won in the Food Organics category, after its donation of 5000 pounds of food to a local food bank gained it high scores in preventing organic waste.

Campuses also compete to see which can collect the most of certain types of items per person. In 2019, Union College of New York collected the most

Upon completing this chapter, you will be able to:

- Summarize major approaches to managing waste, and compare and contrast the types of waste we generate
- Discuss the nature and scale of the waste dilemma
- Evaluate source reduction, reuse, composting, and recycling as approaches for reducing waste
- Describe landfills and incineration as conventional waste disposal methods
- Discuss industrial solid waste and principles of industrial ecology
- Assess issues in managing hazardous waste

◀ **Students at Pacific Lutheran University competing in the Recyclemania tournament**

▲ **The world's biggest collegiate waste management event**

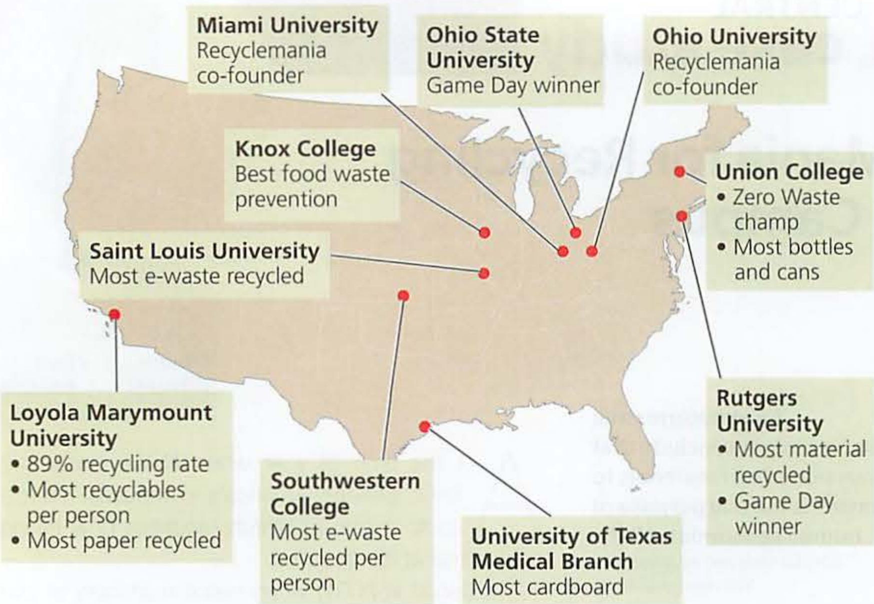

FIGURE 22.1 Eight schools were top winners among 300 participating in Recyclemania in 2019. The event began at Ohio University and Miami University and takes place each spring.

resources and the manufacture of new goods. Each year, students in the event help prevent the release of at least 100,000 tons of carbon dioxide—equal to the emissions output of 21,000 cars or the electricity use of 13,000 homes. By focusing the attention of administrators on waste issues, Recyclemania facilitates the expansion of campus waste reduction programs. Most important, it gets a new generation of young people revved up about the benefits of recycling.

Recyclemania is the largest of a number of campus-based competitions in the name of sustainability. In an event called the Campus Conservation Nationals, schools have competed against one another for savings in water use and energy use. In its biggest year in 2015, more than 345,000 students in 1374 buildings at 125 colleges and universities took part, saving 394,000 gallons of water (equal to 2500 hours in the shower) and 1.9 million kilowatt-hours of electricity (equivalent to taking 182 homes off the power grid for a year).

bottles and cans, Loyola Marymount gathered the most paper, and the University of Texas Medical Branch amassed the most cardboard. Southwestern College in Kansas recycled the most electronic waste per capita and Saint Louis University in Missouri recycled the most total e-waste. Union College topped Harvard University of Massachusetts in the "Race to Zero Waste" for minimizing its waste in one building during one month. Finally, Ohio State University and Rutgers University were champions in the competition to see who could best reduce waste at a home basketball game.

By encouraging all this recycling and waste reduction, Recyclemania cuts down on pollution from the mining of new

Thanks in part to Recyclemania, recycling is the most widespread activity among campus sustainability efforts (pp. 18–19). These diverse efforts include water conservation, energy efficiency, green buildings, transportation options, sustainable food in dining halls, and campus gardens. Students restore native plants and habitats, promote renewable energy, and advocate for carbon neutrality on campus. A growing movement, campus sustainability is thriving because for students, faculty, staff, and administrators, it's satisfying to do the right thing and pitch in to help make campuses more sustainable. And it's even more fun when you can compete and show that you can do it better than your rival school across the state!

Approaches to Waste Management

As the world's population rises and as we produce and consume more material goods, we generate more waste. **Waste** refers to any unwanted material or substance that results from a human activity or process. Waste can degrade water quality, soil quality, air quality, and human health. Waste also indicates inefficiency, so reducing waste can save money and resources. For these reasons, waste management has become a vital pursuit.

For management purposes, we divide waste into several categories. **Municipal solid waste** is nonliquid waste that comes from homes, institutions, and small businesses. **Industrial solid waste** includes waste from production of consumer goods, mining, agriculture, and petroleum extraction and refining. **Hazardous waste** refers to solid or liquid waste that is toxic, chemically reactive, flammable, or corrosive. Another type of waste is wastewater (p. 410), water we use in our households, businesses, industries, or public facilities and drain or flush down our pipes, as well as the polluted runoff from streets and storm drains. (We discuss wastewater in Chapter 15, pp. 415–417.)

There are three main components of **waste management:**

1. Minimizing the amount of waste we generate
2. Recovering discarded materials and recycling them
3. Disposing of waste safely and effectively

We have several ways to reduce the amount of material in the **waste stream,** the flow of waste as it moves from its sources toward disposal destinations (**FIGURE 22.2**). Minimizing waste at its source—called **source reduction**—is the preferred approach. We can achieve source reduction when manufacturers use materials more efficiently or when consumers buy fewer goods, buy goods with less packaging, or use those goods longer. Reusing goods you already own, purchasing used items, and donating your used items for others all help reduce the amount of material entering the waste stream.

The next-best strategy in waste management is **recovery,** which consists of recovering, or removing, waste from the waste

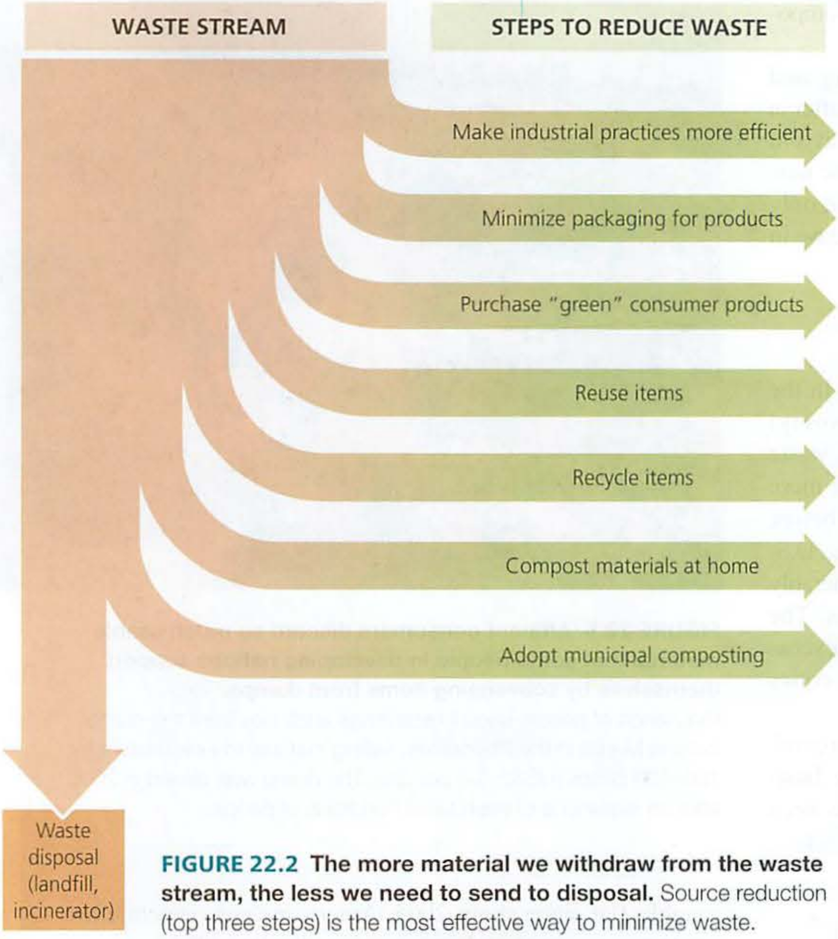

FIGURE 22.2 The more material we withdraw from the waste stream, the less we need to send to disposal. Source reduction (top three steps) is the most effective way to minimize waste.

stream. Recovery includes recycling and composting. **Recycling** is the process of collecting used goods and sending them to facilities that extract and reprocess raw materials that can then be used to manufacture new goods. **Composting** is the practice of recovering organic waste (such as food and yard waste) by converting it to mulch or humus (p. 217) through natural biological processes of decomposition. Recycling and composting are fundamental features of the way natural systems function; all materials in nature are broken down at some point, and matter cycles through ecosystems (Chapter 5). People have taken these concepts from nature and applied them in our society to help cut down on waste and conserve resources.

Regardless of how well we decrease the waste stream through source reduction and recovery, there will likely still be some waste left to dispose of. Disposal methods include burying waste in landfills and burning waste in incinerators. The linear movement of products from their manufacture to their disposal is often described as "cradle-to-grave." As much as possible, however, the modern waste manager attempts to follow a **cradle-to-cradle** approach instead—one in which the materials from products are recovered and reused to create new products. We will first examine how waste managers use source reduction, recovery, and disposal to manage municipal solid waste, and then we will turn to industrial solid waste and hazardous waste.

Municipal Solid Waste

Municipal solid waste is what we commonly refer to as "trash" or "garbage." In the United States, paper, food scraps, yard trimmings, and plastics are the principal components of municipal solid waste, together accounting for two-thirds of what enters the waste stream (**FIGURE 22.3a**). Paper is recycled and yard trimmings are composted at high rates, so after recycling and composting reduce the waste stream, food scraps and plastics are left as the largest components of U.S. municipal solid waste (**FIGURE 22.3b**).

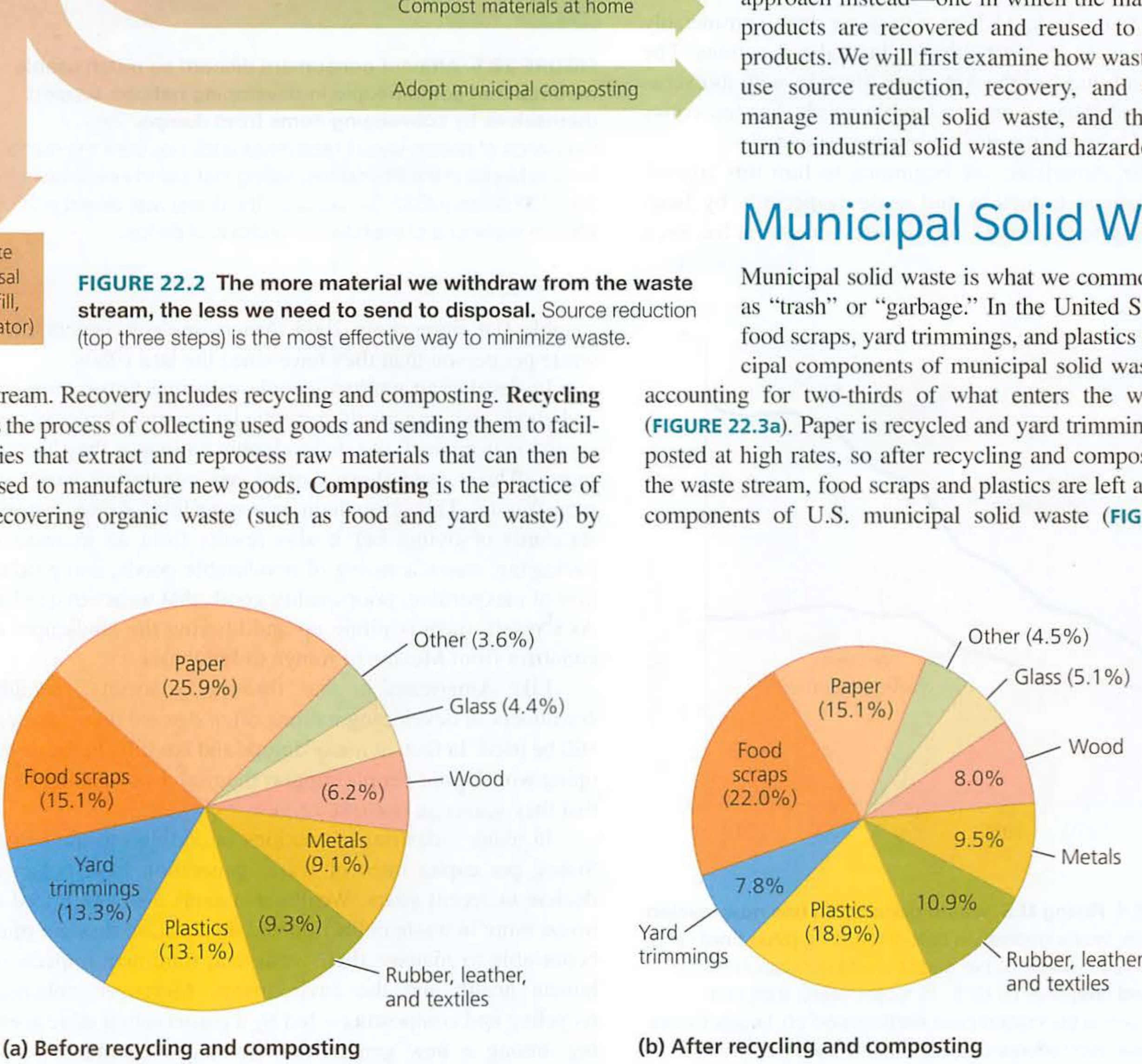

FIGURE 22.3 Components of the municipal solid waste stream in the United States. Paper products make up the greatest portion by weight **(a),** but after recycling and composting removes many items **(b),** the waste stream becomes one-third smaller. Within this reduced waste stream, food scraps are the largest contributor because a great deal of paper is recycled and yard waste is composted. *Data from U.S. Environmental Protection Agency, 2018.* Advancing sustainable materials management: 2015 fact sheet. *Washington, D.C.: EPA.*

In developing nations, food scraps are often the primary component, and paper makes up a smaller proportion.

Most municipal solid waste comes from packaging and nondurable goods (products meant to be discarded after a short period of use). In addition, consumers throw away old durable goods and outdated equipment as they purchase new products. Plastics, which came into wide consumer use only after 1970, have accounted for the greatest relative increase in the waste stream during the past several decades.

Consumption leads to waste

As we acquire more goods, we generate more waste. In the United States since 1960, waste generation (before recovery) has nearly tripled (**FIGURE 22.4**), and per-person waste generation has risen by 67%. Today, Americans produce more than 260 million tons of municipal solid waste (before recovery)—close to 1 ton per person. The average U.S. resident generates 2.0 kg (4.5 lb) of trash per day—considerably more than people in most other industrialized nations. The relative wastefulness of the American lifestyle, with its excess packaging and reliance on nondurable goods, has led critics to label the United States the "throwaway society."

However, Americans are beginning to turn this around. Thanks to source reduction and reuse (especially by businesses looking to cut costs), total waste generation has been roughly flat since about 2005. Americans now generate less waste per person than they have since the late 1980s.

FIGURE 22.5 Affluent consumers discard so much usable material that some people in developing nations support themselves by scavenging items from dumps. Tens of thousands of people used to scavenge each day from this dump outside Manila in the Philippines, selling material to junk dealers for 100–200 pesos (US$2–$4) per day. The dump was closed in 2000 after an avalanche of trash killed hundreds of people.

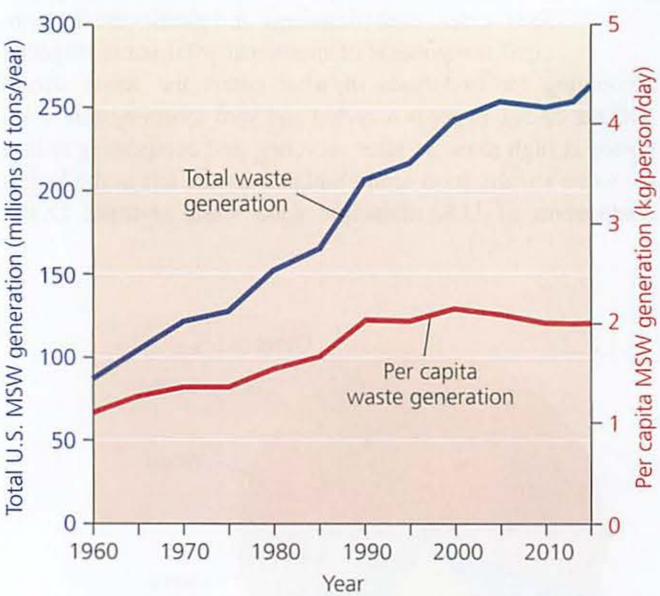

FIGURE 22.4 Rising U.S. waste generation has now leveled off. Total U.S. waste generation before recycling **(blue line)** nearly tripled after 1960, and U.S. per capita waste generation before recycling **(red line)** rose by 67%. In recent years, total and per-person waste generation have each leveled off, largely thanks to source-reduction efforts. *Data from U.S. Environmental Protection Agency, 2018.* Advancing sustainable materials management: 2015 fact sheet. *Washington, D.C.: EPA.*

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In developing nations, people consume fewer resources and goods and, as a result, generate less waste. However, consumption is intensifying in developing nations as they become more affluent, and these nations are generating more and more waste. This growth in waste reflects rising material standards of living, but it also results from an increase in packaging, manufacturing of nondurable goods, and production of inexpensive, poor-quality goods that wear out quickly. As a result, trash is piling up and littering the landscapes of countries from Mexico to Kenya to Indonesia.

Like Americans in the "throwaway society," wealthy consumers in developing nations often discard items that can still be used. In fact, at many dumps and landfills in the developing world, poor people support themselves by selling items that they scavenge (**FIGURE 22.5**).

In many industrialized nations in addition to the United States, per capita rates of waste generation have begun to decline in recent years. Wealthier nations also can afford to invest more in waste collection and disposal, so they are often better able to manage their waste and minimize impacts on human health and the environment. Moreover, enhanced recycling and composting—fed by a conservation ethic growing among a new generation on today's campuses—have been removing more material from the waste stream (**FIGURE 22.6**). As of 2015, U.S. waste managers were recovering 34.7% of the waste stream for composting and recycling, incinerating 12.8%, and sending the remaining 52.5% to landfills.

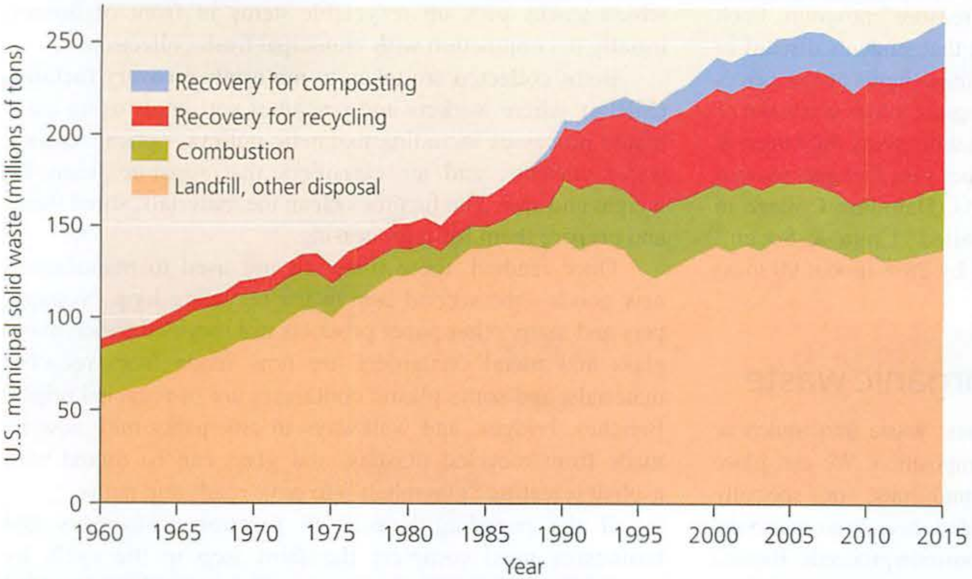

FIGURE 22.6 As recycling and composting have grown in the United States, the proportion of waste going to landfills has declined. As of 2015, 52.5% of U.S. municipal solid waste went to landfills and 12.8% to incinerators, whereas 34.7% was recovered for composting and recycling. *Data from U.S. Environmental Protection Agency, 2018.* Advancing sustainable materials management: 2015 fact sheet. *Washington, D.C.: EPA.*

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Reducing waste is our best option

Reducing the amount of material entering the waste stream is the preferred strategy for managing waste. Recall that preventing waste generation in this way is known as *source reduction*. This preventative approach avoids costs of disposal and recycling, helps conserve resources, minimizes pollution, and can save consumers and businesses money.

One means of source reduction is to reduce the materials used to package goods. Packaging helps preserve freshness, prevent breakage, protect against tampering, and provide information—yet much packaging is extraneous. Consumers can give manufacturers incentive to reduce packaging by choosing minimally packaged goods, buying unwrapped fruit and vegetables, and buying food from the bulk sections of stores. Manufacturers can switch to packaging that is more recyclable. They can also reduce the size or weight of goods and materials, as they already have with aluminum cans, plastic soft drink bottles, personal computers, and much else.

Recently, many policymakers have taken aim at a major source of waste—plastic grocery bags. These lightweight polyethylene bags can persist for centuries in the environment, choking and entangling wildlife (especially in the oceans; Chapter 16) and littering the landscape—yet Americans discard 100 billion of them each year. A number of cities, the states of Maine and Vermont, and more than 20 nations have now enacted bans or limits on their use. Financial incentives are also effective. When Ireland began taxing these bags, their use dropped 90%. IKEA stores began charging for them and saw similar drops in usage. Many businesses now give discounts if you bring your own reusable canvas bags.

Increasing the longevity of goods also helps reduce waste. Because companies seek to maximize sales, they often have a financial incentive to produce short-lived goods that need to be replaced frequently. As a result, increasing the longevity of goods is largely up to the consumer. If consumer demand for goods that last longer is great enough, manufacturers will respond.

Reusing items helps reduce waste

To reduce waste, you can save items to use again or substitute disposable goods with durable ones. **TABLE 22.1** presents a sampling of actions we all can take to reduce waste. Habits as simple as bringing your own coffee cup to coffee shops or bringing sturdy reusable fabric bags to the grocery store can, over time, have an impact. You can also donate unwanted items and shop for used items yourself at yard sales and resale centers. More than 6000 reuse centers exist in the United States, including stores run by organizations such as Goodwill Industries and the Salvation Army. Besides reducing waste, reusing items saves money. Used items are often every bit as functional as new ones, and they are often much less expensive.

On some campuses, students collect unwanted items and resell them or donate them to charity. Students at the University

TABLE 22.1 Some Everyday Things You Can Do to Reduce and Reuse

- Donate used items to charity
- Reuse boxes, paper, plastic wrap, plastic containers, aluminum foil, bags, wrapping paper, fabric, packing material, etc.
- Rent, borrow, or lend items instead of buying them
- Bring reusable cloth bags shopping
- Make double-sided photocopies
- Keep electronic documents rather than printing items out
- Bring your own coffee cup to coffee shops
- Pay a bit extra for durable, long-lasting, reusable goods rather than disposable ones
- Buy rechargeable batteries
- Select goods with less packaging
- Compost kitchen and yard wastes
- Buy clothing and other items at resale stores and garage sales
- Use cloth napkins and rags, not paper napkins and towels

Adapted from U.S. Environmental Protection Agency.

of Texas at Austin run a "Trash to Treasure" program. Each May, they collect 40–50 tons of items that students discard as they move off campus and then resell these items at low prices in August to arriving students. This program keeps waste out of the landfill, provides arriving students with items they need at low cost, and raises $10,000–$20,000 per year that gets plowed back into campus sustainability efforts. Hamilton College in New York runs a similar program, called "Cram & Scram," that reduces Hamilton's landfill waste by 28% (about 90 tons) each May.

Composting recovers organic waste

Composting is the conversion of organic waste into mulch or humus (p. 217) through natural decomposition. We can place waste in compost piles, underground pits, or specially constructed containers. As waste is added, heat from microbial action builds in the interior and decomposition proceeds. Banana peels, coffee grounds, grass clippings, autumn leaves, and other organic items can be converted into rich, high-quality compost through the actions of earthworms, bacteria, soil mites, sow bugs, and other detritivores and decomposers (pp. 81–82, 216). The compost is then used to enrich soil. Home composting is a prime example of how we can live more sustainably by mimicking natural cycles and incorporating them into our daily lives.

On campus, composting is becoming popular. Ball State University in Indiana shreds surplus furniture and wood pallets and makes them into mulch to nourish campus plantings. Ithaca College in New York composts much of its food waste, saving thousands of dollars each year in landfill disposal fees. The compost is used on campus plantings, and student-run experiments showed that the plantings grew better with the compost mix than with chemical soil amendments.

Municipal composting programs—more than 3500 across the United States at last count—divert yard debris out of the waste stream and into central composting facilities, where it decomposes into mulch that community residents can use for gardens and landscaping. Increasingly, these programs are also accepting food scraps for composting. About one-fifth of the U.S. waste stream is made up of materials that can easily be composted. Composting reduces landfill waste, enriches soil, enhances soil biodiversity, helps soil resist erosion, makes for healthier plants and more pleasing gardens, and reduces the need for chemical fertilizers.

Recycling consists of three steps

Recycling, too, offers many benefits. It involves collecting used items and breaking them down so that their materials can be reprocessed to manufacture new items. Recycling today in the United States diverts about 68 million tons of materials away from incinerators and landfills.

The recycling loop consists of three basic steps. The first step is to collect and process used goods and materials, as is being done on so many campuses. Some towns and cities designate locations where residents can drop off recyclables or receive money for them. Others offer curbside recycling, in which trucks pick up recyclable items in front of homes, usually in conjunction with municipal trash collection.

Items collected are taken to **materials recovery facilities** (MRFs), where workers and machines sort items using automated processes including magnetic pulleys, optical sensors, water currents, and air classifiers that separate items by weight and size. The facilities clean the materials, shred them, and prepare them for reprocessing.

Once readied, these materials are used to manufacture new goods—the second step in the recycling loop. Newspapers and many other paper products use recycled paper, many glass and metal containers are now made from recycled materials, and some plastic containers are of recycled origin. Benches, bridges, and walkways in city parks may now be made from recycled plastics, and glass can be mixed with asphalt (creating "glassphalt") to pave roads and paths.

If the recycling loop is to function, consumers and businesses must complete the third step in the cycle by purchasing ecolabeled products (p. 154) made from recycled materials. By buying recycled goods, consumers provide economic incentive for industries to recycle materials and for recycling facilities to open or expand.

Recycling has grown rapidly

Today, nearly 10,000 curbside recycling programs across all 50 U.S. states serve 70% of all Americans. These programs, and the 800 MRFs in operation today, have sprung up only in the past few decades. Recycling in the United States rose from 6.4% of the waste stream in 1960 to 25.8% in 2015 (and 34.7% if composting is included; **FIGURE 22.7**).

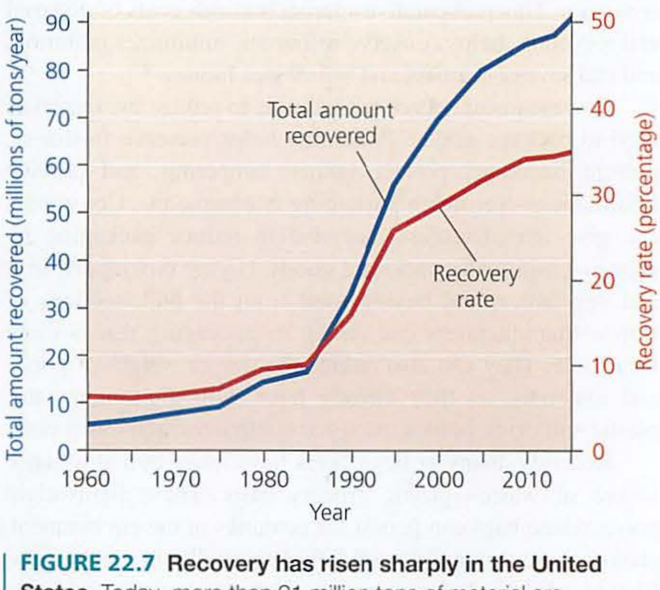

FIGURE 22.7 Recovery has risen sharply in the United States. Today, more than 91 million tons of material are recovered (68 million tons by recycling and 23 million tons by municipal composting), making up one-third of the waste stream. *Data from U.S. Environmental Protection Agency.*

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TABLE 22.2
Recovery Rates for Various Materials in the United States

MATERIAL	PERCENTAGE RECYCLED OR COMPOSTED
Lead-acid batteries	99
Steel cans	71
Newspapers	71
Paper and paperboard	67
Yard trimmings	61
Aluminum cans	55
Tires	40
Glass containers	33
Total plastics	9

Data from U.S. Environmental Protection Agency.

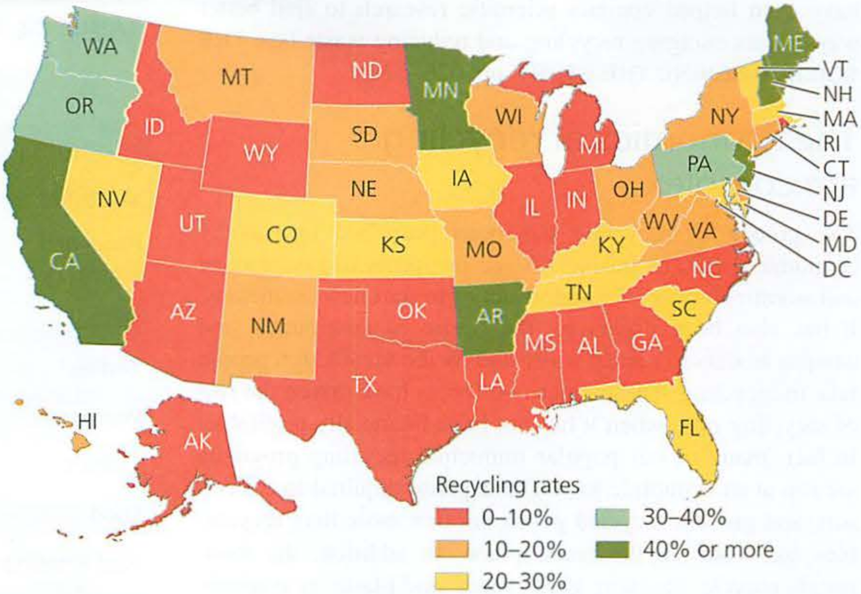


FIGURE 22.8 U.S. states vary greatly in the rates at which their citizens recycle. *Data from Shin, D., 2014.* Generation and disposition of municipal solid waste (MSW) in the United States—A national survey. *New York: Columbia University, Earth Engineering Center.*

Recycling rates vary greatly from one product or material type to another, ranging from nearly zero to almost 100% (**TABLE 22.2**). Recycling rates among states also vary greatly (**FIGURE 22.8**). This variation makes clear that opportunities remain for further growth in recycling.

Many college and university campuses run active recycling programs, although attaining high recovery rates can be challenging in the campus environment. The most recent survey of campus sustainability efforts suggested that the average recycling rate was only 29%. Thus, there appears to be much room for growth. Fortunately, waste management initiatives are relatively easy to conduct on campus because these efforts offer students and faculty many opportunities for small-scale improvements and because people generally enjoy recycling and reducing waste.

Besides participation in Recyclemania, there are many ways to promote recycling on campus. Louisiana State University students initiated recycling efforts at home football games, and over three seasons they recycled 68 tons of refuse that otherwise would have gone to the landfill. "Trash audits" or "landfill on the lawn" events involve emptying trashcans or dumpsters and sorting out recyclable items (**FIGURE 22.9**). When students at Ashland University in Ohio audited their waste, they found that 70% was recyclable, and they used this information to press their administration to support recycling programs. On some campuses, students

WEIGHING the issues

Managing Waste on Your Campus

Does your campus have a recycling program? Does it have composting initiatives? Does it run programs to reduce or reuse materials? Think about the types and amounts of waste generated on your campus. Describe several examples of this waste that you think could be prevented or recycled, and describe how that might be done in each case. If you could do one thing on campus to improve your school's waste management practices, what would it be?

FIGURE 22.9 In a trash audit, students sort through rubbish and separate out recyclables. Events like this "Mt. Trashmore" exercise at Central New Mexico Community College in 2015 show passersby just how many recyclable items are needlessly thrown away.

have even helped conduct scientific research to find better ways of encouraging recycling and reducing waste (see **THE SCIENCE BEHIND THE STORY**, pp. 628–629).

The economics of recycling are complex

The growth of recycling has been propelled in part by economic forces as businesses see prospects to save money and as entrepreneurs see opportunities to start new businesses. It has also been driven by the desire of community and campus leaders to reduce waste and by the satisfaction people take in recycling. These latter two forces have driven the rise of recycling even when it has not been financially profitable. In fact, many of our popular municipal recycling programs are run at an economic loss. The expense required to collect, sort, and process recycled goods is often more than recyclables are worth in the marketplace. In addition, the more people recycle, the more glass, paper, and plastic is available to manufacturers for purchase, which drives down prices.

The low commodity prices of recent years have also posed a challenge to recycling programs. When world oil prices are low, buying new plastic (made from petroleum) can be cheaper than buying recycled plastic; and when market prices of metals are low, buying newly mined metals can be cheaper than buying recycled metals. When recycling is no longer profitable for those in the recycling industry, MRFs may shut down, municipalities may cancel contracts, and recycling companies may go out of business.

Recycling advocates, however, point out that market prices do not take into account external costs (pp. 143, 165)—in particular, the environmental and health impacts of *not* recycling. For instance, it has been estimated that globally, recycling saves enough energy to power more than 6 million households per year. Each year in the United States, recycling and composting together save energy equal to that of 230 million barrels of oil and prevent carbon dioxide emissions equal to those of 39 million cars (**TABLE 22.3**). Recycling aluminum cans saves 95% of the energy required to make the same amount of aluminum from mined virgin bauxite, its source material.

WEIGHING the issues

Costs of Recycling and Not Recycling

Should governments subsidize recycling programs if they are run at an economic loss? What types of external costs—costs not reflected in market prices—do you think would be involved in not recycling, say, aluminum cans? Do you think these costs justify sponsoring recycling programs even when they are not financially self-supporting? Why or why not?

TABLE 22.3 Annual Greenhouse Gas Reductions due to Recovery of Various Materials in the United States

MATERIAL	WEIGHT RECOVERED (MILLIONS OF TONS)	EQUAL TO NUMBER OF CARS TAKEN OFF THE ROAD
Paper and paperboard	43.0	31,000,000
Metals	7.9	4,500,000
Textiles	2.3	1,200,000
Wood	2.5	798,000
Plastics	3.0	760,000
Food	1.8	308,000
Yard trimmings	20.6	220,000
Glass	3.2	210,000
Rubber and leather	1.2	127,000

Data from U.S. Environmental Protection Agency.

China's new policy has upended recycling efforts

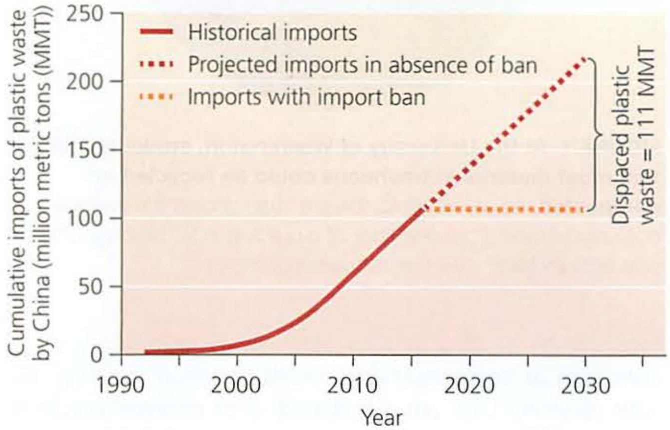
The latest economic complication for recycling efforts has come as a result of steps taken by China. In 2018, recycling programs across the world were thrown into disarray when China cut back sharply on its imports of recyclable materials—particularly plastics—from other nations.

For years, most of the world's recyclable materials were processed in China. Because China was exporting ships full of trade goods and consumer products across the oceans, it was convenient and inexpensive for nations like the United States to load the emptied ships with discarded paper, plastic, and scrap metal for the return journey back to China. Labor costs were low in China, so it was economical for Chinese workers to recycle the material. And China's booming market of a billion people, many of them gaining wealth and moving into the middle class, was creating a huge consumer base for products made from recycled materials. Because it was so easy to rely on this mutually beneficial trade with China, the United States and most other nations failed to invest in building enough domestic infrastructure to process their own recyclables.

Then in 2018, China largely stopped importing recyclables—particularly plastics—from the United States and other nations. The main stated reason was that the materials contained so much contamination (e.g., food residues on containers and nonrecyclable plastics mixed in with recyclable ones) that China no longer found it economical to process the materials. Additionally, labor costs (e.g., workers' wages) were rising, and as China built its own wealth, its consumers were generating more recyclable waste of their own. Finally, as China sought to become an economic superpower and global leader, it wanted to show environmental leadership and did not want to be viewed as a dumping ground for dirty scrap. Together, all these trends led the Chinese government to announce its policy, named National Sword, banning many foreign recyclables.

The new policy threw the U.S. recycling industry into turmoil, and American waste managers have been struggling

(a) Handling plastic waste at a recycling facility in China



(b) China's import policy could strand huge amounts of plastic waste

FIGURE 22.10 China's recent policy restricting imports of recycled material from other countries delivered a shock to the recycling market. While China recycles increasing amounts of its own plastic waste **(a),** recyclers across the United States and other nations are stockpiling materials in hopes of later sales, sending materials to landfills, or shutting down recycling programs. If the world cannot find effective ways to respond, **(b)** by 2030, the Chinese ban may result in 111 million metric tons of plastic not being recycled. *Data from Brooks, A., et al., 2018.* The Chinese import ban and its impact on global plastic waste trade. *Science Advances 4: eaat0131.*

to deal with the consequences. Because the United States has relied on China's MRFs for so long, the United States does not have enough of its own MRFs, and the costs of building a MRF are considerable. Efforts to export recyclables to alternative countries like India, Malaysia, Vietnam, and Thailand mostly failed, as these nations had limited capacity to receive more than they already do. As a result, millions of tons of recyclables across the United States have been stockpiled in warehouses while managers hope for a place to send them in the near future. In many areas, a portion of recyclable materials are simply being sent to the landfill. Municipalities that used to sell scrap plastic for up to $300 per ton now have to pay money to dispose of them instead. Hundreds of recycling programs across the nation and the world are being scaled back or are being scrapped altogether. As a result of this situation, many millions of tons of plastic, and other materials, will probably never be recycled (**FIGURE 22.10**).

Efforts to rebuild the recycling market are underway

In response to the crisis that has followed China's policy steps, recycling advocates are trying to cut down on contamination in the waste stream by doing a better job of educating consumers. One challenge is the sheer variety of products and packaging, which often makes it confusing to know what is recyclable and what is not. The other main challenge is convincing well-meaning people *not* to try to recycle items that cannot be recycled. People often find it difficult to throw away an item that they wish could be recycled, but these good intentions can lead to unfortunate consequences: The more a recycling stream is contaminated with nonrecyclable materials, the harder it is for workers and machinery at MRFs to process the materials. If loads of recyclables are found to have too high a percentage of contamination when they arrive at a MRF, the entire load may be rejected and sent to the landfill instead. As a result, recycling advocates have urged consumers: "When in doubt, throw it out."

In recent years, contamination in the U.S. recycling stream has surpassed 25%—that is, one out of every four items in the stream was nonrecyclable and had to be removed—putting undue burden on MRFs and their workers. One reason for this high contamination rate was a widespread shift from multiple-stream recycling (asking consumers to sort their items into different bins before recycling them) to single-stream recycling (letting consumers mix all recyclables into a single bin). Many municipalities made this shift in an effort to make it easier for consumers to recycle. The shift helped boost recycling rates, but studies show that it also resulted in more trash being thrown in the recycling stream.

With China now demanding that imported recyclables not exceed a contamination rate of 0.5% (1 part in 200), it seems unlikely that China will begin accepting foreign materials any time soon. We can hope that the present crisis will serve to encourage the United States and other nations to expand their own capacities for processing recyclables domestically. More than a dozen U.S. paper mills have already announced plans to expand processing of recycled paper, but it will take several years for this expansion to occur. A bigger challenge will be expanding processing for plastics (or reducing our reliance on plastics), which continue to be produced in a diversity of forms for a wide variety of products.

If we can successfully develop more technologies and methods to use recycled materials in new ways and if we can encourage more manufacturers to use recycled products, markets for recyclables should continue to expand, and new recycling business opportunities may arise. We are just beginning to shift from an economy that moves linearly—from raw materials to products to waste—to a more sustainable economy that moves circularly, taking a cradle-to-cradle approach and using waste products as raw materials for new manufacturing.

THE SCIENCE **behind** the **story**

Can Campus Research Help Reduce Waste?

A student does her part to recycle

Thousands of students on college and university campuses are engaged in efforts to reduce waste. The campus environment also provides opportunities to conduct scientific research on how to better manage waste.

The descriptive research involved in a trash audit (p. 625) is straightforward to conduct and can yield valuable data with practical relevance. At the University of Washington, students and faculty in the UW Garbology Project studied waste on their campus for several years. Working with instructor Dr. Jack Johnson and university waste managers, students sorted through the contents of trashcans, recycling bins, and compost receptacles and discovered that more than 80% of the material thrown in the trash was, in fact, recyclable or compostable (**FIGURE 1**). This information was helpful, because if the university could devise better ways to divert recyclable items and compostable food matter from the waste stream, it could save $225,000 per year on landfill fees.

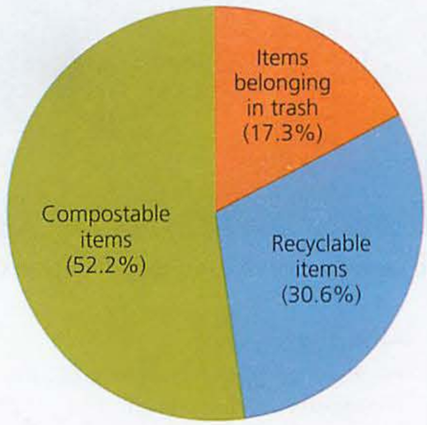


FIGURE 1 At the University of Washington, students found that most material in trashcans could be recycled or composted. As an example, the pie chart shows the average contents of trash from one floor of a building in 2014; only 17% was actually trash. *Data from UW Garbology Project.*

At Western Michigan University, students in Dr. Harold Glasser's course in 2012 audited food waste in three campus dining halls to test what strategies best minimized waste. They found that a dining hall providing made-to-order servings ended up with 0.23 lb/meal of wasted food, whereas a dining hall with a traditional buffet-style serving produced 0.27 lb/meal of food waste. A third dining hall, which featured trayless dining, performed best, showing only 0.18 lb/meal of waste. The students' data thus seemed to support the idea that people waste less food when trays are not provided.

Students and faculty on multiple campuses have also run manipulative experiments to determine how best to encourage recycling and reduce waste. Such research involves comparing data from an experimental treatment condition (such as after new recycling bins are introduced) with baseline conditions used as a control.

An early such study was that of behavioral scientist Timothy Ludwig and others, who in 1998 examined student behavior with recyclable aluminum drink cans at Appalachian State University. The researchers compared recycling rates when recycling bins were in the hallways (the baseline condition) with recycling rates when the bins were brought into classrooms. Because many students consumed drinks in classrooms, the classroom location proved more convenient, and so recycling increased (**FIGURE 2**). This research showed that making recycling containers easier to find and more convenient to use can boost recycling rates.

Similar results were found by graduate student Ryan O'Connor and colleagues at University of Houston–Clear Lake in 2010. Sampling plastic drink bottles from trashcans and recycling bins in three academic buildings, they found that

Financial incentives help address waste

To encourage recycling, composting, and source reduction, waste managers frequently offer consumers economic incentives to reduce the waste stream. In "pay-as-you-throw" garbage collection programs, municipalities charge residents for home trash pickup according to the amount of trash they put out. The less waste one generates, the less one has to pay.

Bottle bills are another approach hinging on financial incentives. In the 10 U.S. states and 25 nations that have adopted these laws, consumers pay a deposit on bottles or cans upon purchase—often 5 or 10 cents per container—and

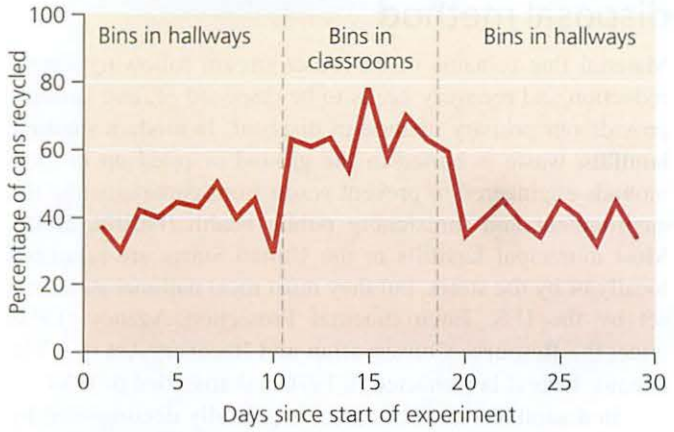


FIGURE 2 At Appalachian State University, recycling rates rose when recycling bins were moved from hallways to classrooms. *Data from Ludwig, T., et al., 1998. Increasing recycling in academic buildings: A systematic replication.* J. Appl. Behavior Analysis *31: 683–686.*

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making recycling bins more colorful or adding more bins had no effect on recycling rates but that moving the recycling bins from hallways and common areas into classrooms increased recycling rates greatly.

In 2017, researchers at Western Michigan University challenged the idea that moving bins to places where people use recyclable items was necessarily the best solution. Instead, graduate student Katherine Binder and others tested the hypothesis that removing all trash cans and recycling bins from classrooms and placing them together side-by-side only in common areas (hallways) would lead to better recycling rates. Within a single campus building, these researchers compared recycling rates on floors where this was done with recycling rates on floors where trash cans and recycling bins were left in the classrooms. Their data supported their hypothesis: Recycling rates rose when trash cans and recycling bins were removed from classrooms, forcing people who needed to dispose of items to walk to centrally located areas, where they encountered clearly marked recycling and trash receptacles to choose between. The research team concluded that this strategy also reduced contamination from incorrectly sorted items and saved money because fewer receptacles were needed.

Researchers have also experimentally tested the influence of educational efforts on recycling behavior. At University of Wisconsin–Stout, student Jessica Van Der Werff ran an experiment in 2008 comparing recycling rates of freshmen who took a recycling workshop during freshman orientation with those who did not. Van Der Werff monitored the trash and recycling from two residence halls throughout the fall semester. She found that students from the residence hall who had attended the workshop showed nearly 40% higher recycling rates (**FIGURE 3**).

Taken together, campus research into waste management has revealed that we can increase recycling rates through education and the strategic location of bins. Students engaged in this work have generated many practical suggestions for reducing waste; they urge that campuses provide enough receptacles, clarify how to sort items correctly, and make it convenient and easy to recycle and compost. By taking such lessons to heart, every campus should be able to significantly reduce its waste stream.

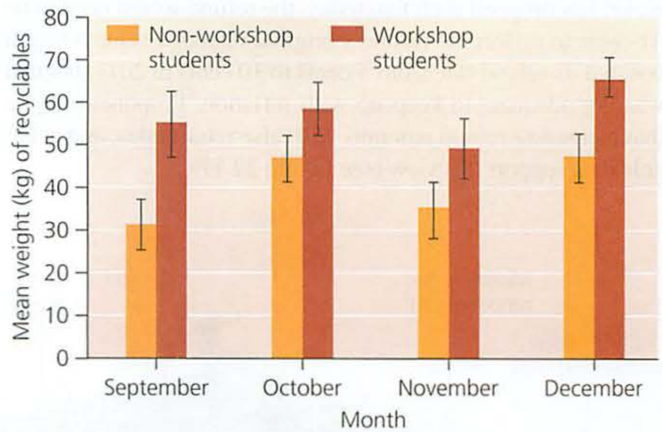

FIGURE 3 At University of Wisconsin–Stout, students who took a workshop on recycling recycled items at a higher rate than those who did not. *Data from Van Der Werff, J., 2008.* Teaching recycling: The relationship between education and behavior among college freshmen and its effect on campus recycling rates. *Undergraduate project report, University of Wisconsin–Stout.*

then receive a refund when they return them to stores or recycling centers after use. The first bottle bills were passed in the 1970s to cut down on litter, but they have also served to decrease the waste stream. Beverage container recycling rates for states with bottle bills are 2.5 times higher than for states without them (**FIGURE 22.11**, p. 630). U.S. states with bottle bills report that their beverage container litter has decreased by 69–84%, their total litter has decreased by 30–65%, and their per capita container recycling rates have risen 2.6-fold.

States with bottle bills now face two challenges. One is to amend these laws to include new kinds of containers, particularly the proliferating diversity of plastic containers. The second challenge is to adjust refunds for inflation. In the half-century since Oregon passed the nation's first bottle bill, the value of a

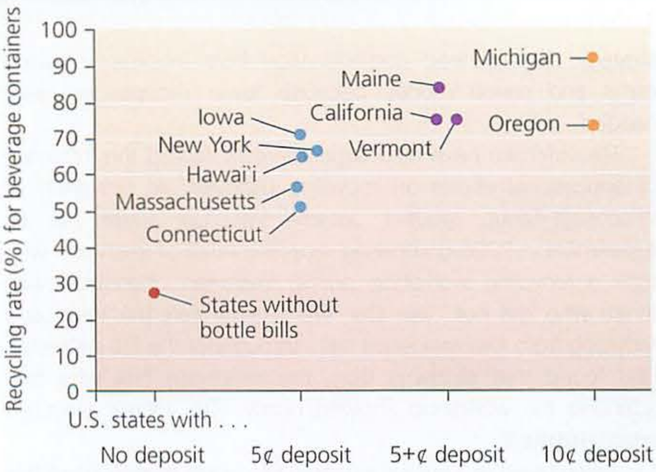

FIGURE 22.11 Bottle bills increase recycling rates, and higher redemption amounts boost these rates further, data suggest. States with bottle bills have much higher recycling rates for beverage containers than states without bottle bills. *Data from Container Recycling Institute, Arlington, VA, 2019.*

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nickel has dropped such that today, the refund would need to be 31 cents to reflect the refund's original intended value. Oregon boosted its refund rate from 5 cents to 10 cents in 2017, but that was not adequate to keep up with inflation. Proponents argue that increasing refund amounts will raise return rates, and available data support this view (see Figure 22.11).

Sanitary landfills are our main disposal method

Material that remains in the waste stream following source reduction and recovery needs to be disposed of, and landfills provide our primary method of disposal. In modern **sanitary landfills,** waste is buried in the ground or piled up in huge mounds engineered to prevent waste from contaminating the environment and threatening public health (**FIGURE 22.12**). Most municipal landfills in the United States are regulated locally or by the states, but they must meet national standards set by the U.S. Environmental Protection Agency (EPA) under the **Resource Conservation and Recovery Act** (p. 173), a major federal law enacted in 1976 and amended in 1984.

In a sanitary landfill, waste is partially decomposed by bacteria and compresses under its own weight to take up less space. Soil is layered along with the waste to speed decomposition, reduce odor, and lessen infestation by pests. Some infiltration of rainwater into the landfill is good, because it encourages biodegradation by bacteria—yet too much is not good, because contaminants can escape if water carries them out.

To protect against environmental contamination, U.S. regulations require that landfills be located away from wetlands and earthquake-prone faults and be at least 6 m (20 ft) above the water table. The bottoms and sides of sanitary landfills must be lined with heavy-duty plastic and 60–120 cm (2–4 ft) of impermeable clay to help prevent contaminants from seeping into aquifers. Sanitary landfills also have systems of pipes, collection ponds, and treatment facilities to collect and treat **leachate,** liquid that results when

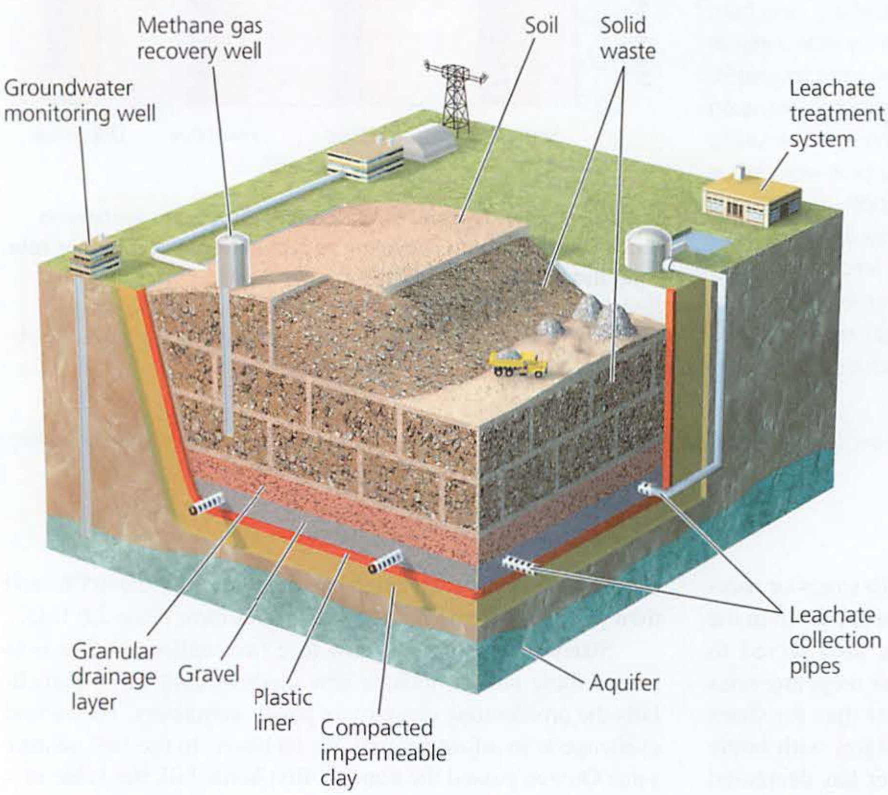


FIGURE 22.12 Sanitary landfills are engineered to prevent waste from contaminating soil and groundwater. Waste is laid in a large depression lined with plastic and impervious clay designed to prevent liquids from leaching out. Pipes draw out these liquids from the bottom of the landfill. Waste is layered with soil, filling the depression, and then is built into a mound until the landfill is capped. Landfill gas produced by anaerobic bacteria may be recovered, and waste managers monitor groundwater for contamination.

FAQ

How much does garbage decompose in a landfill?

You might assume that a banana peel you throw in the trash will soon decay away to nothing in a landfill. However, it just might survive longer than you do! That's because surprisingly little decomposition occurs in landfills. Researcher William Rathje, a retired archaeologist known as the "Indiana Jones of Solid Waste," made a career out of burrowing into landfills and examining their contents to learn about what we consume and what we throw away. His research teams would routinely come across whole hot dogs, intact pastries that were decades old, and grass clippings that were still green. Newspapers 40 years old were often still legible, and the researchers used them to date layers of trash.

substances from the trash dissolve in water as rainwater percolates downward.

Once a landfill is closed, it is capped with an engineered cover consisting of layers of plastic, gravel, and soil. Managers are required to maintain leachate collection systems for 30 years after a landfill has closed, and regulations require that groundwater be monitored regularly for contamination.

Despite improvements in liner technology and landfill siting, however, liners can be punctured, and leachate collection systems eventually cease to be maintained. Moreover, landfills are kept dry to reduce leachate, but the bacteria that break down material thrive in wet conditions. Dryness, therefore, slows waste decomposition. In fact, the low-oxygen conditions of most landfills turn trash into a sort of time capsule. Researchers examining landfills often find some of their contents perfectly preserved, even after years or decades.

In 1988, the United States had nearly 8000 landfills, but today it has fewer than 1800. Waste managers have consolidated the waste stream into fewer landfills of larger size. In many cities, landfills that were closed are now being converted into public parks or other uses (**FIGURE 22.13**). The world's largest landfill conversion project is at New York City's former Fresh Kills Landfill. This site, on Staten Island, was the primary repository of New York City's garbage for half a century, and its mounds rose higher than the nearby Statue of Liberty. Today, New York is transforming the site into a world-class public park—a verdant landscape of ball fields, playgrounds, jogging trails, rolling hills, and wetlands teeming with wildlife that, once completed, will be almost three times bigger than Central Park.

Incinerating trash reduces pressure on landfills

Just as sanitary landfills are an improvement over open dumping, incineration in specially constructed facilities is better than open-air burning of trash. **Incineration,** or combustion, is a controlled process in which garbage is burned at very high temperatures (**FIGURE 22.14**, p. 632). At incineration facilities, waste is generally sorted and metals are removed. Metal-free waste is chopped into small pieces to aid combustion and then is burned in a furnace. Incinerating waste reduces its weight by up to 75% and its volume by up to 90%.

The ash remaining after trash is incinerated contains toxic components and therefore must be disposed of in hazardous-waste landfills (p. 637). Moreover, when trash is burned, hazardous chemicals—including dioxins, heavy metals, and polychlorinated biphenyls (PCBs) (Chapter 14)—may be created and released into the atmosphere. Such emissions inspired a backlash against incineration from citizens concerned about health hazards.

Most industrialized nations now regulate incinerator emissions, and some have banned incineration outright. Engineers have also developed technologies to reduce emissions. Scrubbers (see Figure 17.12, p. 460) chemically treat the gases produced in combustion to remove hazardous components and neutralize acidic gases, such as sulfur dioxide and hydrochloric acid, turning them into water and salt.

FIGURE 22.13 Old landfills, once capped, can serve other purposes. Visitors to Freshkills Park in New York City can enjoy a panoramic view of the Manhattan skyline from atop what used to be an immense mound of trash.

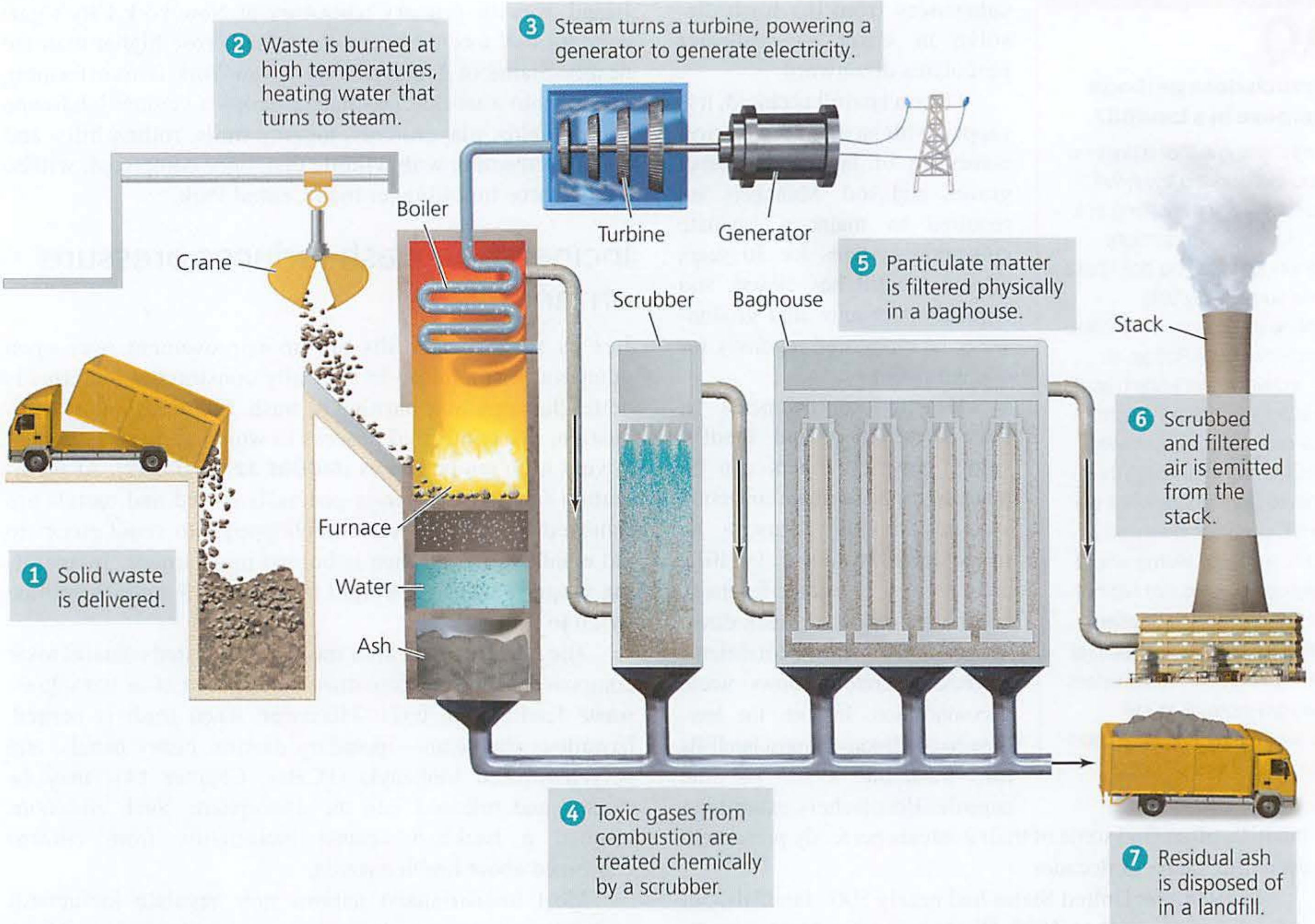


FIGURE 22.14 In a waste-to-energy (WTE) incinerator, solid waste is combusted, greatly reducing its volume and generating electricity at the same time.

WEIGHING **the issues**

Environmental Justice?

Do you know where your trash goes? Where is your landfill or incinerator located? Are the people who live closest to this facility wealthy, poor, or middle-class? What ethnicity are they? How might individuals or communities be compensated for the drawbacks of living near a waste disposal facility?

Scrubbers generally accomplish this either by spraying liquids formulated to neutralize the gases or by forcing the gases through dry lime.

Particulate matter, called *fly ash,* contains some of the worst dioxin and heavy metal pollutants in incinerator emissions. To physically remove these tiny particles, facilities may use a huge system of filters known as a *baghouse*. In addition, burning garbage at especially high temperatures can destroy certain pollutants, such as PCBs. Even all these measures, however, do not fully eliminate toxic emissions.

We can gain energy from trash

Incineration reduces the volume of waste, but it can serve to generate electricity as well. Most incinerators now are in fact **waste-to-energy** (WTE) **facilities,** which use the heat produced by waste combustion to boil water, creating steam that drives electricity generation or that fuels heating systems. When burned, waste generates about 35% of the energy generated by burning coal. Roughly 80 WTE facilities are operating across the United States (mostly in the Northeast and South), with a total capacity to process 95,000 tons of waste per day.

Revenues from power generation, however, are often not enough to offset the considerable financial cost of building and running incinerators. Because it can take many years for a WTE facility to become profitable, companies that build and operate these facilities sometimes require communities contracting with them to guarantee the facility a minimum amount of garbage. On occasion, such long-term commitments have interfered with communities' subsequent efforts to reduce their waste through recycling and source reduction.

Combustion in WTE plants is not the only way to gain energy from waste. Deep inside landfills, bacteria decompose waste in an oxygen-deficient environment. This anaerobic decomposition produces **landfill gas,** a mix of gases roughly half of which is methane (pp. 28, 530). Landfill gas can be collected, processed, and used in the same way as natural gas (p. 530). Today, hundreds of landfills are collecting landfill gas and selling it for energy.

We can recycle material from landfills

Landfills can offer us useful by-products beyond landfill gas. With improved technology for sorting rubbish and recyclables, businesses and entrepreneurs are weighing the economic benefits and costs of rummaging through landfills to salvage materials of value that can be recycled. Steel, aluminum, copper, and other metals are abundant enough in some landfills to make salvage operations profitable when market prices for the metals are high enough. For instance, Americans throw out so many aluminum cans that at 2019 prices for aluminum, the nation buries $5.5 billion of this metal in landfills each year. If we could retrieve all the aluminum from U.S. landfills, it would exceed the amount the world produces from a year's worth of mining ore.

Landfills also offer soil mixed with organic waste that can be mined and sold as premium compost. In addition, old landfill waste can be incinerated in newer, cleaner-burning WTE facilities to produce energy. Some companies are even looking into gaining carbon offset credits (p. 518) by harvesting methane (a greenhouse gas that contributes to climate change) leaking from open dumps in developing nations.

Such approaches have been tried in places from New York to Israel to Sweden to Singapore. The costs of mining landfills and meeting regulatory requirements while commodity prices change unpredictably have meant that investing in landfill mining has been risky, but that could change in the future if prices of commodities rise and landfill mining technologies improve.

Industrial Solid Waste

Industrial solid waste includes waste from factories, agriculture, ore mining, petroleum extraction, and more. Each year, industrial facilities in the United States generate more than 7 billion tons of waste, according to the EPA, about 97% of which is wastewater. Thus, very roughly, 230 million or so tons of solid waste are generated by 60,000 facilities each year—an amount approaching that of municipal solid waste.

Regulation and economics each influence industrial waste generation

Most methods and strategies of waste disposal, reduction, and recycling by industry are similar to those for municipal solid waste. Businesses that dispose of their own waste on site must design and manage their landfills in ways that meet state, local, or tribal guidelines. Other businesses pay to have their waste disposed of at municipal disposal sites. Whereas the federal government regulates municipal solid waste, it is state or local governments that regulate industrial solid waste (with federal guidance). Regulation varies greatly from place to place, but in most cases, state and local regulation of industrial solid waste is less strict than federal regulation of municipal solid waste. In many areas, industries are not required to have permits, install landfill liners or leachate collection systems, or monitor groundwater for contamination.

The amount of waste generated by a manufacturing process is a good measure of its efficiency; the less waste produced per unit or volume of product, the more efficient that process is, from a physical standpoint. However, physical efficiency is not always reflected in economic efficiency. Often it is cheaper for industry to manufacture its products or perform its services quickly but messily. That is, it can be cheaper to generate waste than to avoid generating waste. In such cases, economic efficiency is maximized, but physical efficiency is not. Because our market system awards only economic efficiency, often industry has no financial incentive to achieve physical efficiency. The frequent mismatch between these two types of efficiency is a major reason the output of industrial waste is so great.

Rising costs of waste disposal enhance the financial incentive to decrease waste. Once either the government or the market makes the physically efficient use of raw materials economically efficient as well, businesses will gain financial incentives to reduce their waste.

Industrial ecology seeks to make industry more sustainable

To reduce waste, growing numbers of industries today are experimenting with industrial ecology. A holistic approach that integrates principles from engineering, chemistry, ecology, and economics, **industrial ecology** seeks to redesign industrial systems to reduce resource inputs and to maximize both physical and economic efficiency. Industrial ecologists would reshape industry so that nearly everything produced in a manufacturing process is used, either within that process or in a different one (see **SUCCESS STORY**, p. 635).

The larger idea behind industrial ecology is that industrial systems should function more like ecological systems, in which organisms use almost everything that is produced. This principle brings industry closer to the ideal of ecological economists, in which economies function in a circular fashion rather than a linear one (p. 147). It means taking a cradle-to-cradle approach, in which products and manufacturing systems are designed to maximize reuse and recycling of materials into new products.

Industrial ecologists pursue their goals in several ways:

- They examine the entire life-cycle of a given product—from its origins in raw materials, through its manufacturing, to its use, and finally to its disposal—and look for ways to make the process more efficient. This strategy is called **life-cycle analysis** (p. 267).
- They try to identify how waste products from one manufacturing process might be used as raw materials for another. For instance, used plastic beverage containers can be shredded and reprocessed to make items such as benches, tables, and decks.
- They seek to eliminate environmentally harmful products and materials from industrial processes.
- They study the flow of materials through industrial systems to look for ways to create products that are more durable, recyclable, or reusable. For instance, they seek to design computers, automobiles, and appliances to be easily disassembled so more of their components can be reused or recycled.

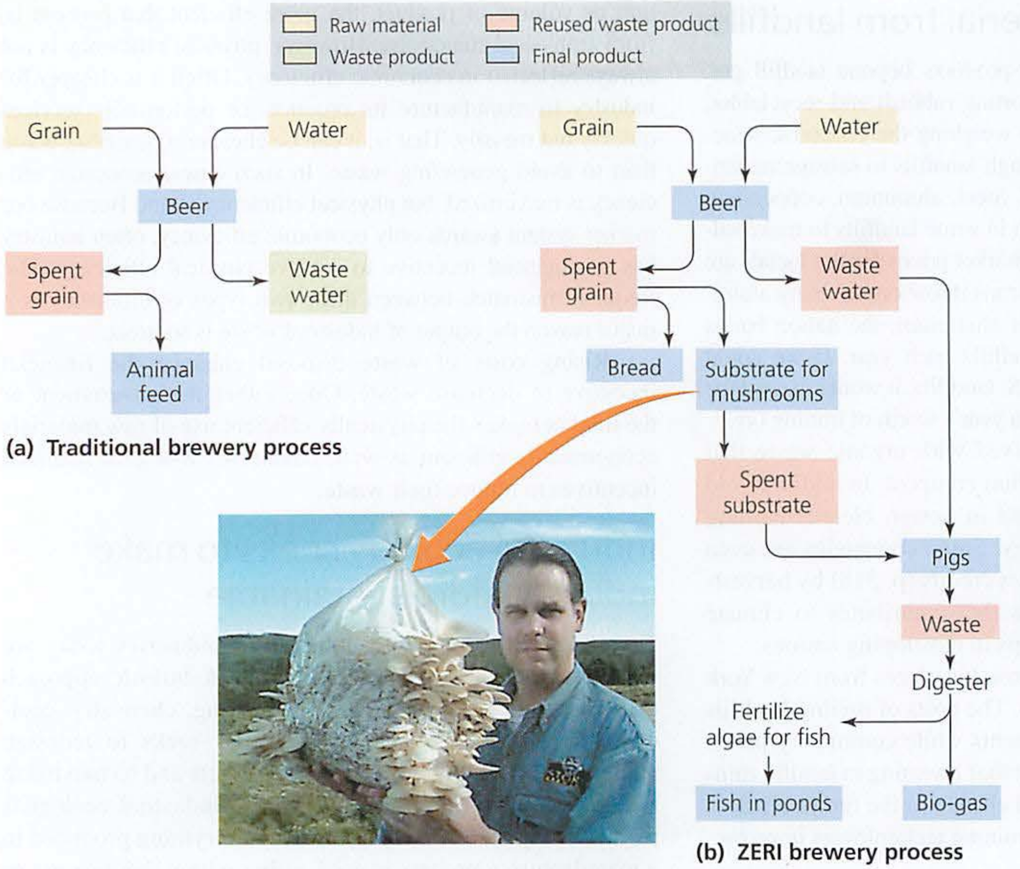


FIGURE 22.15 Creative use of waste products can help us approach zero-waste systems. Traditional breweries **(a)** produce only beer while generating much waste, some of which goes toward animal feed. Breweries sponsored by the Zero Emissions Research and Initiatives (ZERI) Foundation **(b)** use their waste grain to make bread and to farm mushrooms **(photo).** Waste from the mushroom farming, along with brewery wastewater, goes to feed pigs. The pigs' waste is digested in containers that capture natural gas and collect nutrients used to nourish algae for growing fish in fish farms. The brewer derives income from bread, mushrooms, pigs, gas, and fish, as well as beer.

Businesses are adopting industrial ecology

Attentive businesses are taking advantage of the insights of industrial ecology to save money while reducing waste. For example, American Airlines switched from hazardous to non-hazardous materials in its Chicago facility, decreasing its need to secure permits from the EPA. The company used more than 50,000 reusable plastic containers to ship goods, reducing packaging waste by 90%. Its Dallas–Fort Worth headquarters recycled enough aluminum cans and white paper in five years to save $205,000 and recycled 3000 broken baggage containers into lawn furniture. A program to gather suggestions from employees brought more than 700 ideas to reduce waste—and 15 of these ideas saved the company more than $8 million.

The Swiss Zero Emissions Research and Initiatives (ZERI) Foundation sponsors dozens of innovative projects worldwide that attempt to create goods and services without generating waste. One example involves breweries in Canada, Sweden, Japan, and Namibia. Brewers in these projects take waste from the beer-brewing process and use it to fuel other processes (**FIGURE 22.15**). As a result, the brewer can make money from bread, mushrooms, pigs, gas, and fish, as well as beer, all while producing little waste. By attempting to create closed-loop systems, ZERI projects cut down on waste while increasing output and income, often generating new jobs as well.

Few businesses have taken industrial ecology to heart as much as the Atlanta-based international modular carpet tile company Interface, which founder Ray Anderson set on the road to sustainability years ago. Interface asks customers to return used carpet tiles for recycling and for reuse as backing for new carpet. It modified its design and production methods to reduce waste. It adapted its boilers to use landfill gas for energy. Through such steps, Anderson's company cut its waste generation by 80%, its fossil fuel use by 45%, and its water use by 70%—all while saving $30 million per year, holding prices steady for its customers, and raising profits by 49%.

Hazardous Waste

Hazardous wastes are diverse in their chemical composition and may be liquid, solid, or gaseous. By EPA definition, hazardous waste is waste that is one of the following:

- *Ignitable.* Likely to catch fire (e.g., gasoline or alcohol).
- *Corrosive.* Apt to corrode metals in storage tanks or equipment (e.g., strong acids or bases).
- *Reactive.* Chemically unstable and readily able to react with other compounds, often explosively or by producing noxious fumes (e.g., ammonia reacting with chlorine bleach).
- *Toxic.* Harmful to human health when inhaled, ingested, or touched (e.g., pesticides or heavy metals).

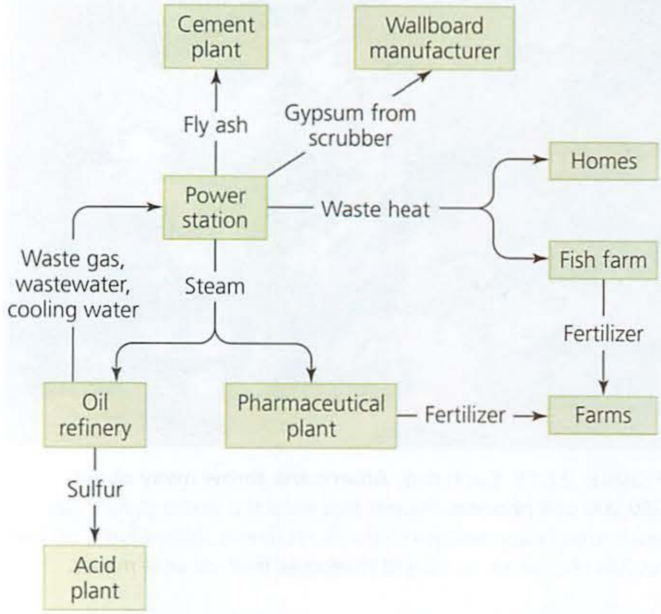
Hazardous wastes are diverse

Industry, mining, households, small businesses, agriculture, utilities, and building demolition all create hazardous waste. Industry produces the most, but in developed nations, industrial

SUCCESS story

Creating an Industrial Ecosystem

One place the ideals of industrial ecology have come to life is the city of Kalundborg, Denmark. Here, starting in 1972, dozens of private and public enterprises gradually formed a network of business relationships that are conserving resources while saving money. Anchoring the Kalundborg Eco-Industrial Park is a coal-fired power plant, the Asnaes Power Station. It sends its excess steam to a nearby Statoil petroleum refinery and a Novo-Nordisk pharmaceutical factory, which use the steam to run their operations. The Statoil refinery sends Asnaes its wastewater, cooling water, and waste gas, which the power plant uses to generate electricity, and sells sulfur to a local acid manufacturer. The power plant sends its waste fly ash to a cement company and sells gypsum removed from its waste gas by a scrubber to a Gyproc factory that makes drywall. Power plants also routinely create large amounts of waste heat, and in Kalundborg, this heat is piped to more than 3000 homes as district heating and to a regional fish farm. Treated sludge from both the fish farm and the pharmaceutical plant is sent to area farms as fertilizer. By efficiently using one another's waste products, the Kalundborg Eco-Industrial Park has reduced pollution, cut greenhouse gas emissions, and conserved resources such as water, coal, and oil—all while saving hundreds of millions of dollars for the enterprises involved.



In a model for industrial ecology, networked enterprises in Kalundborg, Denmark, use one another's waste materials as resources.

→ **Explore the Data** at Mastering Environmental Science

waste disposal is often highly regulated. This regulation has reduced the amount of hazardous waste entering the environment from industrial activities. As a result, households are now the largest source of unregulated hazardous waste.

Household hazardous waste includes a wide range of items, including paints, batteries, oils, solvents, cleaning agents, lubricants, and pesticides. Americans generate 1.6 million tons of household hazardous waste annually, and the average home contains close to 45 kg (100 lb) of it in sheds, basements, closets, and garages. Although many hazardous substances become less hazardous over time as they degrade chemically, two types are particularly hazardous because their toxicity persists over time: organic compounds and heavy metals.

Organic compounds and heavy metals pose hazards

In our daily lives, we rely on synthetic organic compounds (human-made carbon-based chemicals) and compounds derived from petroleum to resist bacterial, fungal, and insect activity. Plastic containers, rubber tires, pesticides, solvents, and wood preservatives are useful to us precisely because they resist decomposition. We use these products to protect buildings from decay, kill pests that attack crops, and keep stored goods intact. However, the capacity of the compounds in these products to resist decay is a double-edged sword, for it also makes them persistent pollutants. Many synthetic organic compounds are toxic because they are readily absorbed through the skin and can act as mutagens, carcinogens, teratogens, and endocrine disruptors (p. 370).

Heavy metals such as lead, chromium, mercury, arsenic, cadmium, tin, and copper are used widely in industry for wiring, electronics, metal plating, metal fabrication, pigments, and dyes. Heavy metals enter the environment when paints, electronic devices, batteries, and other materials are disposed of improperly. Lead from fishing weights and from hunting ammunition accumulates in rivers, lakes, and forests. In older homes, lead from pipes contaminates drinking water, and lead paint remains a toxic problem, especially for infants and children who encounter lead paint in their home environments. Heavy metals that are fat-soluble and break down slowly are prone to bioaccumulate and biomagnify (p. 373). In California's Coast Range, for instance, mercury that has washed downstream from abandoned mercury mines enters lakes and rivers, is consumed by bacteria and invertebrates, and accumulates in increasingly large quantities up the food chain, poisoning organisms at higher trophic levels and making fish unsafe to eat.

E-waste has grown

Today's proliferation of computers, printers, smartphones, tablets, TVs, and other electronic technology has created a

FIGURE 22.16 Each day, Americans throw away about 350,000 cell phones. Phones that enter the waste stream can leach toxic heavy metals into the environment. Alternatively, we can recycle phones for reuse and to recover their valuable metals.

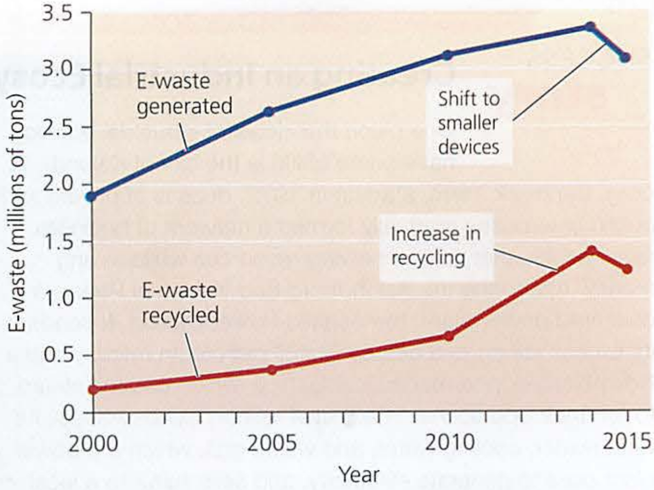


FIGURE 22.17 Increasing amounts of electronic waste are being recycled. The total amount of electronic waste generated each year in the United States has risen, but the shift to mobile devices and tablets has helped decrease this amount since 2011. *Data from U.S. Environmental Protection Agency.*

substantial new source of waste (**FIGURE 22.16**). These products have short life spans before people judge them obsolete, and most are discarded after just a few years. The amount of this **electronic waste**—often called **e-waste**—has grown rapidly and now makes up more than 1% of the U.S. solid waste stream by weight. More than 7 billion electronic devices have been sold in the United States since 1980, and U.S. households discard more than 300 million per year—two-thirds of them still in working order.

Most electronic items we discard have ended up in conventional sanitary landfills and incinerators. However, electronic products contain heavy metals and toxic flame-retardants, and research indicates that e-waste is hazardous and should be treated as such. The EPA and a number of states are now taking steps to keep e-waste out of conventional landfills and incinerators and instead redirect it to hazardous-waste sites.

Fortunately, the downsizing of many electronic items and the shift toward mobile devices and tablets mean that fewer raw materials by weight are now going into electronics being manufactured—and as a result, U.S. e-waste generation appears to have recently leveled off. In addition, more and more electronic waste today is being recycled (**FIGURE 22.17**; and see **Success Story** in Chapter 23, p. 659). Americans now recycle 40% of their e-waste, by weight. Increasingly, used electronics are collected by businesses, nonprofit organizations, or municipal services and are processed for reuse or recycling. Campus e-waste recycling drives are proving especially effective (see Table 1.3, p. 18).

Devices collected for recycling are shipped to facilities and taken apart, and the parts and materials are refurbished and reused in new products. There are serious concerns, however, about health risks that recycling may pose to workers doing the disassembly. Wealthy nations ship much of their e-waste to developing countries, where low-income workers disassemble the devices and handle toxic materials with minimal safety regulations. Environmental justice and workplace safety concerns will need to be resolved if electronic recycling is to be conducted safely and responsibly.

Another challenge is that the recent conversion of television and computer monitor technology from cathode-ray tubes to LCD and plasma screens has meant that there is no longer much demand for recycled cathode-ray tubes. As a result, old cathode-ray tubes (rich in toxic lead) are piling up in recyclers' warehouses and are at risk of never being recycled.

Besides keeping toxic substances out of our waste stream, e-waste recycling helps us recover rare and lucrative trace metals used in electronics. A typical cell phone contains up to a dollar's worth of precious metals (p. 659). By one estimate, 1 ton of computer scrap contains more gold than 16 tons of mined ore from a gold mine, and 1 ton of iPhones contains more than 300 times more. Every ounce of metal we can recycle from a manufactured item is an ounce of metal we don't need to mine from the ground. Thus, "mining" e-waste for metals helps reduce the environmental impacts of mining the earth. For example, several recent Olympic Games have produced their gold, silver, and bronze medals (**FIGURE 22.18**) partly from metals recovered from recycled and processed e-waste!

We regulate the disposal of hazardous waste

For many years, we discarded hazardous waste without special treatment. In some cases, people did not know that certain substances were harmful to human health. In other cases, it was assumed that the substances would disappear or be sufficiently diluted in the environment. A number of well-publicized pollution incidents in the 1970s—such as the resurfacing of toxic chemicals in a residential area at Love Canal in upstate New York years after their burial—convinced the public that hazardous waste deserves special attention and treatment.

Many communities now designate sites or special collection days to gather household hazardous waste or designate

FIGURE 22.18 Medals for winning athletes at the 2020 Olympic Games in Tokyo, Japan, were made partly from precious metals recycled from discarded e-waste.

facilities for the exchange and reuse of hazardous substances (**FIGURE 22.19**). Once consolidated, the hazardous waste is transported for treatment and disposal.

Under the Resource Conservation and Recovery Act, the EPA sets standards by which states manage hazardous waste. The act also requires large generators of hazardous waste to obtain permits. Finally, it mandates that hazardous materials be tracked "from cradle to grave." As hazardous waste is generated, transported, and disposed of, the producer, carrier, and disposal facility must each report to the EPA the type and amount of material generated; its location, origin, and destination; and the way it is handled. This process is intended to prevent illegal dumping and to encourage the use of reputable waste carriers and disposal facilities.

Because current U.S. law makes disposing of hazardous waste quite costly, irresponsible companies sometimes illegally dump waste, creating health risks for residents and financial headaches for local governments forced to deal with the mess (**FIGURE 22.20**). At the international scale, companies from industrialized nations often find it cheaper to pay cash-strapped developing nations to take hazardous waste—or cheaper still, to dump it illegally. In nations with lax environmental and health regulations, workers and residents are often uninformed of or unprotected from the health dangers of this waste. This global environmental justice issue (p. 139) continues despite the Basel Convention, an international treaty crafted to limit such practices.

High costs of disposal, however, have also encouraged conscientious businesses to invest in reducing their hazardous waste. Many hazardous materials can be broken down by incineration at high temperatures in cement kilns. Other hazardous materials can be treated with bacteria that break down harmful components and synthesize them into new compounds. In a process called **bioremediation** (p. 30), various plants, fungi, and microbes have been used (and sometimes specially bred or engineered) to take up specific contaminants from soil and then break down organic contaminants into safer compounds or concentrate heavy metals in their tissues. The organisms are eventually harvested and disposed of.

FIGURE 22.19 Many communities designate collection sites or collection days for household hazardous waste. Here, workers handle waste from a collection event in Brooklyn, New York.

We use three disposal methods for hazardous waste

We have developed three primary means of hazardous-waste disposal: landfills, surface impoundments, and injection wells. These methods do nothing to diminish the hazards of the substances, but they help keep the waste isolated from people, wildlife, and ecosystems. Design and construction standards for landfills that receive hazardous waste are stricter than those for ordinary sanitary landfills. Hazardous waste landfills must have several impervious liners and leachate removal systems and must be located far from aquifers.

FIGURE 22.20 Unscrupulous individuals and businesses sometimes dump hazardous waste illegally to avoid disposal costs.

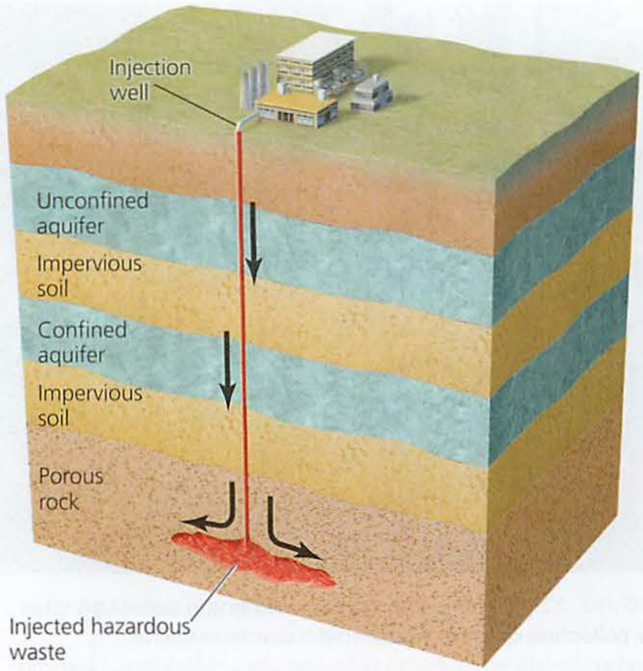


FIGURE 22.21 Liquid hazardous waste is pumped deep underground by deep-well injection. The well must be drilled below any aquifers, into porous rock isolated by impervious clay.

Liquid hazardous waste, or waste in dissolved form, may be stored in **surface impoundments,** shallow depressions lined with plastic and an impervious material, such as clay. The liquid or slurry is placed in the pond and water is allowed to evaporate, leaving a residue of solid hazardous waste on the bottom. This process is repeated, and eventually the dry residue is removed and transported elsewhere for permanent disposal. Impoundments are not ideal. The underlying layer can crack and leak waste. Some material may evaporate or blow into surrounding areas. Rainstorms may cause waste to overflow and contaminate nearby areas. For these reasons, surface impoundments are used only for temporary storage.

In **deep-well injection,** a well is drilled deep beneath the water table into porous rock, and wastes are injected into it (**FIGURE 22.21**). The process aims to keep waste deep underground, isolated from groundwater and human contact. However, wells can corrode and can leak wastes into soil, contaminating aquifers, and deep-well injection may very occasionally induce earthquakes. Roughly 34 billion L (9 billion gal) of hazardous waste are placed in U.S. injection wells each year.

Radioactive waste is especially hazardous

Radioactive waste is particularly dangerous to human health and is persistent in the environment. The dilemma of disposal has dogged the nuclear energy industry for decades (p. 572). The United States has no designated site to dispose of its commercial nuclear waste if Yucca Mountain in Nevada is removed from consideration (p. 573). Instead, waste will continue to accumulate at the many nuclear power plants spread throughout the nation (see Figure 20.12, p. 573).

Currently, a site in the Chihuahuan Desert in New Mexico serves as a permanent disposal location for radioactive waste from military sources. The Waste Isolation Pilot Plant was the world's first underground repository for transuranic waste from nuclear weapons development. The mined caverns holding the military waste are located 655 m (2150 ft) below ground in a huge salt formation thought to be geologically stable. This site became operational in 1999 and receives shipments of waste from 23 other locations.

Contaminated sites are being cleaned up, slowly

Many thousands of former military and industrial sites remain contaminated with hazardous waste in the United States and virtually every other nation on Earth. For most nations, dealing with these messes is simply too difficult, time-consuming, and expensive. In 1980, however, the U.S. Congress passed the Comprehensive Environmental Response Compensation and Liability Act (CERCLA; p. 173). This law established a federal program to clean up U.S. sites polluted with hazardous waste. The EPA administers this cleanup program, called the **Superfund.** Under EPA auspices, experts identify sites polluted with hazardous chemicals, take action to protect groundwater, and clean up the pollution. Later laws also charged the EPA with cleaning up **brownfields,** lands whose reuse or development is complicated by the presence of hazardous materials.

High-profile events in two locations received extensive media coverage and were instrumental in leading to the Superfund legislation. Outside of Louisville, Kentucky, at a site called *Valley of the Drums,* hazardous waste began leaking from 100,000 metal drums, contaminating waterways with 140 types of chemicals. And in *Love Canal,* a residential neighborhood in Niagara Falls, New York, more than 800 families were evacuated in 1978–1980 after toxic chemicals buried by a company and the city in past decades rose to the surface (**FIGURE 22.22**). The chemicals contaminated homes and an elementary school and apparently led to birth defects, miscarriages, and other health impacts.

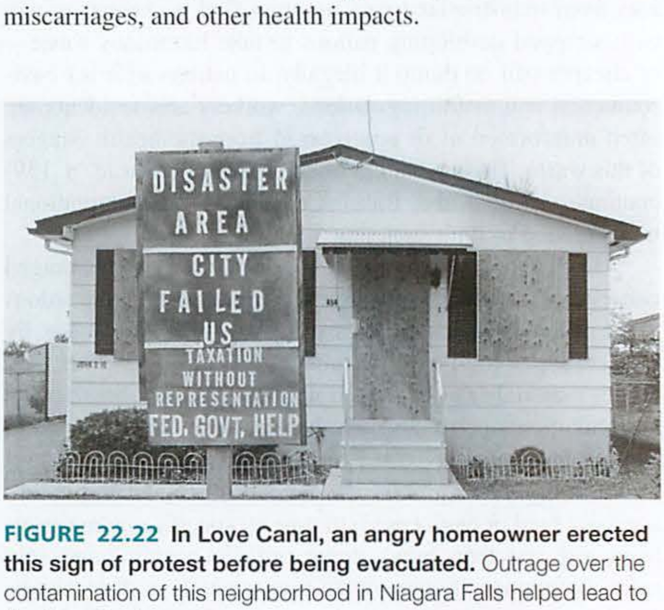


FIGURE 22.22 In Love Canal, an angry homeowner erected this sign of protest before being evacuated. Outrage over the contamination of this neighborhood in Niagara Falls helped lead to the Superfund program.

Once a Superfund site is identified, EPA scientists evaluate how near the site is to homes, whether wastes are confined or likely to spread, and whether the pollution threatens drinking water supplies. Sites judged to be harmful are placed on the National Priorities List and ranked according to the risk to human health that they pose. Cleanup proceeds as funds are available. Throughout the process, the EPA is required to hold public hearings to inform area residents of its findings and to receive feedback.

The objective of CERCLA was to charge the polluting parties for the cleanup of their sites, according to the *polluter-pays principle* (p. 165). For many sites, however, the responsible parties cannot be found or held liable, and in such cases—roughly 30% so far—cleanups have been covered by taxpayers and from a trust fund established by a federal tax on industries producing petroleum and chemical raw materials. Congress let the tax expire, however, and the trust fund went bankrupt in 2004, so taxpayers are now shouldering the entire burden. As the remaining cleanup jobs become more expensive, fewer are being completed.

As of 2019, 1337 Superfund sites remained on the National Priorities List, and only 413 had been cleaned up or otherwise removed from the list. The average cleanup has cost more than $25 million and has taken nearly 15 years. Many sites are contaminated with hazardous chemicals we have no effective way to deal with. In such cases, cleanups simply aim to isolate waste from human contact, either by building trenches and barriers around a site or by excavating contaminated material and shipping it to a hazardous-waste disposal facility. For all these reasons, the current emphasis in the United States and elsewhere is on preventing hazardous-waste contamination in the first place.

CENTRAL CASE STUDY connect & continue

TODAY, our society can celebrate great progress in addressing its waste management challenges: Recycling and composting efforts now allow Americans to divert one-third of all solid waste away from disposal. Students on college and university campuses are making great contributions in accelerating these trends. The enthusiasm of students for recycling is apparent each year in the success of Recyclemania—and this competition is just the tip of the iceberg. Most campuses have their own recycling and waste reduction programs, which continue to grow and evolve as students and staff find new and innovative ways of inspiring people to reduce waste.

If you would like to encourage waste reduction efforts on your own campus, there are many sources of information and advice you can consult, most of them easily accessible online. Longtime campus sustainability leaders such as the American Association for Sustainability in Higher Education and the National Wildlife Federation's Campus Ecology program offer a plethora of online resources for waste reduction and many other pursuits. A number of private waste management companies, including the largest one in the United States, Waste Management, Inc., are now also teaming up with campuses to help with the logistics of creating and maintaining workable waste strategies and programs.

One new and active student-focused resource is the Post-Landfill Action Network (PLAN), a group connecting colleges and universities that want to work together to educate, inspire, and empower students to make positive change on their campuses. PLAN organizes an annual Students for Zero Waste Conference, as well as various workshops and events around the country. Established by students from the University of New Hampshire, the group now links several dozen U.S. schools.

Engagement and successes on campus have helped fuel advances in waste management throughout society at large. Still, our prodigious consumption habits continue to create voluminous amounts of products and packaging, some of which is difficult or impossible to recycle. Our waste management efforts are marked by a number of challenges, including the cleanup of Superfund sites, the safe disposal of hazardous and radioactive waste, the proliferation of plastics and electronic waste, and the need to respond to China's recent ban on imported recyclable materials. These dilemmas make clear that the best solution is to reduce our generation of waste and to pursue a cradle-to-cradle approach. Finding ways to reduce, reuse, and efficiently recycle the materials and goods that we use stands as a key ongoing challenge for our society.

- **CASE STUDY SOLUTIONS** Does your college or university participate in Recyclemania? If so, describe how it has done so, what events it has staged, how successful these events were, and how this success might be improved. If not, peruse the Recyclemania website (http://recyclemania.org), and describe how you think. your school might compete effectively in Recyclemania. What events, programs, or strategies do you think would be most effective on your campus to give it a shot at winning one of the categories in Recyclemania?

- **LOCAL CONNECTIONS** On your campus, what efforts are being made to encourage recycling? Is there a composting program? How do the dining halls deal with food waste? Does the campus host any waste reduction events? Is there a student group helping address waste issues? Consult several online sources, such as the ones discussed in this Connect & Continue section, to learn more about the wide range of activities and strategies that students, faculty, and staff are pursuing on many campuses to help reduce waste. What is being done on other campuses that your school is not doing? Describe at least three waste reduction strategies or activities you would like to see your campus pursue, and explain why. What would you need to do to get such an effort off the ground?

- **EXPLORE THE DATA** Recycling and composting have made great strides, but much more progress could be made. → **Explore Data** relating to the case study on **Mastering Environmental Science.**

REVIEWING Objectives

You should now be able to:

+ **Summarize major approaches to managing waste, and compare and contrast the types of waste we generate**

Source reduction, recovery, and disposal are the three main components of waste management. Source reduction is preferred, and recovery is the next best. Municipal solid waste comes from homes, institutions, and small businesses. Industrial solid waste comes from manufacturing, mining, agriculture, and petroleum extraction and refining. Hazardous waste is toxic, chemically reactive, flammable, or corrosive. (pp. 620–621)

+ **Discuss the nature and scale of the waste dilemma**

Developed nations generate far more waste than developing nations, but developed nations are beginning to decrease their waste, whereas waste in developing nations is increasing as population and consumption grow. (p. 622)

+ **Evaluate source reduction, reuse, composting, and recycling as approaches for reducing waste**

Reducing waste before it is generated is the best management approach. Reusing items helps reduce waste. Composting creates organic matter for gardening and farming, whereas recycling removes 26% of the U.S. waste stream. Bottle bills are one way in which financial incentives can motivate people to reduce waste. The economics of recycling are complex, however, and recent policy changes by China have increased challenges for recycling efforts by restricting international trade in recyclables. (pp. 623–630)

+ **Describe landfills and incineration as conventional waste disposal methods**

Sanitary landfills are our main disposal method. Properly built and maintained, they guard against contamination of groundwater, air, and soil. Incinerators reduce waste volume by burning it. Pollution control technology removes most pollutants from incinerator emissions, but some pollutants escape, and toxic ash needs to be disposed of in landfills. To make the most of our waste, we are harnessing energy from landfill gas and generating electricity from incineration, and we are also starting to recycle materials from landfills. (pp. 630–633)

+ **Discuss industrial solid waste and principles of industrial ecology**

Regulations differ, but industrial solid waste management is similar to that for municipal solid waste. Industrial ecology provides ways for industry to enhance efficiency and studies how industrial systems can mimic ecological systems with a cradle-to-cradle approach. (pp. 633–635)

+ **Assess issues in managing hazardous waste**

Organic compounds, heavy metals, electronic waste, and radioactive waste are common types of hazardous waste. Hazardous waste is regulated and monitored, yet illegal dumping occurs, and no fully satisfactory method of disposing of hazardous waste has yet been devised. The Superfund program cleans up hazardous-waste sites, but cleanup is a long and expensive process. (pp. 634–639)

SEEKING Solutions

1. How much waste do you generate? Look into your waste bin at the end of the day and categorize and measure the waste there. List all other waste you may have generated in other places throughout the day. How much of this waste could you have avoided generating? How much could have been reused or recycled?
2. Of the various waste management approaches covered in this chapter, which ones are your community or campus pursuing? Would you suggest pursuing any new approaches? If so, which ones, and why?
3. Can manufacturers and businesses benefit from source reduction if consumers were to buy fewer products as a result? How? Given what you know about industrial ecology, what do you think the future of sustainable manufacturing may look like?
4. **THINK IT THROUGH** You are the president of your college or university. Your students participate in Recyclemania each year and want you to make the school a leader in waste reduction and industrial ecology. Consider the industries and businesses in your community and the ways they interact with facilities on your campus. Bearing in mind the principles of industrial ecology, can you think of any novel ways in which your school and local businesses might mutually benefit from one another's services, products, or waste materials? Are there waste products from one business, industry, or campus facility that another might put to good use? What steps would you propose to take as president?
5. **THINK IT THROUGH** You are the CEO of a major corporation that produces containers for soft drinks and a wide variety of other consumer products. Your company's shareholders are asking that you improve the company's image—while not cutting into profits—by taking steps to reduce waste. What steps would you consider taking?

CALCULATING **Ecological Footprints**

For years, the "State of Garbage in America" survey has documented the capacity of Americans to generate prodigious amounts of municipal solid waste (MSW). According to the most recent survey, on a per capita basis, Missouri residents generate the least MSW (4.5 lb/day), and Hawai'i residents (and that state's many tourists) generate the most (15.5 lb/day). The average for the entire country is 6.8 lb MSW per person per day. Calculate the amount of MSW generated in 1 day and in 1 year by each of the groups listed, if they were to generate MSW at each of the rates shown in the table.

GROUPS GENERATING MUNICIPAL SOLID WASTE	AMOUNT OF MSW GENERATED, AT THREE PER CAPITA GENERATION RATES					
	U.S. AVERAGE (6.8 LB/DAY)		MISSOURI (4.5 LB/DAY)		HAWAI'I (15.5 LB/DAY)	
	DAY	YEAR	DAY	YEAR	DAY	YEAR
You	6.8	2482				
Your class						
Your state						
United States						
World						

Data from Shin, D., 2014. *Generation and disposition of municipal solid waste (MSW) in the United States—A national survey*. New York: Columbia University, Earth Engineering Center.

1. Suppose your town of 50,000 people has just approved construction of a landfill nearby. Estimates are that it will accommodate 1 million tons of MSW. Assuming that the landfill is serving only your town and that your town's residents generate waste at the U.S. average rate, for how many years will it accept waste before filling up? How much longer would a landfill of the same capacity serve a town of the same size in Missouri?
2. One study has estimated that the average world citizen generates 1.47 pounds of trash per day. How many times more does the average U.S. citizen generate?
3. The same study showed that the average resident of a low-income nation generates 1.17 pounds of waste per day and that the average resident of a high-income nation generates 2.64 pounds per day. Why do you think U.S. residents generate so much more MSW than people in other "high-income" countries, when standards of living in those countries are comparable?

Mastering Environmental Science

Students Go to **Mastering Environmental Science** for assignments, an interactive e-text, and the Study Area with practice tests, videos, and activities.

Instructors Go to **Mastering Environmental Science** for automatically graded activities, videos, and reading questions that you can assign to your students, plus Instructor Resources.