GRAND CHALLENGE 3:

Design a Future Without Pollution or Waste

In nature, waste is a resource. One organism's waste is repurposed to sustain another. Since the Industrial Revolution, human society has adopted a more linear model. Resources and energy are used to manufacture products, which are then used and ultimately discarded as waste when those products are no longer wanted (Figure 3-1). This linear model of "take-make-dispose" has been successful in providing affordable products to billions of people and advancing their standard of living. However, this production model generates over a billion tons of discarded products and by-products globally each year (see Box 3-1), and uses large amounts of energy and resources that are never recaptured. An analysis of five high-income countries found that one-half to three-quarters of annual resource inputs are returned to the environment as waste within a year.[159] Despite improved efficiency in the use of resources, the overall production of waste in many countries, including the United States, continues to increase.[160]

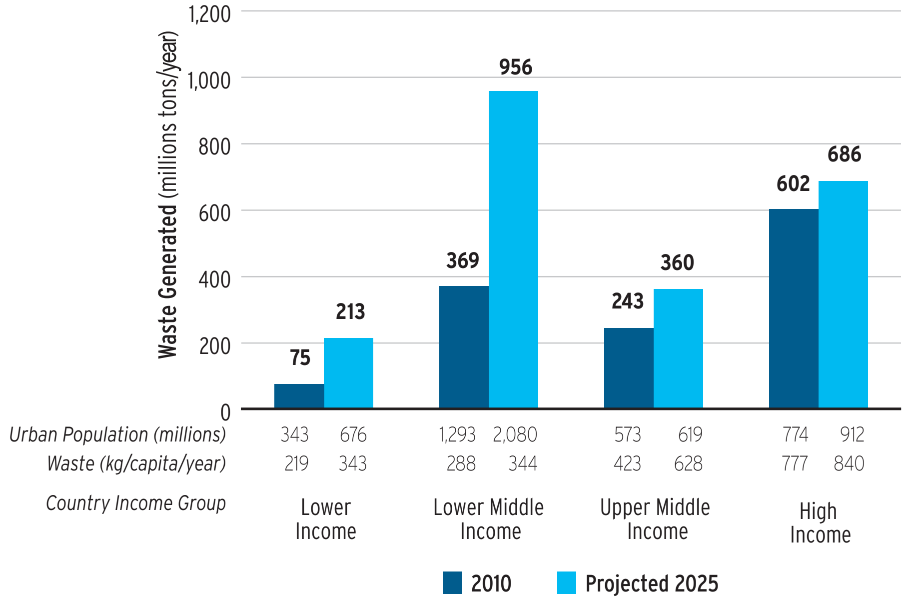
The "take-make-dispose" model introduces large amounts of pollutants into the water, soil, and air. Throughout much of the 20th century, large-scale chemical production combined with inappropriate chemical handling and waste disposal created a daunting array of legacy hazardous waste sites globally.[165] Technologies to characterize these sites and contain and remove hazardous contaminants have advanced significantly over the past three decades, and there have been many successes.[166] However, there remain at least 126,000 hazardous waste sites with residual contamination in the United States alone, about 12,000 of which are considered unlikely to be remediated to the point of unrestricted use with current technology. Some of these sites will require monitoring, treatment, and oversight in perpetuity.[167] Meanwhile, new concerns associated with legacy contaminants continue to be discovered (Box 3-2).

FIGURE 3-1. The linear model of resource extraction, manufacturing, consumption, and disposal ("take-make-dispose") dominates global economies. This model produces ever-increasing amounts of garbage while wasting resources and generating excess pollution.

BOX 3-1. RETHINKING CONSUMPTION AND WASTE

Energy, water, and food resources are routinely wasted along supply chains. For example, food waste includes harvest spillage or damage, losses during processing, and produce thrown away because of blemishes or spoilage (see Challenge 1). For computers and other electronic devices, waste is generated from mining raw materials and from manufacturing processes. Once in use, many end products do not take long to become waste themselves. The plastic sandwich bag that is manufactured from petroleum or the foil wrapper derived from refined bauxite ore are often used for a matter of hours before being discarded. The service life of electronic products continues to shrink due to technical advancement, style preferences, or planned obsolescence.

Globally, about 80 percent of consumer goods, excluding packaging, are disposed after a single use with no plan or ability to be reused, recycled, or biodegraded.[161] Municipal solid waste generated per year is expected to double by 2025[162] and triple by 2100.[163] This upward trajectory is occurring despite increases in recycling and reuse in the developed world primarily because the increasing size of the middle class, which accounts for the bulk of consumer goods spending (see figure below). In 2015, there were more than 3 billion people in the middle class worldwide, and by 2030, the middle class is anticipated to expand by another 2 billion people.[164] Much of this growth is in the developing world, where modern environmentally sound methods to manage waste are less common. Encouraging less consumption, developing product designs and manufacturing that minimizes waste, and increasing recycling and reuse globally is a major opportunity and responsibility of the environmental engineer that will preserve resources for future generations and reduce waste and pollution.



Current and projected urban waste generation by income level and year.

BOX 3-2. EMERGING CHALLENGES WITH LEGACY CONTAMINATION

New concerns associated with legacy contaminants continue to be discovered. For example, per- and polyfluoroalkyl substances (PFAS), which include over 3,000 compounds, have been produced worldwide since the 1940s for use as water-resistant coatings in manufacturing and in fire-fighting foams commonly used at military and civilian airports.[183] Over the past decade, these chemicals, sometimes called "forever chemicals" because they do not biodegrade, have been increasingly detected in surface water and groundwater, sometimes at levels exceeding the U.S. Environmental Protection Agency's (EPA's) lifetime health advisory level (70 ng/L, established based on exposure to two PFAS compounds).[184] Based on EPA sampling of public water supplies in the United States, up to 15 million people live in areas where their drinking water exceeds the EPA health advisory level.[185] However, in mid-2018, the Agency for Toxic Substances and Disease Registry stated in a draft toxicology risk assessment that the EPA level may be 7 to 10 times too high for two common PFAS compounds to protect against health risks.[186] Continued research is needed to determine the scope of the problem, assess the risks posed by the many different chemicals, and develop water treatment options where appropriate to inform policy decisions for use and management of these compounds.

Rapidly developing countries are also facing escalating environmental crises as a consequence of major economic growth without regard for socioenvironmental costs. A key example is China, where industrial development combined with insufficient environmental protection over the past three decades has resulted in widespread soil contamination. China's first national soil survey results are alarming: nearly 20 percent of agricultural lands are classified as polluted.[187] The pollution stems from atmospheric deposition of heavy metals and direct irrigation using industrial wastewater,[188] and human exposure is evidenced by heavy metal contamination in China's rice crop.[189] The scale of environmental cleanup needed to address this problem is similarly alarming, with cost estimates of China's current land remediation plan as much as $69 billion by 2020.[190]

Environmental engineers can help address legacy contamination problems using sustainable remediation approaches. These include stakeholder engagement and life-cycle analysis to identify the best long-term solutions that are socially acceptable and economically viable while minimizing negative side effects of cleanup activities, such as air pollution and ecosystem degradation.[191]

Over the past few decades, the amount of pollution produced by some industries and activities has dropped precipitously thanks to research and technology advances and effective policy interventions (see Challenge 5). For example, regulations on heavy-duty diesel fuel emissions, the development of ultra-low-sulfur diesel fuel, and new emission control technologies have helped reduce particulate matter and nitrogen oxide emissions by more than 90 percent in diesel truck and bus engines put into use since 2010 in the United States.[168] Nevertheless, large quantities of untreated sewage, industrial by-products, and vehicle emissions continue to find their way into the water, soil, and air.[169] Human activities are causing nitrogen and phosphorus to accumulate in bodies of water[170] and greenhouse gases to accumulate in the atmosphere (see Challenge 2).[171] Toxic chemicals have been detected in people and wildlife in every corner of the globe, from the Arctic wilderness to remote tropical islands.[172]

Because of improvements in living conditions, including water treatment, sanitation, and health care, the 20th century saw a doubling of life spans globally,[173] but pollution continues to have profound effects on human health. Pollution contributes

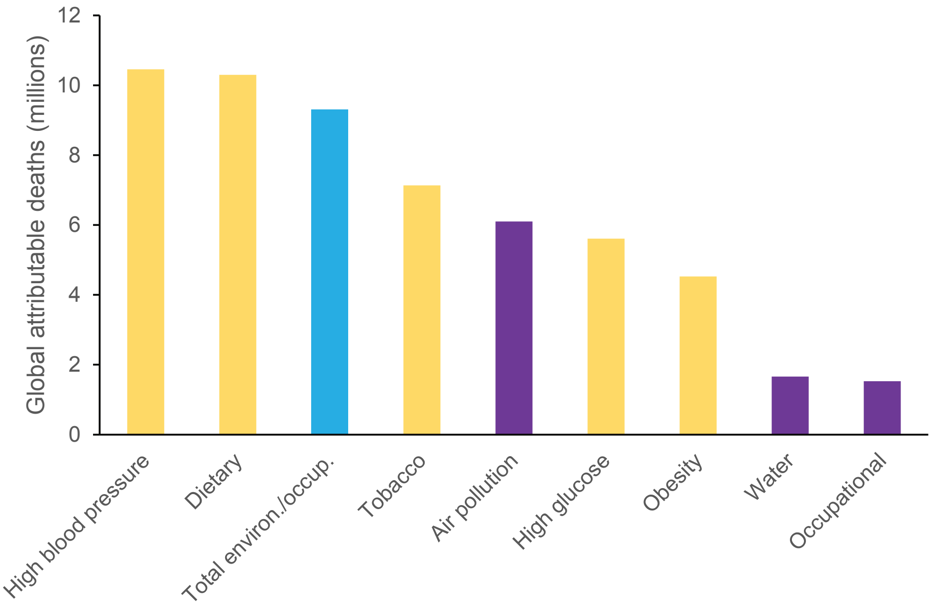


FIGURE 3-2. Global estimated deaths by risk factor and by total environmental and occupational causes (blue), which are disaggregated and shown individually in purple. Air pollution–attributable deaths are primarily linked to particulate matter pollution and indoor burning of solid fuels. Water-related risks are associated with diarrheal disease from unsafe water and poor sanitation. The estimated occupational deaths include 0.33 million from injury, but the remainder are from pollution-related causes, such as asbestos, carcinogens, and airborne particulate matter. The risk factors are not exclusive of one another.

to the leading causes of death worldwide including heart disease, stroke, and chronic lung disease. One of every six deaths in 2015—about 9 million deaths worldwide—can be attributed to disease from exposure to pollution (Figure 3-2).[174] Air pollution causes two-thirds of the premature pollution-related deaths, while unsafe drinking water and sanitation account for nearly 20 percent.[175] More than 90 percent of the world's population lives in areas where air quality does not meet health standards.[176] Although the problems are worse in low- and middle-income countries where the sources of air pollution are minimally controlled, air pollution is estimated to cause nearly 400,000 premature deaths annually in high-income countries.[177] Because these estimates do not account for compounds whose effects are not well characterized, for example, chemicals thought to cause endocrine disruption, the true toll of the health effects of chemicals is likely underestimated.

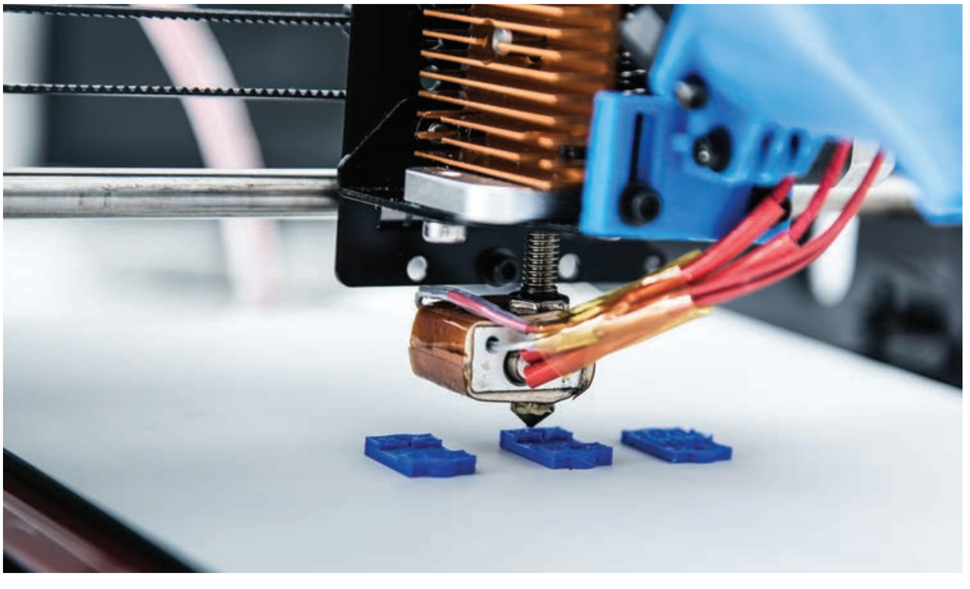
Pollution also harms natural ecosystems. Metals leaching into streams from abandoned mines have been linked with reduced biodiversity, and trace organic chemicals, such as pharmaceuticals, have been associated with reproductive anomalies including the feminization of male fish.[178] Millions of tons of plastic end up in the oceans every year,[179] creating large floating islands of garbage, and small plastic particles ("microplastics") are accumulating in the food chain with a largely unknown effect.[180] Wastewater discharges, urban and agricultural runoff, and fossil fuel combustion sources have overloaded lakes, estuaries, and rivers with nutrients, fostering algal blooms that can deplete oxygen and produce toxins.[181] All of these ecological problems ultimately harm human health and disrupt industries such as fisheries and agriculture. In 2014, for example, about 500,000 residents of Toledo, Ohio, were ordered not to use their tap water for days due to toxins produced by an algal bloom in Lake Erie.[182]

Challenges posed by pollution and waste will intensify as the world's population grows, people live in ever higher densities, standards of living increase, and industrial production expands to meet increasing demands. Two new approaches will be required to achieve economic progress while minimizing negative health and environmental impacts and sustainably managing Earth's resources. First, a new paradigm of waste management and pollution prevention is needed—one that shifts from a linear model of resource extraction, production, use, disposal, and cleanup toward one designed to prevent waste and pollution from the outset. Second, innovative approaches are needed to recover valuable resources from the waste we do produce. Ideally the two approaches are closely coupled. These new approaches will require life-cycle and systems thinking to identify sustainable solutions that minimize the amount of energy and resources consumed and the amount of waste and pollution generated through all components of production and use.

Preventing Pollution and Waste Through Improved Design

Every day, new chemicals and materials are manufactured, elements are mined from the earth, fuels are burned, and fertilizers and pesticides are made and used. These activities are undertaken to support functions and provide services—such as the production of food, medicines, clothing, building materials, and electronics—that are vital to our society and economy. The question is now how to provide these functions and services without generating the types and scale of pollution and waste that have harmed human health and ecosystems in the past.

The solution requires working toward a circular economy designed to prevent harmful waste and pollution from the outset. Within a circular economy, processes are designed to minimize waste, products and waste materials are reused if possible, and materials that cannot be reused are remanufactured or recycled (Figure 3-3). Organic wastes that cannot be reused are converted to other useful products such as chemicals, materials, or fuels. Pollution prevention is also considered at every design stage to minimize negative impacts. Using materials



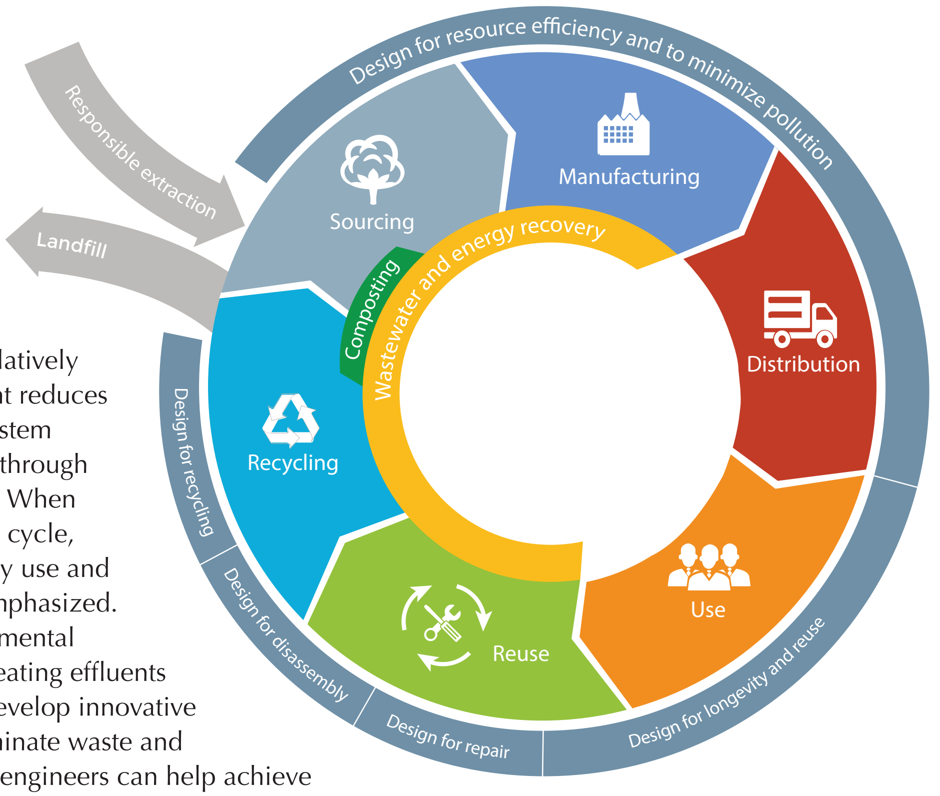


FIGURE 3-3. Sharply reducing waste and pollution requires new approaches to design based on life-cycle thinking.

and chemicals that are relatively benign in the environment reduces risks to human and ecosystem health as they are cycled through the economy and society. When considering the entire life cycle, designs that reduce energy use and promote efficiency are emphasized. By thinking beyond incremental improvements (such as treating effluents on site) and working to develop innovative new approaches that eliminate waste and pollution, environmental engineers can help achieve a sustainable future.

Design is the stage that most influences the types and amounts of waste or pollution that will be generated. At the design stage, engineers are able to help select and evaluate the characteristics of the final outcomes, considering material, chemical, and energy inputs; effectiveness and efficiency; aesthetics and form; and specifications such as quality, safety, and performance. In the development of new systems, this stage is ideal for innovation and creativity and represents a key opportunity to integrate environmental goals into the specifications of the products or processes. Through life-cycle and systems thinking—as well as green chemistry and green engineering, which emphasize designs that ensure that inputs, outputs, and processes are as inherently nonhazardous as possible—new designs can be implemented that rely on more benign materials and less energy, that do not generate much waste, and that do not shift environmental burdens from one place to another. Benefits of such an integrated approach include wise use of resources, improved human health, and enhanced protection of natural systems. Advances needed to support a circular economy include efficient and effective separation and recycling technologies and market forces or government incentives that recognize the broader impacts of pollution and waste (see Challenge 5).

Many of the most successful interventions focus on preventing the production or release of pollution or waste. This strategy is generally easier and less expensive than remediating contamination sites after toxins are dispersed in the environment. For example, perchloroethylene, a widely used solvent for dry cleaning fabrics and metal degreasing operations and a likely carcinogen,[192] has been replaced in these applications with supercritical carbon dioxide, which has low toxicity and is chemically stable, readily available, and easily recyclable. Another example is the recent movement away from subtractive manufacturing, a process by which three-

dimensional objects are constructed by successively cutting material away from a solid block of material. Instead, additive manufacturing,for example, 3-D printing constructs objects by successively depositing material in layers without the need to generate waste by cutting material away. A growing number of zero-waste businesses and communities aim to reuse, recycle, or recover at least 90 percent of discarded material while also aiming to produce no pollutants to air, water, or land.[193]

Eliminating the use of the most toxic chemicals is an important part of green design. To develop nonpolluting components and processes and prevent future contamination, it will be important to fill knowledge gaps about the full environmental risks of new and existing contaminants. For example, methyl-*tert*-butyl ether (MTBE) was added to gasoline to help reduce emissions in vehicle exhaust. However, MTBE became a groundwater quality problem once gasoline leaked from underground storage tanks because MTBE was able to migrate farther and was more resistant to biodegradation than other compounds in gasoline.[194] Of the more than 140,000 new chemicals that have been introduced since 1950, fewer than half have been subject to human safety or toxicity testing.[195] EPA's Pollution Prevention Framework can be used to estimate physical properties, which are then used to predict environmental concerns such as toxicity, mobility, persistence, and bioaccumulation, but more development and validation is needed. In addition, there are significant needs related to risk communication to help the public and decision makers understand the true costs of pollution.

Capturing the Value of Waste

Under a linear production model, resources are used inefficiently and can become depleted as landfills expand. Recovering resources from waste recaptures the value of those materials and minimizes environmental impacts from further resource extraction. Localized or distributed recovery and reuse also reduces the energy requirements and pollution associated with transportation of materials and waste. Resource recovery can also address local resource shortages in economically depressed or geographically isolated communities.

Today's common waste recovery efforts focus on recycling plastic, glass, paper, aluminum, and scrap metals, but much more is possible with advances in engineered environmental processes that allow the extraction of specific components from waste mixtures. Precious and rare-earth metals could be retrieved from electronic waste[196] and potentially even mined from landfills. Carbon capture systems could be used to turn carbon dioxide into forms that are useful for applications ranging from building materials to plastics to greener solvents.[197] Nutrients in wastewater could be captured for use as fertilizers (see Box 3-3).

Many of today's municipal and agricultural waste streams are rich in organic carbon, which could be recovered and channeled toward chemical manufacturing or energy recovery.[198] The amount of energy contained in wastewater is equivalent to several multiples of the amount of energy required to treat it.[199] Energy recovery has been implemented at numerous centralized wastewater treatment plants, including in Oakland, California, and in Strass, Austria, by converting a fraction of the incoming organic carbon to biogas to produce heat and electricity.[200] However, technologies have not yet been developed to cost-effectively capture the full potential of the embedded energy.[201]

Recovery of resources from waste streams has long been practiced, but in a nonsystematic fashion. In Dharavi, India, one of the largest slums in the world, people have built a thriving economy, employing approximately 250,000 people, based on recovering waste generated in Mumbai. "Gobar gas," produced from anaerobic digestion of animal waste, is used for cooking and community-scale lighting in rural and urban communities, particularly in Southeast Asia and sub-Saharan Africa. Fly ash and gypsum by-products of coal combustion have been used in the manufacturing of concrete and wallboard.[207]

BOX 3-3. NUTRIENT RECOVERY

Nutrients present in wastewater can cause problems for the environment and infrastructure, such as algal blooms in lakes and estuaries and buildup of the mineral struvite in the mechanical systems of wastewater treatment plants. Globally, humans release about 30 percent more phosphorus and twice as much nitrogen into the environment, mostly from fertilizers, than aquatic ecosystems can bear without degrading habitats.[202] Reusing nutrients in existing waste streams can help mitigate these challenges while producing valuable services. For example, reuse of municipal wastewater or agricultural runoff for irrigation can reduce fertilizer use.

Innovative approaches to cost-effectively recover and reuse nitrogen and phosphorus from waste streams rather than mining new phosphorus or synthesizing new nitrogen could conserve natural resources, reduce pollution, and save energy. Phosphorus is an increasingly scarce natural resource with limited mineable reserves,[203] but the phosphorus available from human urine and feces could account for 22 percent of the global phosphorus demand.[204] Recovering phosphorus from waste thus helps to preserve phosphorus reserves for the future, but further advances in waste separation are needed to achieve the technical and economic viability for widespread adoption.[205] In addition, producing reactive nitrogen for fertilizer from inert nitrogen gas in the atmosphere requires a considerable amount of energy and creates further imbalance in the global nitrogen cycle.[206] Some wastewater facilities have been successful in extracting phosphorus to create a commercial fertilizer, but in most cases, recovery of phosphorus and nitrogen from wastewater using *current* technologies is not economically viable.

Resource recovery is rapidly being integrated into existing manufacturing, agricultural, and industrial practices, but much work remains to be done to realize its potential, both in terms of recovery yields and the types of resources that can be cost-effectively recovered. A significant impediment to utilization of waste is that existing traditional waste streams have not been systematically characterized with resource recovery in mind. Local, regional, and global inventories of waste materials are needed to identify opportunities for reuse or inputs to other production schemes. With this information, appropriate technologies for resource recovery can then be developed using physical, chemical, and biological processes that capture the maximum financial, social, and environmental benefits. This information could also lead industries to redesign their resource extraction and manufacturing processes to reduce waste and more efficiently and cost-effectively recover and reuse valuable resources.

Results of public programs to reduce, reuse, and recycle have been mixed. The United States, for instance, recycles or composts 35 percent of its municipal waste and less than 10 percent of its plastics,[208] but higher rates are possible. Six countries recycle or compost more than half of their waste, led by Germany at 65 percent and South Korea at 59 percent.[209] In 2016, nearly 48 million metric tons of electronic waste were produced globally, representing a value of approximately $60 billion in raw materials, and only 20 percent of this waste was recycled.[210] EPA reports that electronic waste accounts for 70 percent of heavy metals in landfills, such as mercury, lead, and cadmium.[211] Waste streams are often heterogeneous, complex mixtures that currently require significant resources and energy to separate. Sorting technology has been developed and commercialized for some wastes, such as separating organic from inorganic wastes. The extent of resource recovery from wastes could be enhanced by improved, cost-effective waste separation techniques.[212]

Effective waste recovery requires attention not only to scientific and engineering capabilities but also to economic and behavioral factors. Considerations of financial viability and feasibility include the cost of the recovery technology, the quality of the recovered product, the market for the product, any adverse environmental impacts, and measures required to manage and prevent them. Governments can also develop incentives to encourage waste recovery that account for broad societal and environmental benefits of these programs (see Challenge 5).

Many of these advances are focused on large urban areas, where the highest volumes of waste are generated. However, there is also substantial potential to harvest the value of waste streams that are smaller or more intermittent to benefit rural communities. For example, decentralized resource recovery systems could be developed, particularly for sewage, food, animal, and agricultural waste.

What Environmental Engineers Can Do

With training in environmental chemistry, microbiology, hydrology, transport processes, solid waste management, water and wastewater treatment, and air pollution—as well as skills in life-cycle and systems thinking—environmental engineers bring important capabilities toward designing a future without pollution and waste (see Box 3-4). Technological advances combined with innovative new materials and designs can be used to conserve natural resources and minimize adverse effects on human health and the environment. These complex challenges demand solutions that consider broad costs and benefits throughout the life cycle, including human health risks, environmental impacts to water, soil, and air, as well as social and financial impacts (see Challenge 5). Environmental engineers can help analyze the impacts of innovative manufacturing and resource recovery approaches compared to the life-cycle impacts of traditional processes to identify the most promising solutions.

For many pollutants, although the knowledge and technology exist to reduce exposure, the greater challenges are economic, political, and social. For example, billions of people worldwide use solid fuel–burning cookstoves for daily meal preparation, creating large amounts of particulate matter pollution. It is possible to design cookstoves that are much cleaner burning to benefit health, local environmental quality, and climate, but there are cultural, economic, and logistical hurdles to their adoption.[213] Improving resource recovery in developed countries may require people to change their behaviors and accept new approaches to waste separation. An interdisciplinary approach applying social and cultural knowledge is crucial to overcoming such hurdles to guide the development and adoption of sustainable solutions.

BOX 3-4. EXAMPLE ROLES FOR ENVIRONMENTAL ENGINEERS TO DESIGN A FUTURE WITHOUT POLLUTION OR WASTE

Environmental engineers have essential skills needed to move toward a future without pollution or waste. Examples of ways environmental engineers can contribute include

Preventing Pollution and Waste

- Redesign products and their production processes to promote resource efficiency, longevity, reuse, repair, and recycling while minimizing pollution.
- Develop and use tools to better predict the risks of new and existing chemicals in the environment, including toxicity, fate, and transport.
- Quantify and document the life-cycle consequences associated with producing commonly used resources and products and the broad costs and benefits of alternative approaches designed to reduce pollution and waste. Work with social and behavioral scientists to communicate this information to inform the decisions of consumers, manufacturers, and governments that could incentivize these efforts.
- Manage or remediate existing legacy hazardous waste and contaminated sites to eliminate harmful exposures and return sites to productive use.

Capturing the Value of Waste

- Quantify waste-stream characteristics and identify opportunities to reuse or recover materials traditionally considered as waste.
- Identify products that could be manufactured with recycled and reused materials that would have lower cost, lower greenhouse gas emissions, and require less energy to produce.
- Develop new resource-recovery technologies and processes for cost-effective recovery of materials and energy from the waste stream.
- Work with other sectors including public health, architecture, and urban planning to integrate engineering designs, processes, and technologies to develop effective approaches to resource recovery with broad societal benefits.