Municipal Solid Waste and the Environment: A Global Perspective

Sintana E. Vergara[1] and George Tchobanoglous[2]

[1]Energy and Resources Group, University of California, Berkeley, California 94720-3050; email: sintana@berkeley.edu

[2]Civil and Environmental Engineering, University of California, Davis, California 95616; email: gtchobanoglous@ucdavis.edu

Annu. Rev. Environ. Resour. 2012. 37:277–309

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

This article's doi:
10.1146/annurev-environ-050511-122532

1543-5938/12/1121-0277$20.00

Keywords

waste governance, climate change, behavior change, reuse and recycling, informal sector, electronic waste, solid waste management

Abstract

Municipal solid waste (MSW) reflects the culture that produces it and affects the health of the people and the environment surrounding it. Globally, people are discarding growing quantities of waste, and its composition is more complex than ever before, as plastic and electronic consumer products diffuse. Concurrently, the world is urbanizing at an unprecedented rate. These trends pose a challenge to cities, which are charged with managing waste in a socially and environmentally acceptable manner. Effective waste management strategies depend on local waste characteristics, which vary with cultural, climatic, and socioeconomic variables, and institutional capacity. Globally, waste governance is becoming regionalized and formalized. In industrialized nations, where citizens produce far more waste than do other citizens, waste tends to be managed formally at a municipal or regional scale. In less-industrialized nations, where citizens produce less waste, which is mostly biogenic, a combination of formal and informal actors manages waste. Many waste management policies, technologies, and behaviors provide a variety of environmental benefits, including climate change mitigation. Key waste management challenges include integrating the informal waste sector in developing cities, reducing consumption in industrialized cities, increasing and standardizing the collection and analysis of solid waste data, and effectively managing increasingly complex waste while protecting people and the environment.

Contents

1. INTRODUCTION

The production of solid waste is an inevitable consequence of human activity, and its management directly impacts the health of the people and environment surrounding it. Globally, people are discarding growing quantities of waste, and its composition is more complex than ever before, as plastic and electronic consumer products diffuse. These two trends pose a challenge to cities, which are charged with protecting their citizens from their waste. The goal of this article is to provide a global overview of municipal solid waste (MSW) and the environment. We begin by presenting differences in waste composition and quantities for different regions of the world and then discuss how waste management systems have evolved to handle this waste, noting trends in waste governance, technologies, and policies, in both industrialized and industrializing settings. Finally, we explore how waste production and management impact air and water quality and public health, as well as how they contribute to climate change. Because waste management is a context-specific challenge, in addition to looking at broad global trends and key differences between countries, we examine more closely waste management processes in a few places: waste history in the United States, electronic waste recycling in China, and informal collection in Colombia.

1.1. What Is Municipal Solid Waste?

Though widely understood as a concept, waste—garbage, rubbish, discards, junk—eludes definition, varying by who defines it. Engineers define MSW as materials that are discarded from residential and commercial sources (1, 2) or as materials that have ceased to have value to the holder (3). Anthropologists hold that garbage is factual evidence of a culture, that "what people have owned—and thrown away—can speak more eloquently, informatively, and truthfully about the lives they lead than they themselves ever may" (4, p. 54). Ecologists claim that there is no waste in nature (5), and industrial ecologists view waste as "a right thing in a wrong place, like a pig in the parlor instead of the barnyard" (6, p. 1050). How waste is treated reflects its definition; refuse workers in hauling waste to a landfill treat it as valueless, and waste pickers who recover materials from refuse treat it as ore (7). Despite the variety of meanings given to waste, its presence and proliferation are undisputed.

Municipal solid waste (MSW): all solid or semi-solid materials disposed by residents and businesses, excluding hazardous wastes and wastewater

1.2. The Changing Nature of Waste

Demographic changes are concentrating waste in cities. Waste production tends to increase with wealth, urbanization, and population (2, 8, 9). While the global population is rising, the distribution of the population is changing more dramatically. The world is urbanizing at a rapid and unprecedented scale, and most of this urbanization is occurring in small- and medium-sized cities within low-income nations (10). The same areas that are seeing the greatest urbanization trends are also home to a billion new consumers—people from 20 developing and transition nations whose combined spending capacity is equal to that of all US consumers (11). This newly affluent population is dramatically increasing their consumption of meat, cars (the cars owned in the developing world grew 89% from 1990 to 2000, with China's fleet increasing 445% and Colombia's 217%), electricity, and other consumer goods (11). Two consequences result from this increased consumption: More natural resources are used (to produce those goods), and more waste is produced (when consumers discard them).

1.3. Solid Waste Management Challenges

Postconsumer waste, through its production and management, affects air quality, water quality, and public health, and it contributes to climate change (8). Improperly managed waste can affect the environment at different scales. Open dumping of wastes contaminates nearby water bodies with organic and inorganic pollutants. It also threatens public health by attracting disease vectors and exposing people living near the waste to the harmful products

GHGs: greenhouse gases

Waste hierarchy: a classification of waste management technologies, ordered by their environmental desirability

Integrated waste management: the purposeful management of all municipal waste flows, aimed at protecting human and environmental health

within (3). Incineration of waste emits a variety of pollutants, including dioxins and furans (2, 12), persistent organic pollutants that mix globally and harm human and ecological health. Waste management also emits a variety of greenhouse gases (GHGs); the most significant sources are landfills, which emit methane as organic waste decomposes. The Intergovernmental Panel on Climate Change estimates that waste management emits less than 5% of the global GHG emissions (and emits 9% of methane released globally), but this estimate is uncertain and variable, as waste management can act as either a net source or sink of GHGs (8, 13). Because waste poses a threat to people and the environment, provision of waste management services has often fallen to cities, which are charged with providing public goods to their citizens. Global trends in waste production—the increasing quantity and complexity of MSW—compound the challenge, making waste management "one of the biggest challenges of the urban world" (14, p. 1).

1.4. Managing Waste in a Sustainable Manner

Cities and their citizens use a number of technologies, policies, and behaviors to control the negative impacts of their waste and to find beneficial reuses for it. This combination of methods constitutes waste management, which can be divided into six functional elements that describe the path that waste takes from creation to disposal: waste generation, waste handling at the source, collection, transport, processing and transformation, and disposal (2). Though the particular activities may take different forms in different places, the elements are universal. After producing waste, the generator handles it, placing it in a receptacle or separating it by component. The waste may then be collected by a formal or informal actor and transported to another site, where it may be processed and transformed into new products. Waste transformation can take many forms, discussed in **Tables 1** and **2**. For example, organic waste can be converted to energy via anaerobic digestion (15), to a liquid fuel via biochemical pathways (16), and to humus via composting (17); it can also be used directly as feed for animals or applied to agricultural fields. Any waste remaining, or that is not processed into another product, may then be disposed of in a controlled or uncontrolled manner.

Two guiding frameworks have been central in affecting waste management decisions: the waste hierarchy and integrated waste management (12). Since the early 1990s, the waste hierarchy has guided waste management policy by defining which waste management technologies should be used preferentially. From most to least environmentally friendly, the hierarchy lists the following: waste reduction, reuse, recycling and composting, energy recovery, and landfilling (1). More recently, the hierarchy has been critiqued for its lack of scientific basis, its difficulty to implement, and its failure to account for specific local situations, which should dictate which technologies are appropriate and preferable (3). Integrated waste management has emerged as a very different approach. Composed of a set of principles by which to handle waste in an environmentally and economically sustainable, socially acceptable manner (2, 3, 12), integrated waste management is "integrated" because it advocates a holistic view that includes all waste flows in society and aims to control all its resulting solid, liquid, and gaseous emissions. Because of its focus on flexibility and specificity to local conditions, integrated waste management does not prescribe solutions, as does the waste hierarchy; rather, it holds principles that allow locales to develop their own systems in response to their contexts. The establishment of integrated waste management systems is a goal for most cities (3).

2. SOLID WASTE: QUANTITIES, COMPOSITION, AND VARIABILITY

More than one billion metric tons of MSW are presently discarded worldwide, and forecasts predict this will grow to 2.2 billion by 2025 (18). Although a number of studies cite

Table 1 Biogenic waste conversion technologies

Processes	Descriptions of processes
Composting	Composting is the decomposition and stabilization of the organic fraction of municipal solid waste carried out by a microbial community under controlled, aerobic conditions. In practice, compost systems may be closed or open and may occur at the household or municipal scale. Most biogenic matter can be composted, and the resulting product (compost) can be used as a soil conditioner or fertilizer (2). Composting fulfills four waste management objectives: to reduce the volume of waste, to stabilize waste, to sterilize waste, and to produce a valuable product from the waste (3, 17). Worms may also produce compost; they eat biogenic waste, and their castings provide a nutrient-rich soil amendment (63, 65).
Anaerobic digestion	Anaerobic digestion is a bacterially mediated process occurring in the absence of oxygen in which microbes consume biomass and release biogas [carbon dioxide (CO_2) and methane (CH_4)]. Biogas can be burned for electricity, and the solids can be aerobically digested to produce compost (66). The production of biogas from the anaerobic digestion process depends on the feedstock, pH, temperature, moisture, and the carbon-to-nitrogen ratio of the feedstock (15). Codigestion of food waste and wastewater sludge increases biogas production and offers combined wastewater and solid waste treatment for resource-constrained communities (67, 68).
Municipal solid waste to ethanol	The conversion of MSW to ethanol is not yet a commercial reality, but it is technically possible (16). MSW to ethanol is a promising technology because it uses a ubiquitous feedstock (MSW) to create a cleaner liquid fuel for a rapidly motorizing, carbon-constrained world. Two barriers to its widespread implementation, beyond its commercial development, are the need for well-separated organic waste and the capital cost of building a specialized facility.
Municipal solid waste to biodiesel	Another emerging technology uses the larvae of black soldier flies, grown on organic waste, to create biodiesel (69). Both methods of liquid fuel production use a widely available substrate and do not use food feedstocks, which contribute to global land-use change (70). This technology does not require a specialized facility.
Biochar production	Thermal treatment of biogenic waste under oxygen-deficient conditions (pyrolysis) creates biochar, a soil amendment that provides agricultural benefits as well as long-term carbon sequestration (71–74).

alarmist numbers about the rise of solid waste production, it must be recognized that these numbers are highly uncertain. The quantity and composition of waste is fundamentally important in the selection of the strategies and technologies used for its management, as discussed in Sections 3 and 4.

2.1. Waste Quantities and Composition

As people gain wealth, they tend to throw more away, and the materials discarded are more complex (8, 9, 19–21). For these reasons, waste characteristics vary greatly between cities, with industrialized cities tending to throw away greater quantities of waste, containing more recyclable goods and electronics (22), and industrializing cities discarding less and having high biodegradable fractions in their waste. Local climatic conditions and energy sources also affect the nature of waste. In Ulan Bator, Mongolia, for example, where coal is used for home heating, ash constitutes 60% of the municipal waste produced in the winter and only 20% in summer months (18).

Waste generation rates for a selection of the world's cities are illustrated in **Figure 1**. The corresponding waste composition for the cities shown in **Figure 1** is presented in **Figure 2**. In **Figure 1**, waste production is plotted against the Human Development Index, a comparative measure of well-being for nations and cities, calculated by the United Nations Development Programme. This indicator is based on measures such as literacy and life expectancy to provide an overall assessment of the city's level of development. These data were taken from a single source for which a consistent definition of MSW was applied:

Table 2 Nonbiogenic waste conversion technologies

Processes	Description of processes
Incineration	Incineration is the controlled burning of waste at a high temperature (64), designed to attain complete combustion of wastes. All carbon in the waste is converted to carbon dioxide (CO_2), all hydrogen to water (H_2O), and all sulfur to sulfur dioxide (SO_2). By-products include ash, air emissions (NO_x, CO, CO_2, SO_2, PM, dioxins, furans, and others), heat, and energy. Although the heat and energy provide societal and environmental benefits (depending on the type of energy being displaced), the air pollutants emitted represent a burden. Modern incinerators have pollution controls that can lower the pollutant emissions to acceptable levels. Cyclones, electrostatic precipitators, and fabric filters remove particulate matter from the flue gas; scrubbers remove acid gases; catalytic reduction and temperature control minimize NO_x emissions; and activated carbon removes dioxins, furans, and heavy metals from the flue gas (64). The appropriateness of incineration as a waste management technology depends on local waste characteristics and public acceptance. For an efficient combustion process, incinerated wastes should have a low moisture content ($<50\%$) and a high heating value (>5 MJ/kg). Waste incineration is rarely appropriate in less-industrialized cities, where waste is mostly biogenic. Even though popular resistance to waste incineration is strong in some places (e.g., the United States), incineration is popular in Europe and Japan (2).
Pyrolysis and gasification	Pyrolysis and gasification convert waste to energy by burning fuel in an oxygen-deficient environment. Both are endothermic processes. Pyrolysis is the oxidation of waste in the absence of oxygen, and gasification oxidizes waste in an air-lean environment. Used widely by Amazonian indigenous people to create char (*terra preta*) as a soil amendment, pyrolysis is also used by modern commercial processes to produce charcoal, methanol, and coke. Gasification produces syngas (CO, CH_4, and H_2) and a solid (unburned waste and char, a carbon-rich solid). The syngas can be burned as a fuel, and char can be used as a fuel or a soil amendment (64).
Recycling	Recycling is the reprocessing of discarded materials into new products. The environmental benefits of recycling derive from the savings in both virgin natural resources and energy (85), although these benefits vary locally. Recycling requires a supply (collected, separated materials) and a demand (a market for the recycled product). The recycling chain varies in formality across the globe, but there is an increasingly globalized market for recyclable materials. There are two driving forces for recycling waste materials: their commodity value and their service value. The commodity value derives from its economic value. This value drives all private recycling activities, including the unregulated recycling prevalent in less-industrialized nations. The service value is the savings to the waste management system, which no longer has to handle the waste. This diversion value, along with concern for the environment, drives municipal recycling programs common in more industrialized nations (14).

all commercial and household waste (excluding wastewater, industrial, and construction waste).

Some general trends between cities and their waste characteristics are evident when comparing **Figures 1** and **2**. The more wealthy and developed a city is, the more waste it produces. Poorer nations tend to have higher organic fractions in their waste, and richer cities tend to have more complex waste compositions. The World Bank (18) provides a current overview of global waste production and characterizes waste production by region, as shown in **Figure 3**. This figure shows that for most regions, waste production seems to level off with urbanization, at about 1 kg per capita per day. But the wealthiest nations—those belonging to the Organisation for Economic Co-operation and Development (OECD)—are outliers, producing far more waste than do other regions—four times more than African and south Asian consumers, and twice as much as the rest of the world. Although the waste generation data presented in **Figure 3** are estimates that contain uncertainty, given the variability in waste generation rates and composition, and the large areas for which these estimates are given, they

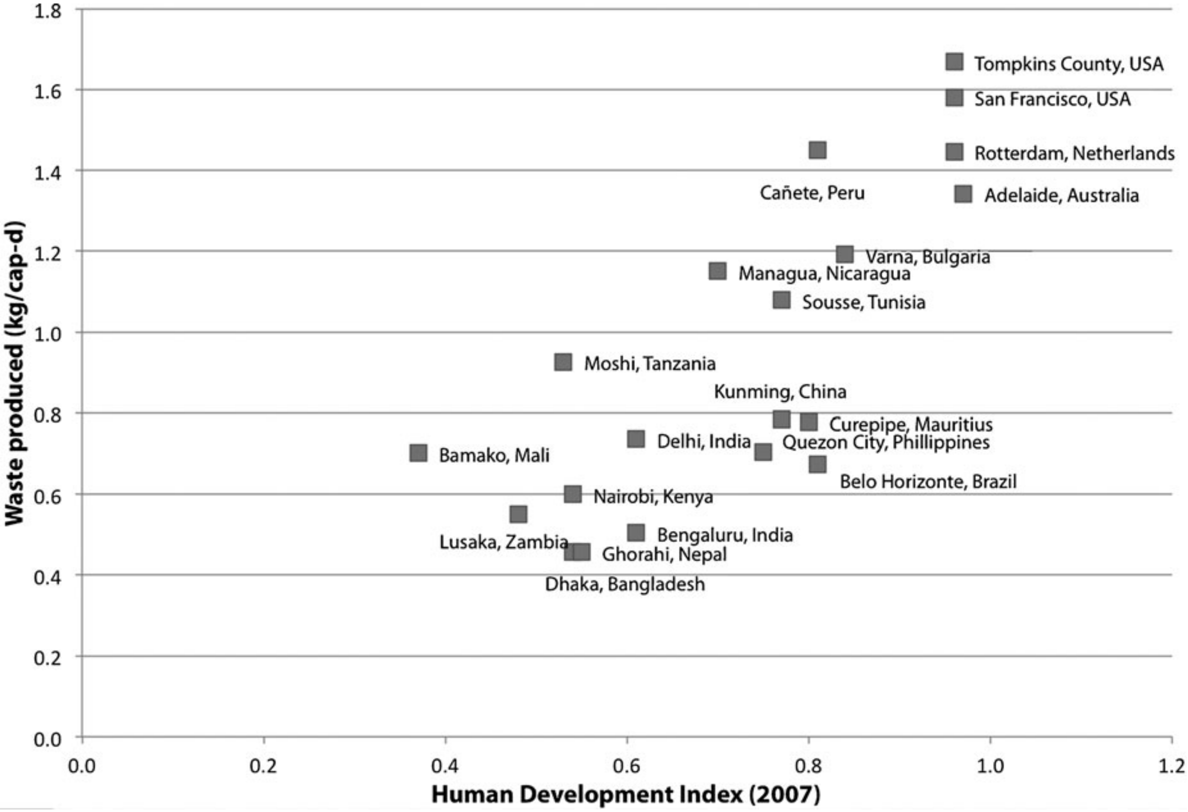

Figure 1

Per capita waste generation rates versus Human Development Index for 20 selected cities. Data are from Reference 14. Abbreviation: kg/cap-d, kilogram per capita per day.

represent a first-order estimate of regional differences in waste production and composition.

2.2. Variability of Waste Production and Composition

Not only does composition of waste vary between cities, it varies within a city over time. Over a short timescale, waste characteristics tend to vary seasonally, changing in quantity and composition over the course of the year (see Reference 21). Over a longer time frame, waste discarded by citizens reflects technological and cultural trends. In a unique study, Walsh (23) examined waste composition in New York City over a century, and identified a number of cultural trends. Until 1950, ash was the most abundant material found in MSW because most homes burned coal for heating and cooking. Glass entered the waste stream after the 1960s, when nonreturnable glass and steel containers took the place of refillable glass bottles. Plastics appeared in the waste stream in 1971 (23).

More recently, global consumers have adopted a variety of electronic products; this has led to a great increase in e-waste. In Nigeria, for example, the proliferation of cell phones has caused people to discard their landlines (24). In the United States, consumers rapidly adopt technological changes in televisions, computers, and cell phones. Of the 2.25 million metric tons of e-waste they produced in 2007, US consumers stored 75% of their obsolete electronics in their home, sent 18% to be recycled, and disposed of the rest in landfills (25). The penetration of electronic

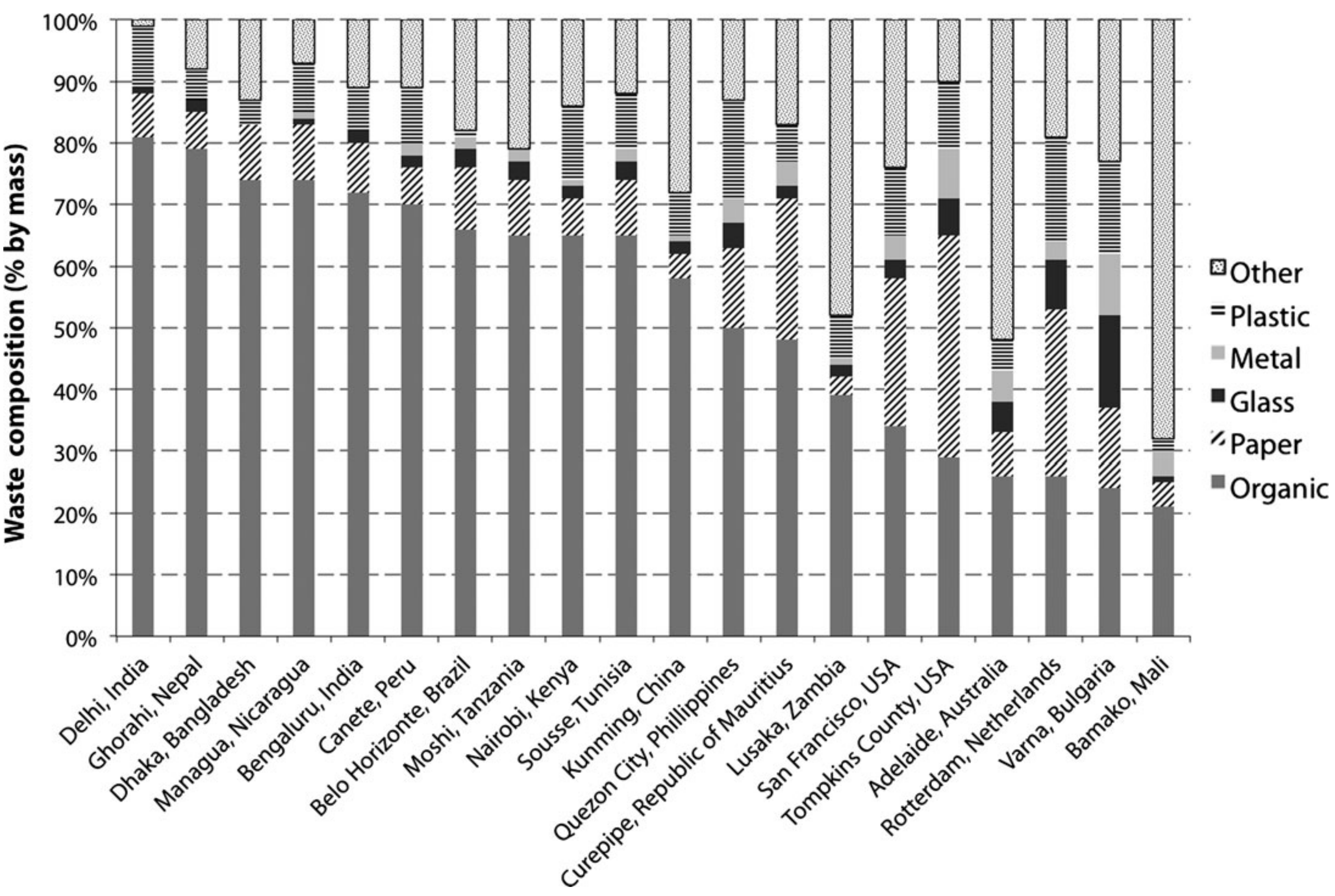

Figure 2

Waste composition for 20 selected cities (14).

goods in Latin America is nearly as high as that of industrialized nations (26). Globally, 4,000 metric tons of e-waste are discarded per hour, flowing from industrialized to industrializing nations. Though China is the global receiver of e-waste, it is also emerging as a major consumer, with its own e-waste production increasing 14% per year (27).

2.3. Uncertainty in Solid Waste Data

Comparing waste characteristics between cities is very difficult, owing not only to the variability discussed above, but also to the uncertainty in the reported data. Most solid waste data are not collected regularly, and there is no universal standard for the definition and measurement procedures for MSW. Although many definitions include household and commercial waste, some include street sweepings and industrial waste, some measure at the point of disposal, and some measure at the point of generation. Nor do cities follow a standard method for measuring composition, so two identical samples can be analyzed, and each can receive a different estimate (28). The lack of a global database on waste production, using a standardized definition of waste, is a key gap in the literature (3, 29).

The solid waste data that do exist are generally unreliable because they are often outdated or estimated using regional averages (rather than measured); some are inaccessible (30). While the quality of solid waste data for the world's wealthiest nations is quite good, owing to standard definitions and regular bookkeeping from the OECD (31), there is no such centralized trove of data for less-industrialized countries. The UN-Habitat (14) provides an excellent overview of the state of solid waste in the world; its contributors collected uniform data and lessons learned from 20 cities. Solid waste data in less-industrialized countries, if they exist, are generally collected by municipality or by an academic study focused on that area. We note a number of trends for work on MSW within the academic community. First, there is a dearth of solid waste research focused on Africa, although four recent works aim to fill that gap (32–35). Second, the number of published studies on MSW in Asia is growing, especially on China and India. Finally, most work focuses on urban areas. Waste generation is lower and more disperse in rural areas, so it is even harder to track. At the city level, informal uses of waste often go unreported, so these system losses are either absent or unexplained in cities' waste databases (18).

2.4. Variability in Waste Management Strategies and Technologies

Concurrent with local variation in waste characteristics, each location employs a variety of waste treatment methods, ranging from low to high technological treatment. Generally, higher-income cities employ more technological methods for waste management—mechanized collection, separation, and treatment—whereas lower income cities tend to rely on higher labor, lower technology options. Open dumping is a common waste management method in the less-industrialized countries, and landfilling is the most prevalent waste technology worldwide (14).

The growing complexity of MSW challenges historical waste management methods. In Bamako, Mali, organic waste is applied directly to agricultural fields, closing the cycle from production to consumption with only one step. But "increasing amounts of plastics—many related to the practice of packing water in small 'pillows,' which did not exist in 2002—makes this practice an increasing problem for the environment" (14, p. 126). Similarly, many rural homes have historically buried or burned their trash, a treatment that is mostly benign for organic waste, but creates toxins when the waste contains heavy metals or plastics. The household's ability to safely manage its own waste declines as its waste becomes more complex.

3. EVOLUTION OF SOLID WASTE MANAGEMENT

The evolution of solid waste management can be understood by considering the drivers and circumstances that lead to the development of solid waste management programs. In less-industrialized countries, the informal sector is an important waste service provider, whereas local government tends to be the sole service provider in industrialized countries. More recent trends in solid waste management are identified in Section 6.

3.1. Drivers in Waste Management Development

Four imperatives drive the development of waste management plans: public health, environmental protection, resource recovery, and climate change (36). Cities are also choosing to improve their waste management for aesthetic reasons. Any combination of drivers may be motivating changes in a city's waste management, at any given time, though the dominant driver tends to change over time.

3.1.1. Public health. Public health tends to be the motivating factor in development of waste policies in places where little waste management infrastructure exists. In Haiti, for example, waste is commonly dumped in an uncontrolled manner, creating a public health hazard and motivating change (37). Health concerns are important drivers in places such as China (38), which have low levels of safe disposal. In extreme cases, public health calamities, such as the spread of disease in Surat, India, after uncollected waste clogged drains and contributed to flooding, spark widespread public interest in improving waste management (14). Waste management's specific impacts on public health are discussed in Section 5.3.

3.1.2. Environmental protection. Environmental protection tends to drive waste management policies where there is strong legislation protecting the air, water, and land (36), but also where environmental degradation is highly visible. In the island nation of Mauritius, the need to protect the ocean and the coral reefs led directly to the construction of a landfill (14). On islands, the visibility of waste and its impact can impel adoption of waste management policies to protect the environment. Similarly, environmental protection is an important driver in Rotterdam, Netherlands, where the city's environmental fragility, exemplified by its high water table, has catalyzed the adoption of policies that minimize landfilling and maximize beneficial reuse of MSW. The need to protect the environment through effective waste management may also be externally driven; Bulgaria was required to improve its waste system to become a member of the European Union (14). The environmental impacts of waste production and management are explored in Section 5.

3.1.3. Resource recovery. Although resource recovery also provides environmental benefits, it drives changes in waste management through economic signals. Where resources are scarce, materials are recovered, repaired, or reused, rather than discarded. Resource recovery was the dominant mode of waste handling in preindustrial societies; Strasser (39) provides a nice history of the trade in waste materials in the preindustrial United States. Resource recovery is an important driver in cash-poor cities throughout the developing world; is crucial to the economies of India and China, which depend on secondary materials; and is the motivating force behind informal recycling systems (36).

3.1.4. Climate change. Climate change has emerged as a driving force for changes in waste management in both industrial and industrializing nations (36). The threat of climate change has made GHG emission reductions from waste management a policy goal for many states. Though waste contributes only modestly to global GHG emissions ($<5\%$), waste management has the potential to be either a net source or sink of GHGs (8). Because landfills are the largest source of these gases within waste management systems, and because these emissions are growing in developing nations, many waste projects in less-industrialized countries have focused on containing these emissions through the construction of new sanitary landfills. Where OECD nations may look to reduce the carbon emissions from their waste management to meet national emission reduction targets, industrializing nations are increasingly using the Clean Development Mechanism from the Kyoto Protocol to fund improvements in their waste management plans and so must select GHG-abating waste management projects to qualify (8).

3.1.5. Aesthetics of modernity. Often, aesthetic concerns—the desire to create a clean, modern city (40–42)—motivate the establishment of good waste collection systems, which is the first step in managing municipal waste. In developing countries, image and pride associated with clean streets is an important driving force for improving waste management. The city's image has been identified as the most important driving force in Delhi's waste management development, propelling city authorities to project a world-class city before hosting the 2010 Commonwealth Games (14). Modernization is an explicit goal in Bogotá, Colombia, where the District Recycling Plan calls for a mechanized recycling system to gradually displace the informal one that currently exists (43). Tourism rewards clean cities; in Bulgaria, tourism's economic benefits drive efforts to collect Varna's waste. Though the concern for appearances may not lead to overall effective waste management, it encourages higher waste collection rates (14).

3.2. Historical Development of Waste Management Systems in the United States

The historical development of solid waste management is characterized by shifts from informal to formal arrangements, and local to regional management.

3.2.1. Shift from informal to formal waste management. In the United States in preindustrial times, the household was the locus of waste management, and it wasted little. The value of materials was high enough that families repaired and reused their goods, such that they rarely purchased or discarded materials. Women would make and repurpose clothing, for example, until they became rags, which they would then trade with ambulant peddlers for pots. Peddlers provided the collection and transportation that linked home and industry, effectively carrying materials that were waste in one place (rags) to a place where they were instead raw materials (pulp) (39).

Changing consumption patterns paved the way toward more centralized waste management. After the Industrial Revolution, household reuse and recycling habits dwindled as people were able to purchase more goods, and their incentives to accumulate waste to trade with peddlers declined. By the end of the nineteenth century, the two-way trade between households and industry, linked by peddlers, "had given way to specialized wholesalers and waste dealers.... For the first time in human history, disposal became separated from production, consumption and use" (39, p. 109). As households stopped managing their own waste, companies began selling packaged products, and "middle class people learned to toss things in the trash, attracted by [its] convenience.... As cities and towns took responsibility for collecting and disposing of household refuse, it became easier to throw things out. Ever-increasing amounts of trash demanded complex systems ... promoting the notion among citizens that refuse was a technical concern, the province of experts who would take care of whatever problems trash presented" (39, p. 113). Cities began to produce more waste as people learned to buy more and to throw things away, and as governments took responsibility for managing what people discarded. The locus of waste management shifted from the household to the city, and waste was redefined as a technical, municipal concern.

The movement toward formalized management of waste required two shifts in waste governance: a weakening of the institutional ties between informal waste workers (e.g., peddlers) and citizens, and citizens' embrace of "the Progressive position that government—and not free enterprise—was responsible for public health and should exercise that responsibility in the matter of refuse" (39, p. 120). These shifts occurred simultaneously. As peddlers were pushed out by a newfound ease of shopping and discarding, a new class of scavengers appeared, who picked through garbage in cities (rather than exchanging directly with citizens). Their activities, "reuse, recycling, and bricolage, became identified as activities of the poor" (39, p. 136), further eroding household recycling habits. Municipalities passed laws that weakened the position of these recyclers by "[dropping] regulations requiring citizens to separate their trash" (39, p. 135) and more directly by prohibiting the informal waste trade. Officials in New York City barred households from selling "rags and other wastes to ragmen who appeared at the door . . . [instead requiring people] to take unwanted materials to licensed second-hand dealers, 'men who had fixed places of business.' With a single stroke, the streets would be free of refuse and of the poor who made their livings spearing debris and pushing it on carts" (39, p. 140). A combination of cultural changes that encouraged disposal, and an earnest effort by municipalities to take responsibility for their city's waste led to a shift from informal, decentralized management to formal, centralized waste management in the United States.

3.2.2. Shift in technology. The technological shift in waste management over the nineteenth and twentieth centuries was profound. Collection in New York was gradually mechanized; initially, people and horses collected waste, then cable cars and trolleys did, and finally, trucks. Where urban waste management began as a way to remove waste from cities (and dump it just outside), it evolved to provide different waste treatment services. The first large-scale waste incinerator was built in the United States in 1885, and home incinerators became widespread in the mid-twentieth century. The first centralized recycling center was established in Chicago in 1904. Sanitary landfilling—controlled disposal of waste to minimize its impact on the surrounding environment—was invented in 1934, and by the 1960s was the most common waste treatment method in the United States (44).

3.2.3. Shift from municipal to regional waste management. The interplay of the drivers discussed above led to a shift from local to municipal to regional management of waste. Municipalities invested in solid waste only after tackling the more pressing public health hazard of unmanaged sewage. The United States quickly urbanized; urban population grew from 11% in 1840 to 51% in 1920, and with increasing population density came the accumulation of untreated wastewater and disease outbreaks (44). After investing in regional infrastructure for wastewater management, cities did not have the budget to do the same for solid waste, so it was at first managed locally (45).

But the passage of legislation to protect the environment made local waste management prohibitively expensive. The Clean Air Act (1970) regulated emissions from MSW incinerators, landfills, and composting facilities, and meeting the standards set was too costly for smaller operations. The Resource Conservation and Recovery Act (1976) was the definitive legislation that altered the scale of waste management activities. It defined solid and hazardous waste, established strict standards for sanitary landfills, and prohibited the open dumping of wastes. The Resource Conservation and Recovery Act's passage immediately caused the closing of open dumps and led to a precipitous decline in the number of landfills (2). Because it was more expensive to keep a landfill (or other waste facility) that met environmental standards, regions invested in fewer, larger landfills that served multiple municipalities (44), resulting in regional-scale waste management.

3.3. Evolution of the Informal Sector as a Waste Service Provider

Although in the United States, and in many other industrialized nations, municipalities have provided waste management services to its citizens, mostly through capital-intensive, government-financed infrastructure projects, an alternate model of provision has arisen in developing cities. There, informal actors, small businesses, and entrepreneurs have filled in gaps in public service provision, propelled by economic incentives.

3.3.1. Informal public good provision. In the provision of public goods—goods that are nonexcludable and nonrival—to citizens, political scientists define two relevant entities: the government (as the purveyor of goods) and civil society (as the receiver of goods). Demand for public goods is associated positively with a community's economic development (46) and the strength of political groups within civil society (47). This demand is negatively associated with group heterogeneity, possibly owing to the difficulty of organizing collective action when the group has a diverse set of preferences (46–48). A higher supply of public goods is associated with government capability, measured by fiscal resources of the city and the professionalism of officials (46), and the incentives for the political sector to provide services (49, 50). These associations are consistent with the observation that richer, more homogeneous cities have higher rates of public good (water, wastewater, waste) service provision.

In cases where government supply of public goods is lacking, actors within civil society may fill gaps through informal work, jobs "not legally recognized by the state" (7, p. 117). Informality is often used to govern transactions by those who are marginalized by the existing economic order, as "a mechanism for adapting to shortcomings in modern . . . regulated states. Rather than operating in the absence of formal systems, formal and informal modes of exchange thrive in the 'interstices of the formal system'" (51, p. 17). Because these interstices can be quite large in resource-constrained states, informal employment is widespread in developing nations, constituting 50%–75% of nonagricultural jobs in Asia, Latin America, and Africa. This employment takes hold in areas where the government "lack[s] the resources to meet the demands of urbanization and enforce laws . . . Rapid urbanization in developing countries has created pressures that have constrained the capacity of cities to provide adequate employment, waste disposal, water supply . . . and housing" (52, p. 1). Informal actors find employment by providing urban services not provided by the state.

3.3.2. The informal waste sector. The informal provision of waste services is ubiquitous in most cities in less-industrialized countries. Globally, 2% of people depend on waste for their livelihood (53). There are an estimated two million scavengers in China alone (38). The informal sector of waste management consists of people who separate, collect, dispose, and resell waste; the work done is "small-scale, labor-intensive . . . unregulated and unregistered, [and] low-technology" (54, p. 797). The term informal is "used to describe the relationship between workers and the state" (55, p. 2020)—not their level of organization. Though informal, the sector is often complex, is able to recover a high proportion of recyclables, and is flexible enough to quickly adapt to changing economic conditions (54).

Although informal waste workers are ubiquitous, the niches they inhabit—and their overall importance in the waste management of a city—are quite varied. They may be the only players providing primary collection for a city, as in Port au Price, Haiti (56), or Delhi, India (30). In Delhi, an innovative collaboration between the formal and informal sectors manages city waste. Informal workers collect waste from households and transport it to temporary storage units (*dhalaos*). From there, private companies and the municipality provide secondary collection. The New Delhi Municipal Council subsidizes this system, realizing that it is unable to provide primary collection to its city. In Bamako, Mali, informal microenterprises use donkey-drawn carts to collect 300,000 metric tons of waste per year, covering 57% of the city, and deliver waste to secondary collection sites in a private-to-private arrangement between the enterprises and the waste generators (14).

3.3.3. Operation of the informal waste sector.

Though sometimes involved in waste collection and disposal, the informal sector is most commonly involved in waste recycling, as itinerant waste buyers, street pickers, dump pickers, truck pickers, workers in junk shops, or processors of waste materials (54). Unlike municipal recycling programs found in industrialized cities, informal recycling is driven by the profits made from the resale of recovered materials. In Bogotá, Colombia, informal collectors remove materials from bags of waste that would otherwise be sent to landfills; they reroute materials from a path of waste into a recycling chain (43). In many cities, this work is done farther along on the waste value chain. An estimated 12,000 people live and work in municipal dumps in Manila, 15,000 live on Mexico City's dumps, and 20,000 in Calcutta's (57).

While developed nations prohibited the informal recycling that was prevalent early in their industrialization and have had to build their recycling rates anew, many developing nation cities remain centers of material recovery and reuse through the participation of people who scavenge goods from city waste and resell the materials to manufacturers. The incentive to collect recyclable material is economic. Because their wages come from resale, and not through contracts with the city, informal sector recycling is a free service provided to the municipality—essentially, a "a subsidy by the poor to the rest of the city" (14, p. 138) that provides a livelihood for workers (58) as well as environmental and waste management services to the city.

The recycling rate achieved by informal workers varies by locale. Informal actors in Turkey recycle 10%–15% of the waste produced (59); 13% of waste produced in Bogotá, Colombia, is recycled or reused informally by recyclers (43); and the *Zabbaleen*, informal and historic recyclers, recycle about 80% of waste in Cairo, Egypt (7), outperforming the formal recycling sector in many developed nations.

The level of organization of informal waste work also varies tremendously, with *Zabbaleen* in Cairo representing an extremely well-organized, highly effective organization (see References 7 and 60–62), and individual waste picking from dumps representing the lowest level of organization and power (54) and the highest level of personal health risk. Although the integration of this sector into an integrated solid waste management plan has been recognized as essential for less-industrialized cities, "a necessary first step toward integration is to recognize the economic, social and environmental benefits that result from informal recycling" (54, p. 805). Future research should focus on the evaluation of these benefits, as well as the associated costs.

3.3.4. Relationship between the informal and formal waste sector.

Waste management systems are not either formal or informal; they are both. Waste management systems fall along a "formal-informal continuum, with different categories of workers who interact, overlap and may themselves change category in response to changing circumstances" (14, p. 72). The flexibility of the informal sector allows it to endure; it adapts to opportunities within cities. Formal and informal waste management interact fluidly and symbiotically (51); both may thrive within the same city. The formal-informal waste combination can take many shapes: a public-private partnership, as in Delhi, or private collection via microentrepreneurs, as in Zambia. Collection may be officially municipal but with widespread informal collection of recyclables, as in Bogotá, Colombia (43), or collection may be provided by private corporations, as in the United States (2). Informal collection may exist in highly regulated waste management systems alongside formal collection programs, as in Berkeley, California, where scavengers pluck materials from already-sorted recycling bins and garbage.

Though the dynamic nature of the informal sector challenges its analysis, understanding the functioning of the informal sector is essential for implementing waste recovery projects in less-industrialized cities (58). Some cities—such as Belo Horizonte, Brazil, and Buenos Aires, Argentina—have made notable efforts in both understanding and integrating the informal sector into their waste management plans (58). But these cities' active integration of the informal waste sector is atypical; many municipal governments aim instead to forcibly remove their informal workers (53). The scale of the informal waste sector in developing cities, and its importance as a form of livelihood for workers, makes the integration of the informal waste sector into waste management plans a central obstacle facing the development of integrated waste management plans in developing nations (3).

4. CURRENT STATUS OF SOLID WASTE MANAGEMENT: TECHNOLOGIES AND POLICIES

Just as the governance of waste has evolved over time toward regionalization and formalization so have the technologies and policies used to minimize the negative environmental and social impacts of waste. The technologies used vary by locale but span the functional elements of waste management systems: waste generation, waste handling at the source, collection, transport, processing and transformation, and disposal (2). Waste generation and waste handling at the source are dependent on human behavior, and municipalities tend to use policies (rather than technologies) to affect changes to these elements.

4.1. Waste Management Technologies

The principal technologies employed to manage solid waste are (*a*) waste collection, (*b*) waste transfer and transport, (*c*) waste processing and transformation, and (*d*) disposal. The functions of these technologies are illustrated in **Figure 4**. These technologies, along with behavior changes, are considered below.

4.1.1. Waste collection. The ability to manage a complex and massive quantity of waste is dependent on an effective collection system. Collection is the interface between the generator and the waste management system; it is the process of removal of waste rejected from generators, which prevents its accumulation in cities and allows for its treatment (63). The first, and sometimes only, step in the formal waste management of a city, waste collection is generally the most expensive component: Middle-income cities spend 50%–60% of their waste management budgets on collection, and low-income cities spend about 80% (2, 18).

The mode of collection employed influences the quality and quantity of recovered material and thus "determines which waste management options can be used" (3, p. 193). If waste is collected such that materials are separated, then processing of like components is more feasible and efficient than if materials are comingled. In industrialized countries, many cities provide separate collection for waste destined for the landfill, for recyclable products, and for green waste (63). Source separation involves a trade-off between user participation and efficient sorting: asking users to sort their own waste raises the likelihood that waste components can be treated appropriately, but asking users to do too much lowers the probability that they will participate at all (2). In contrast, the personal relationship between the consumer and the collector in informal arrangements can encourage consumers to regularly separate their recyclables. In Bogotá, Colombia, for example, some consumers and informal recyclers have an agreed exchange: consumers separate their waste for the collector, and he removes their waste and provides sweeping services. There, consumers are willing to separate waste when there is an incentive to do so (43).

A great variety of collection technologies exist and fall into two general categories: mechanized and nonmechanized. In industrialized cities, motorized vehicles collect nearly 100% of urban waste (see **Figure 4**), which they deliver to a landfill, a transfer station, and/or a processing facility. A combination of motorized and nonmotorized vehicles collects solid waste in less-industrialized cities, where collection rates tend to be lower (18; see **Figure 5**). Where an informal recycling sector is active, as in Bogotá, Colombia, workers use a variety of methods—burlap sacks, tricycles, human- and

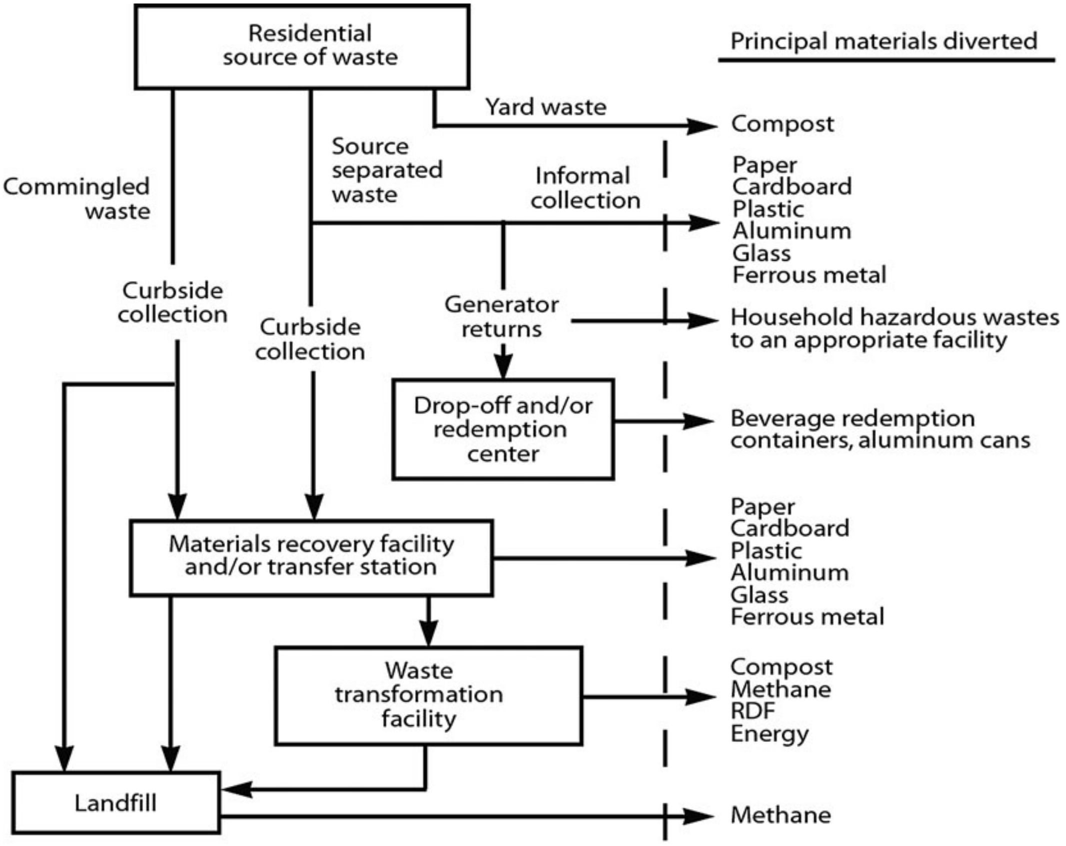

Figure 4

Flow of waste material through a waste management system. Abbreviation: RDF, refuse-derived fuel.

horse-drawn carts, and pickup trucks—to collect recyclable materials from disposed waste. The variety of collection vehicles represents the diversity of capital investments that each collector is able to make and his flexibility, allowing him to reach small alleys and neighborhoods inaccessible to large trucks. The modes of collection also affect the quantities of waste each worker may collect in a day (43).

More research should focus on improving waste collection rates in less-industrialized cities. Recently, resource-constrained cities began combining formal and informal collection, utilizing both motorized and nonmotorized vehicles to increase efficiency. In Delhi, informal workers use nonmotorized vehicles to transport waste from households to small transfer stations, where larger collection vehicles collect the waste. Delhi's system privatizes primary collection, allowing the informal sector to take charge of this labor-intensive work (14), and allows the municipality to take over where larger trucks are more efficient. This symbiosis between formal and informal systems allows less-industrialized cities to adapt to their local conditions and maximize collection efficiency.

4.1.2. Waste transfer and transport. Transfer and transport involves two steps: (*a*) the transfer of wastes from the smaller collection vehicles to the larger transport vehicle and (*b*) the transport of wastes to a processing or disposal site (2).

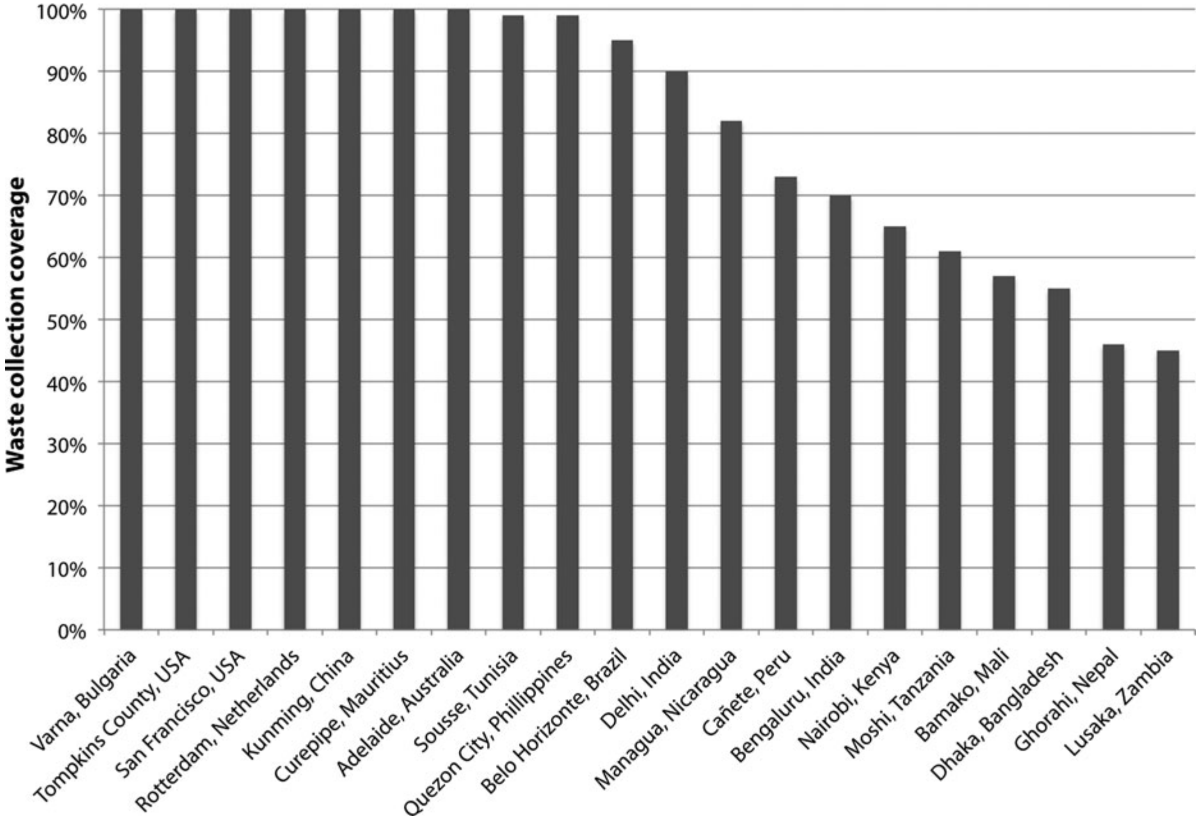

Figure 5

Municipal solid waste collection rates for selected global cities. Industrialized cities invest more money in solid waste and are able to achieve high collection rates. Less-industrialized cities invest a larger fraction of their total solid waste budgets on collection, but they have lower rates, due to budgetary shortfalls and the difficulty of reaching informal settlements. The informal sector often plays an important role in collecting waste materials in industrializing cities. Data are from Reference 14.

4.1.3. Waste processing and transformation. After collection, waste may be transformed into useful products. Transformation processes may reduce the volume and weight of waste requiring disposal and can recover resources and energy from waste. The organic fraction of waste can be transformed to soil amendments or energy via biological processes (see **Table 1**). Nonbiological transformation processes recover materials or energy from MSW (see **Table 2**). Two technologies harness human behavior change as a means to repurpose waste: reuse and waste reduction. Municipalities (or private entities) select waste processes to use according to their waste management objectives.

4.1.4. Waste processing. Waste is processed remote from the source of waste generation. Source-separated wastes are usually processed at materials recovery facilities, transfer stations, or combustion facilities (2, 3, 63). In less-industrialized countries, processing may occur at landfill disposal sites (57). Processing often includes manual or mechanized separation of waste components by size, size reduction by shredding, separation of ferrous metals using magnets, and volume reduction by compaction and combustion (2).

4.1.4.1. Biogenic waste transformation. The oldest biogenic transformation methods use biological systems to convert the oldest of wastes—biogenic wastes—into energy and soil amendments. The degradation of organic waste is a natural process, mediated by microorganisms, and people commandeer this process to extract useful resources from waste (4, 17, 64). These technologies are of particular interest in less-industrialized countries, where solid waste is mostly biodegradable. Two new technologies convert solid waste to liquid fuel, thus providing a market incentive to separate waste at the source. One historic technology is receiving increased attention for its carbon sequestration potential. These technologies are presented in **Table 1**.

4.1.4.2. Nonbiogenic waste transformation. Incineration, pyrolysis, gasification, and recycling are processes that use waste as an energy or material resource. Thermal treatment provides a number of waste management services: It reduces the volume of waste, it destroys harmful chemicals and pathogens, and it can produce electricity and heat (2, 64). Recycling is the reprocessing of discarded materials into new products (63). Nonbiogenic transformation processes are described in **Table 2**.

4.1.5. Waste disposal. Every waste management system requires a method of final disposal. In an urban world in which waste complexity is high, complete reuse and recycling of waste is very difficult. The most basic form of disposal, open dumping, directly exposes people and the environment to waste products. Sanitary landfills are facilities designed to limit the health and environmental impacts of waste (2). Equipped with liners, leachate collection, and gas extraction systems, they collect and treat the byproducts of waste degradation (e.g., methane, leachate). Between open dumps, which have no environmental controls, and sanitary landfills, which mimic a long-lived plastic bag for waste, a continuum of disposal options exists (63).

Although McDougall (3) identifies the need for less-industrialized countries to transition from open dumps to sanitary landfills, there are important trade-offs to consider. Because waste budgets are limited, a city's investment in a landfill may prevent subsequent investment in other waste technologies. However, waste in less-industrialized countries is mostly biogenic (14), so landfilling this waste will result in the production of methane, a powerful GHG (8). Thus, investing in sanitary landfills will immediately protect public and environmental health (3) but will increase GHG production and will limit waste reuse options. Research should be directed toward the implementation of biogenic treatment technologies as central waste management technologies in developing country contexts.

4.1.6. Behavior change as a waste management "technology." Waste reuse and waste reduction are two very effective methods of reducing the impact of waste on the environment, and their implementation relies on consumer behavioral change.

4.1.6.1. Waste reuse. In the United States, "old-fashioned habits of reuse and recycling have been virtually abandoned . . . disposal has been disengaged from . . . household production and assigned to the technocrats who oversee . . . sanitary landfills" (39, p. 266). American households have ceased to be centers of material production and reuse, and consumer culture, with its emphasis on convenience and fashion, has encouraged the creation of lighter-weight, shorter-lived products. Although vestiges of reuse remain (or a return to reuse practices), such as garage sales and craigslist exchanges, product reuse is a minor sink for waste products in the industrialized countries. Demonstrating the rarity of these practices, in the United States today, people "who reuse junk in clever and innovative ways [are] considered artists" (39, p. 287).

Many cities in less-industrialized countries remain centers of reuse. Though few cities keep records of waste reuse activities, and academic attention to this phenomenon is scarce, much anecdotal evidence suggests that reuse behaviors are prevalent in developing economies (75, 76). In cities such as Bogotá, Colombia, the streets on Sundays are lined with flea markets selling books, clocks, and clothing recovered from waste. In an innovative model of entrepreneurship, Trashy Bags, a company centered in Accra, Ghana, pays consumers for their empty water sachets. The company uses these bags—often discarded by citizens after drinking water from them—as raw materials to make bags, raincoats, hats, and wallets. By paying consumers for their waste, the company gives citizens an incentive to collect their waste products, and fewer plastic bags are dumped openly (43). Examples of design for reuse and repair—a concept reemerging in industrialized markets—are also ubiquitous in developing cities. Refillable glass bottles and repair shops for a variety of goods are common. But cultures of reuse and repair are under threat. The falling prices of consumer goods, the allure of consumer culture, the planned obsolescence of products, and even improved waste collection encourage disposal over reuse (11, 77).

Biogenic waste reuse is common in rural and agricultural settings throughout the world. MSW is directly used for agriculture in Bamako, Mali, in a practice called *terreautage*. Informal collectors sell partially decomposed waste to farmers, who apply it directly to their fields (14). This practice of direct waste reuse benefits the waste management system and the environment but has also prevented institutionalized composting and landfill development.

4.1.6.2. Source reduction. The intentional minimization of waste production is another means by which individuals can reduce the environmental impact of their waste (78). The benefits from producing less waste are analogous to the concept of negawatts (79), the effective increase in energy supply through energy conservation. Reduction may be a cultural practice, the way that our grandparents bought fewer objects and reused more (39), or it can be a form of environmental activism. Wilson (in Reference 14) reviews evidence of waste reduction campaigns and finds that a variety of measures are needed for source reduction to be a significant sink for waste products. Although waste prevention may seem like a simple fix—as compared to investing in technology—behavior change is difficult to sustain (80). A number of barriers exist at a societal and individual level, including the allure of the modern consumer culture, which associates status with product acquisition (81), and the difficulty of breaking habits. For more widespread adoption of waste reduction, people need more reuse infrastructure, access to more product refills, services to replace product ownership [such as tool-lending libraries (14)], and incentives to reuse products. Widespread waste reuse in less-industrialized nations, and historically in industrialized nations, suggests that people reuse waste when there are incentives to do so.

Source reduction: the intentional reduction in waste produced by generators

EPR: extended producer responsibility

4.2. Governmental Policies

Governments use waste management policies to encourage behaviors and the use of effective treatment technologies. These policies can take the form of regulations or incentives.

4.2.1. Regulations. The most basic form of environmental regulation of waste limits the emission of pollutants to the environment. Legislation, such as the Clean Air Act and the Clean Water Act in the United States, sets a maximum level of pollutants that may be released; more specific waste legislation, such as the Resource Conservation and Recovery Act, defines precisely where waste treatment technologies may be built and the environmental standards with which they must comply (2, 44). These laws are “end-of-pipe” regulations (12); they limit emissions, and represent an engineering approach to environmental protection. This class of legislation is often the first step that a state takes toward protecting the environment.

Extended producer responsibility (EPR) regulations seek to incentivize the production of more responsible waste, rather than limit end-of-pipe emissions. Many European countries have used EPR to manage waste. The Green Dot system in Germany sets specific guidelines for material packaging—and the Green Dot on the package signifies its compliance—and holds the producer of the

WEEE: waste electrical and electronic equipment

PAYT: pay as you throw tax

goods responsible for its end-of-life management (63). Similarly, the Waste Electrical and Electronic Equipment (WEEE) Directive, passed in Europe in 2003, gives producers of electric equipment full responsibility for their disposal (27). These legislations seek to change the nature of the waste over time, by incentivizing producers to design products that are easier to manage.

Bans are another form of regulation, used to phase out materials that are harmful to environmental or public health. The EU Landfill Directive calls for the phasing out of landfilling of organic waste: states must reduce the amount of biodegradable waste that they landfill to 35% of the 1995 levels by 2016 (8). A number of cities and states have banned the use of plastic bags, including Delhi (India), the state of Maharashtra (India), San Francisco (United States), and Rwanda.

4.2.2. Taxes and incentives. Taxes are another way that cities can affect the quantity or composition of MSW produced. Although most consumers pay for their waste management though a monthly flat fee, a system called "pay as you throw" (PAYT) taxes consumers on the basis of the quantity of waste they produce. If you produce more waste, you pay more (19, 82). Consumers often pay by the bag or can, but some weight-based systems exist in Denmark and Germany. PAYT has been implemented in the European Union, Australia, Korea, Canada, Mexico, and Japan (83), and the system has been associated with waste reduction. "PAYT systems reward any and all behaviors (including recycling, composting and source reduction) that reduce the amount of garbage disposed" (84, p. 2783). Though this form of taxation has been broadly successful in reducing waste production, it has also been associated with illegal dumping (83, 84).

Other taxes target specific types of waste that are harder to manage. Many European nations (e.g., Denmark), as well as China, levy a plastic bag charge, which discourages their purchase, and creates a revenue stream that can be used to improve waste management (38). Advanced waste disposal fees are commonly charged for electronic products—whose end-of-life management is complicated—and for products covered by EPR (27).

4.2.3. Goals. Finally, like the targets set by nations seeking to reduce their GHG emissions, states create goals for changing their waste management systems. The European Union aims to eliminate biodegradable waste from landfills, and the state of California passed legislation in 1989 (AB 939) to reduce the amount of waste sent to landfills by 50% in 2000 (2, 63).

4.3. Metrics for Assessing Solid Waste Management Technologies and Policies

The purpose of waste management policies and technologies is to protect human and environmental health. Metrics assess whether these goals are being reached. Technology-specific metrics cover performance; examples include total resulting emissions to air and water, and whether they meet the reigning standards. The effectiveness of a policy may be measured by the changes it has impelled. For example, a metric for PAYT programs may be the reduction in waste production per capita since its implementation. Increasingly, waste management systems as a whole are measured by their life-cycle GHG emissions, and alternative waste management plans are compared using that metric (e.g., References 78 and 85).

Waste management metrics also measure citizens' access to waste services and effective waste governance. Examples include percent waste collected, percent waste disposed of in a controlled manner, percent waste captured by system, user inclusivity, financial sustainability, institutional coherence, and the age of the last available waste report (14).

4.4. Life-Cycle Assessment of Waste Management Options

Life-cycle assessment (LCA) has emerged as an essential method to quantify the environmental benefits and drawbacks of solid waste management options (3, 8, 86). LCA is defined as "the examination, identification, and evaluation of the relevant environmental implications of a material, process, product or system across its lifespan from creation to waste, or preferably to recreation in the same or another useful form" (87, p. 18). In addition to following the standard guidelines of LCA outlined by the ISO 14040 (88, 89), recent waste LCA analyses have generally adopted a system boundary that includes the waste management system, from the moment of disposal until conversion to an emission or a reusable product (90). Product manufacture, distribution, and use are usually outside the system boundaries for these analyses (91). Waste LCAs often make a "zero-burden assumption," which takes waste as a starting point, ignoring the upstream environmental burdens associated with that waste (3, 92). Additionally, biogenic carbon from waste is widely assumed to have no global warming potential, as its carbon was recently sequestered from the atmosphere (85, 93–95). Many waste LCA methodologies state that biogenic emissions should be reported even when given a global warming potential of zero (94), but this is often not done in practice.

Unfortunately, differences in system boundaries and accounting methods have led to a number of inconsistencies between LCA studies. The use of different waste LCA models (e.g., the USA's WARM model, Denmark's EASEWASTE) has also lead to different results when analyzing the same system, owing to differences in system boundaries and other ingrained assumptions (78, 96).

In future waste LCA studies, every effort should be made to develop a common framework for defining appropriate system boundaries, so that studies may be studied and compared (and differences between studies cannot be attributed to modeler choices). The modeling results should also be considered under different scenarios of carbon accounting. Finally, the waste LCA field is shifting toward consequential modeling of decisions and is broadening from being engineering exercises to considering the social, economic, and environmental implications of waste decisions.

5. SOLID WASTE AND ITS IMPACT ON THE ENVIRONMENT

Solid waste production and management emit pollutants that contribute to climate change as well as impact public and ecological heath. Before discussing these impacts, we consider the nature of these emissions.

5.1. Emission of Pollutants from Solid Waste

Solid waste affects the environment through emissions to the air, land, and water resulting from its production and management. The technologies designed to minimize the environmental impact of waste also impact the environment. Emissions to the environment from various solid waste management technologies are reported in **Table 3**.

5.2. Waste Management and Climate Change

Climate change is among the most urgent of society's challenges, threatening biodiversity and human security, and causing increases in temperature, extreme weather, sea-level rise, and melting glaciers, among other impacts (13). Although waste management currently contributes modestly to global GHG emissions, it has the potential to be either a net source or sink of the gases (8). This potential can be illustrated through an example. A well-operating recycling system will efficiently collect separated waste paper from the waste stream, and the collected paper will be used to produce new paper. This recycling system has three sources of GHG benefits.

1. By displacing the use of virgin paper, fewer trees need to be harvested. The trees left standing are a GHG sink.
2. Less energy is used in the production of paper from old paper than would be in making paper from the raw material (trees).

Table 3 A summary of the direct environmental impacts of various waste technologies[a]

Environmental sink	Pollutants emitted from various waste technologies					
	Dumping/ landfill[b]	Incineration	Composting	Land application	Recycling	Transport
Air	CO_2, CH_4, odor, noise, VOCs, GHGs (CO_2, CH_4, N_2O)	SO_2, N_2O, HCl, CO, CO_2, dioxins, furans, PAHs, VOCs, GHGs, Hg	Odor, GHGs (minor)	Bioaerosols, odor, GHGs (minor)	GHGs (minor)	CO_2, SO_2, NO_x, odor
Soil	Heavy metals, organic compounds	Fly ash, slag	Minor impact	Bacteria, viruses, heavy metals, PAH, PCBs	Landfilling of residues	
Water	Leachate, heavy metals, organic compounds	Fallout of atmospheric pollutants	Leachate	Bacteria, viruses, heavy metals	Wastewater from processing	Fallout of atmospheric pollutants (e.g., nitrate)

[a] Adapted from Reference 102.

[b] Abbreviations: GHG, greenhouse gas; PAH, polycyclic aromatic hydrocarbon; PCB, polychlorinated biphenyl; VOC, volatile organic compound.

3. The paper collected no longer has to be managed as a waste, and the emissions resulting from its transport and disposal are prevented.

However, if that same paper is collected as part of an inefficient recycling system, by trucks collecting comingled waste, then energy is expended, but few benefits are seen. Soiled paper cannot be recycled, so the collected paper is wasted, and none of the above benefits are realized. The GHG emissions resulting from a waste technology depend on their implementation.

Mitigation of climate change from the waste sector can take many forms. Indirect GHG reductions may occur through decreased waste production (requiring less collection, transport, and treatment) or through increased recycling (decreasing the need to mine virgin resources). Increased composting and/or anaerobic digestion, improved landfill gas collection, and energy production from landfill gas directly decrease GHG emissions (63). Even though waste management's contribution to climate change is uncertain, owing to a lack of reliable data, displacement of materials and energy through waste reuse offer the largest opportunities for GHG abatement (8). Because their anaerobic environment encourages methane production, landfills are the largest source of GHGs in the waste sector. Methane emissions from landfills in industrialized countries have stabilized, but landfill methane from less-industrialized nations are increasing, as population, consumption, and landfill construction are all on the rise (8). Because landfills prevent further waste reuse and result in methane production, waste diversion from landfills should be a priority for cities seeking to reduce GHG emissions from waste management.

5.3. Waste Management and Public Health

Waste directly impacts public health, and these impacts are locally specific and variable. Waste affects people through its mismanagement and its technological management. A lack of proper waste management leads to waste accumulation, which attracts disease vectors, can clog drains, and create habitats for mosquitoes (97). Open burning of waste (or incineration without proper controls) emits a number of toxic substances, which directly harm people (98).

The illegal export of toxic waste exposes the populations that receive it to harm (99–101). But even advanced waste management technologies carry health risks. Living and working near landfills has been associated with congenital birth defects, proximity to incinerators is linked with cancer incidence, and breathing air near composting facilities is correlated to respiratory illness (102). From a health perspective, phasing out open dumping and open burning of wastes are priorities.

Waste affects people and public health differentially; poor waste management affects the poor more than the wealthy. Poor people are more likely to live near waste, and they are also more likely to be waste workers, whose occupation necessarily involves exposure. Solid waste workers tend to have higher injury rates and higher infection rates, as well as higher occupational hazard rates than the baseline population (14). Informal waste workers face higher risks because they often lack protective clothing and work under unregulated conditions (97, 102). More research is needed to explore the relationship between MSW and health, particularly focusing on the occupational health of informal recyclers in less-industrialized countries because the few studies that exist suffer from confounding factors and a lack of evidence of direct exposure (102).

5.4. Waste Management and Ecological Health

Waste management and disposal are a form of land-use change, altering the habitat of the species with which humans share the planet. But the emission of toxic chemicals is a more acute impact, harming flora and fauna. The most hazardous of these wastes—hospital, electronic, and industrial hazardous wastes—can be released directly to the environment if dumped or burned openly. MSW directly affects the health of oceans.

Millions of metric tons of plastic enter the ocean each year (103), leading to a 6:1 ratio of plastics to other marine debris in some places (104). The impacts of this persistent waste are severe: At least 267 species ingest or are entangled by plastics, leading to increased morbidity and mortality (103, 105). Because plastics absorb persistent organic pollutants, they concentrate toxins and become vectors of poisons that bioaccumulate through the food chain (106, 107). Finally, plastic waste can inhibit gas exchange from the sediments when it settles and can act as carriers for invasive species (103). Because the quantity of waste is vast and the entry points to the ocean dispersed, it is not known how much MSW ends up in the ocean or precisely where it comes from. More research is needed to quantify the contribution of poorly managed MSW on ocean health, tourism, and global fisheries.

5.5. Electronics Recycling: Material Recovery versus Public Health in China

The environmental benefits of reuse and recycling are at odds with the protection of public and ecological health when it comes to WEEE. As electronic consumer goods—televisions, mobile phones, washing machines—are globalizing, so are the reverse supply chains that handle these materials at their end of life (27, 99). Electronic goods are mostly consumed in the industrialized world and sent to the less-industrialized world for recycling, often under the guise of "bridging the digital divide" between them (24, p. 1474). Globally, most e-waste (80%) flows to Asia, and most of what reaches Asia (90%) goes to China (27), where lax environmental standards and cheap labor set the stage for profitable electronics recycling. The profit potential and the tremendous rate of global e-waste production—4,000 metric tons per hour—have made China the "largest dumping site of e-waste in the world" (100, p. 733).

Driven by a large supply of electronic waste—China alone generated 1.7 million metric tons in 2006 (100)—and a strong demand for second-hand electronics and the raw materials found within, the e-waste recycling sector is characterized by informality. Ongondo et al. (27) estimate that 98% of the 70,000 employees in the e-waste sector work informally. The industry is informal because in China, and in other e-waste recycling nations (e.g., Nigeria, Kenya, India), there is limited recycling infrastructure in the form of legislation or take-back programs, allowing informal operators to maximize profits by ignoring public health or environmental standards and by outcompeting formalized operations that do comply with them (100).

The informality of e-waste recycling allows workers to maximize resource extraction at the expense of public and environmental health. WEEE recycling is a "'backyard industry,' [that uses] primitive processes" (99, p. 6446) to extract resources and resell goods. In China, workers aim to repair and resell all electronics; those that cannot be repaired are dismantled and sold for parts. The dismantling processes used—including bare-handed separation, removing parts from circuit boards over open fires, burning cables and plastics to retrieve valuable metals, and dumping unusable materials (100)—maximize the reuse of the materials found in e-waste, but threaten public and environmental health. These processes release and create toxic metals and organic pollutants, which impact air, water, land, and health quality (see References 99–101). In Guiyu, China, a major e-waste recycling center, heavy metal and organic pollutant concentrations in the soil, water, and air far exceed US Environmental Protection Agency standards, and human exposure to dioxins and furans are 15–56 times greater than the World Health Organization guidelines (99). Children in Guiyu have higher lead blood levels than do those in nearby, non-WEEE-recycling towns (99). Although the benefits of e-waste recycling are globalized, i.e., a decrease in extraction of new heavy metals, and an increase in access to electronic goods, the burdens are borne by the ecosystems and communities where e-waste recycling takes place.

Minimizing these negative impacts is difficult because e-waste is produced globally and is not governed by one single body. China has enacted legislation restricting the use of hazardous substances in electronics and requiring producers to share in the responsibility in their end of life, but it should also seek to encourage recycling efforts that uphold health and environmental standards. Globally, work should focus on offering financial incentives to consumers for proper e-waste collection and recycling, and establishing EPR programs to involve all electronics producers in effective waste management (100).

6. RECENT TRENDS: TOWARD BUILDING MORE PERFECT WASTE MANAGEMENT SYSTEMS

Waste management studies and policies are shifting in response to new information and new challenges. In waste governance, there is increased interest in public participation in decision making, as well as a growing understanding of waste management as more than a merely technical problem. Generally, waste management has been broadening to include nonengineering disciplines and the public, specifically focusing more on households and consumers as active participants. Conceptual approaches, such as industrial ecology (IE), encourage a new framing of the waste management system, suggesting that an improved balance with our surrounding environment can be found by imitating waste management systems found in nature. Stemming from this interest in closing the loop from production to consumption, the importance of the effective design of products has emerged as another way to improve the end-of-life management of materials. Many global waste management studies have concluded that waste management requires locally specific solutions. And finally, in less-industrialized countries, cities are attempting to modernize their waste management, often through motorization, privatization, and a struggle to involve the informal sector.

6.1. New Conceptual Approaches: Industrial Ecology

Increased attention to resource recovery and recycling has prompted scholars, policy makers, and even industries to consider new approaches to waste management. IE was born out of the desire to reconceptualize waste as an input, not only an output. The IE system is like a biological system, seeking not to minimize waste production but to maximize the use of waste materials as inputs into other processes (108). The IE approach breaks substantively with end-of-pipe solutions and with pollution prevention because these approaches define waste as a necessary environmental harm to be minimized, whereas IE approaches view waste as a resource to be harnessed (77). Although only recently defined, examples of IE reach far back in history. Desrochers (6) looks at Victorian industries and finds that reuse and repair were the dominant modes of their waste management because "creating wealth out of industrial by-products typically proved more favorable in the long run than throwing them away " (6, p. 1042). In fact, he found that the birth of the IE concept occurred a full century before it was given such a name. In 1875, the Victorian industrialist Simmonds stated: "wherever we turn we find that the most trivial things may be converted into gold, the refuse and lumber of one manufacture or workshop is the raw material of another" (6, p. 1040). Desrochers argues that market barriers implemented in the twentieth century, such as environmental legislation regulating the use of waste, are responsible for the widespread decline in industrial resource recovery.

An IE approach leads to three changes in waste management: a move from waste legislation to material flow legislation (6), purposeful design of materials for reuse (108), and colocation of industries so that they may interact symbiotically (109). By ceasing to make a distinction between waste and other products, governments will remove barriers to recycling and reuse. These barriers can be seen in Austria, where any product labeled as waste must be considered under the very stringent waste management laws—even if the product is functionally equivalent to a nonwaste product on the market. In the United States too, when a product has been labeled as discarded or hazardous, its further use requires major bureaucratic approval (6). Designing waste for its repair and reuse facilitates its conversion to a useful product. A bicycle is an example of an object designed for reuse: It is easily disassembled, and as parts wear down, each may be replaced independently. Finally, the colocation of industries has occurred spontaneously in industrial parks; the most famous is in Kalundborg, Denmark. Here, an oil refinery, a coal-fired power plant, a gypsum board production facility, a pharmaceutical plant, the city of Kalundborg, and surrounding farms share water resources, waste water flows, steam, electricity, and feedstocks, such that wastes from one facility flow into the next as an input (109).

Industrial ecology (IE): the study of energy and material flows through industrial systems, using wastes from one process as an input into another

6.2. Recognizing the Importance of Producers and Consumers in Waste Management

Increasingly, waste scholars and policy makers are recognizing the importance of manufacturers in designing waste products and of using responsible materials. The green chemistry movement seeks to "design chemical products and processes that reduce or eliminate the use and generation of hazardous substances" (110, p. 272). This purposeful design may decrease overall energy consumption and facilitate the product reuse.

More research is now focusing on consumption as another process influencing the quantity and composition of waste produced. Consumption is a social and cultural process, dependent on a variety of factors that are not fully understood. Understanding consumption, and what drives sustainable consumption, is the first step toward affecting the nature of waste produced. Consumers have started their own movements from voluntary simplicity—a movement to consume and produce little (111, 112)—to green consumption (12). The green consumption movement is concerned with both decreasing material consumption and consciously choosing to buy environmentally responsible products (113). Understanding the factors that lead to sustainable purchasing and waste behaviors is an active area of research.

Green consumption is composed of purchasing choices, habits, and recycling (113). These behaviors are the result of peer influence, identity, and reflexive action. An individual's purchasing habits are linked to his environmental attitudes; having a strong environmental ethic is associated with willingness to pay more for green products and to engage in more waste reduction and reuse behaviors. For recycling behaviors, "normative social influence" has a dominant effect (113, p. 207; 114). A person's self-identity also affects her purchasing behaviors (113); if a person identifies as an environmentalist, she is more likely to engage in green consumption behaviors. A recent proliferation of environmental labeling suggests that consumers make choices based on the best-available information, but in fact, most consumption choices are not conscious—they are mundane, habitual acts. (Labeling can also be misleading; see Reference 115 on the desirability of biodegradability.) Then, tackling baseline behavior is necessary to affect consumer behavior change. From the perspective of policy makers seeking to encourage environmentally friendly waste behaviors, marketing approaches could help increase the adoption of green consumption behaviors to make them more normal and mainstream (80).

At present, these theoretical and practical approaches have led to societal changes, from the construction of eco-industrial parks to the proliferation of environmental labeling on consumer products, but these approaches have not yet become mainstream. Research on the economic benefits of utilizing waste as a resource, and on incentivizing consumer behavior change, would help popularize these alternatives.

6.3. Waste as Not Just a Technical Problem

The attention that both production and consumption are receiving as nodes in the waste management chain mark a more general trend away from seeing waste management as simply a technical problem with technical solutions. Increasingly, waste management is understood as a process that requires cooperation from users, good governance, and public participation (14). Stakeholder participation in waste management decisions is an essential component of sustainable waste management systems (116). The recognition of human factors in waste management is relatively new but widespread. Integrated waste management requires the inclusion of generators, providers, and information. In New York, the Tompkins County's landfill selection process illustrates how participation can make the difference between a poorly and a well-functioning system. Local authorities needed to site a new landfill, so they asked communities what they would want in return if they were selected to host a landfill, and the citizens made a list of requirements. The selected community was happy to receive a new school, a guarantee for stable housing prices, and a host fee. The waste company provided these requests for a small fraction of what is normally spent in legal battles with communities, and the community received valuable benefits (14).

6.4. The Need for Local Solutions

Waste studies are beginning to recognize that there is no one-size-fits-all solution to managing waste. A great number of variables—environmental, social, cultural, and economic—determine the appropriate set of technologies and policies needed to govern and manage waste in a city. The diversity of cities and the waste they produce point to the need for context-specific waste management methods. Many attempts to import waste solutions from industrialized to less-industrialized countries have failed because waste studies assumed that developing world waste systems were "incomplete copies of an ideal system that operates in developed countries" (14, p. 4). In 1984, the Municipal Corporation of Delhi built an incinerator designed to process 300 metric tons of MSW/day and produce 3 MW with Danish technical assistance. The plant was designed to treat source-separated waste, even though this behavior was not practiced by households or the municipality. Because the waste composition was wetter and less-energy dense than the designs called for, the incinerator closed within a week (117, 118). Cities are recognizing the need for adapted, local, sustainable waste management solutions that take the local context as a starting point, not an imported technology.

6.5. Modernizing Waste Systems in Less-Industrialized Countries

Finally, a combination of factors is leading to the modernization of waste management systems in less-industrialized countries. A number of forces drive this process, including those named in Section 3.1. As part of the modernization process, cities have moved toward the privatization and the motorization of waste management systems. Although privatization does give a financial incentive to operate efficiently, private companies do not have an incentive to provide full coverage to cities; instead, they have incentives to reach those who can afford to pay. The motorization of collection is also a part of many cities' waste management plans. Bogotá, Colombia, has passed a law outlawing the use of horses on streets by 2012, which would put the thousands of people who depend on horses to collect recyclables out of business (119). The integration of the informal sectors as cities modernize their waste systems is a key future challenge. A final trend in the less-industrialized cities is toward receiving carbon financing for waste management. The Clean Development Mechanism is used to finance carbon-abating projects in developing countries, and because a GHG accounting methodology exists for landfilling, the majority of waste projects financed in this manner have been landfills. Perversely, increasing the number of landfills in areas that have a high biodegradable fraction in their waste may result in greater GHG emissions (8).

7. THE FUTURE

Our planet is producing more, increasingly complex solid waste, and this waste is concentrated in cities. People have created a number of technologies and policies to manage this waste as well as to minimize the environmental and public health hazards posed by it. Promising trends in the integrated management of MSW range from innovative institutional arrangements to increased attention on the role that the consumer plays in creating and treating waste, and to new technologies that treat waste as a resource. Challenges still remain, and the largest among them include the following: integrating the informal sector into long-term waste management plans in less-industrialized countries, collecting more data on waste production and treatment, using standardized definitions for waste, managing increasing quantities of increasingly complex waste, and abating the GHG emissions that arise from solid waste.

SUMMARY POINTS

1. MSW quantity and composition vary with cultural, climatic, and socioeconomic variables.
2. MSW is growing in quantity and complexity, so its sustainable management is challenging. The case of e-waste recycling in China illustrates the health and environmental trade-offs in the management of complex wastes.
3. Public health, resource recovery, environmental protection, climate change, and the quest for modernity drive cities to improve their waste management systems.
4. Households in the United States were centers of product reuse and repurposing. As consumption increased, waste was managed more formally and at a larger scale, and citizens learned to throw things away. Cities in less-industrialized countries remain centers of product reuse.

5. Waste production and management affect air, water, and soil quality, as well as public health; modes of waste reuse offer environmental and health benefits.
6. The informal sector provides urban waste services in less-industrialized countries. This work brings social and environmental benefits to cities, as well as public health burdens.

FUTURE ISSUES

1. New conceptual approaches (e.g., IE) are emerging to manage waste as a resource.
2. More attention should be given to manufacturers' and consumers' ability to affect the nature of MSW produced through the design of products for reuse and repair and through purchasing choices, respectively.
3. Interdisciplinary approaches to waste management are needed because waste is not simply a technical problem.
4. The recognition that waste management solutions are local and contextual should lead to a greater diversity of successful urban waste management systems.
5. Much diversity can be seen in the informal waste sector in less-industrialized cities. Cities must explore trade-offs between public and environmental health, employment, and possibilities for waste reuse as they seek to modernize and formalize their waste systems. To integrate the informal sector in their municipal waste management plans, cities require more quantitative analysis of the services provided by the informal sector.
6. More and standardized data collection and research is needed on waste generation and management, especially in less-industrialized nations. Although LCA has emerged as a key method to analyze the environmental impacts of waste management systems, there remains a need for a common framework to define appropriate system boundaries.
7. Methods of waste reuse, especially common in less-industrialized cities, should be studied more and their environmental benefits and costs should be quantified.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The authors thank the ARER editorial team and anonymous reviewers who provided insightful comments and suggestions to this article.

LITERATURE CITED

1. Williams PT. 2005. *Waste Treatment and Disposal*. West Sussex, UK: Wiley. 380 pp.
2. Tchobanoglous G, Kreith F. 2002. *Handbook of Solid Waste Management*. New York: McGraw-Hill. 2nd ed.
3. McDougall F, White P, Franke M, Hindle P. 2001. *Integrated Solid Waste Management: A Life Cycle Inventory*. Oxford, UK/Malden, MA: Blackwell Sci. 2nd ed.

4. Rathje WL. 1992. *Rubbish!: The Archaeology of Garbage*. New York: HarperCollins
5. McDonough W. 2002. *Cradle to Cradle: Remaking the Way We Make Things*. New York: North Point
6. Desrochers P. 2002. Industrial ecology and the rediscovery of inter-firm recycling linkages: historical evidence and policy implications. *Ind. Corp. Change* 11(5):1031–57
7. Assaad R. 1996. Formalizing the informal? The transformation of Cairo's refuse collection system. *J. Plan. Educ. Res.* 16(2):115–26
8. Bogner J, Abdelrafie AM, Diaz C, Faaij A, Gao Q, et al. 2007. Waste management. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer. Cambridge, UK /New York: Cambridge Univ. Press
9. Johnstone N, Labonne J. 2004. Generation of household solid waste in OECD countries: an empirical analysis using macroeconomic data. *Land Econ.* 80(4):529–38
10. Cohen B. 2004. Urban growth in developing countries: a review of current trends and a caution regarding existing forecasts. *World Dev.* 32(1):23–51
11. Myers N, Kent J. 2003. New consumers: the influence of affluence on the environment. *Proc. Natl. Acad. Sci. USA* 100:4963–68
12. White P, Franke M, Hindle P. 1999. *Integrated Solid Waste Management: A Lifecycle Inventory*. New York: Chapman & Hall
13. IPCC. 2007. Climate Change 2007: Impacts, adaptation and vulnerability. In *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson. Cambridge, UK: Cambridge Univ. Press. 976 pp.
14. UN Habitat. 2010. *Solid Waste Management in the World's Cities*. London: UN Hum. Settl. Programme
15. Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. 2011. The anaerobic digestion of solid organic waste. *Waste Manag.* 31(8):1737–44
16. Kalogo Y, Habibi S, MacLean HL, Joshi SV. 2006. Environmental implications of municipal solid waste-derived ethanol. *Environ. Sci. Technol.* 41(1):35–41
17. Diaz LF, de Bertoldi M, Bidlingmaier W, Stentiford E. 2007. *Compost Science and Technology*. Amsterdam/ Boston: Elsevier
18. Hoornweg D, Bhada-Tata P. 2012. *What a Waste: Waste Management around the World*. Washington, DC: World Bank
19. Kinnaman TC. 2009. The economics of municipal solid waste management. *Waste Manag.* 29(10):2615–17
20. Zhen-shan L, Lei Y, Xiao-Yan Q, Yu-mei S. 2009. Municipal solid waste management in Beijing city. *Waste Manag.* 29(9):2596–99
21. Gómez G, Meneses M, Ballinas L, Castells F. 2009. Seasonal characterization of municipal solid waste (MSW) in the city of Chihuahua, Mexico. *Waste Manag.* 29(7):2018–24
22. Dangi MB, Pretz CR, Urynowicz MA, Gerow KG, Reddy JM. 2011. Municipal solid waste generation in Kathmandu, Nepal. *J. Environ. Manag.* 92(1):240–49
23. Walsh DC. 2002. Urban residential refuse composition and generation rates for the 20th century. *Environ. Sci. Technol.* 36(22):4936–42
24. Nnorom IC, Osibanjo O. 2008. Electronic waste (e-waste): material flows and management practices in Nigeria. *Waste Manag.* 28(8):1472–79
25. Wagner TP. 2009. Shared responsibility for managing electronic waste: a case study of Maine, USA. *Waste Manag.* 29(12):3014–21
26. Boeni H, Silva U, Ott D. 2009. E-waste recycling in Latin America: overview, challenges and potential. In *Recycling, Waste Treatment and Clean Technology*, Global Symposium, Cancun, Mex., Oct. 12–15, 2008, ed. B. Mishra, pp. 615–23. Red Hook, NY: Curran Assoc.
27. Ongondo FO, Williams ID, Cherrett TJ. 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Manag.* 31(4):714–30
28. Lebersorger S, Schneider F. 2011. Discussion on the methodology for determining food waste in household waste composition studies. *Waste Manag.* 31(9–10):1924–33

29. Beede DN, Bloom DE. 1995. The economics of municipal solid waste. *World Bank Res. Obs.* 10(2):113–50
30. Wilson DC, Araba AO, Chinwah K, Cheeseman CR. 2009. Building recycling rates through the informal sector. *Waste Manag.* 29(2):629–35
31. OECD. 2008. *OECD Factbook. 2008: Economic, Environmental, and Social Statistics: Municipal Waste*. Paris. **http://www.oecd-ilibrary.org/sites/factbook-2008-en/08/02/02/index.html;jsessionid=3cjh6uqov1wuq.epsilon?contentType=/ns/Chapter,/ns/StatisticalPublication&itemId=/content/chapter/factbook-2008-62-en&containerItemId=/content/book/factbook-2008-en&accessItemIds=&mimeType=text/html**
32. Couth R, Trois C. 2010. Carbon emissions reduction strategies in Africa from improved waste management: a review. *Waste Manag.* 30(11):2336–46
33. Couth R, Trois C. 2011. Waste management activities and carbon emissions in Africa. *Waste Manag.* 31(1):131–37
34. Friedrich E, Trois C. 2011. Quantification of greenhouse gas emissions from waste management processes for municipalities—a comparative review focusing on Africa. *Waste Manag.* 31(7):1585–96
35. Parrot L, Sotamenou J, Dia BK. 2009. Municipal solid waste management in Africa: strategies and livelihoods in Yaoundé, Cameroon. *Waste Manag.* 29(2):986–95
36. Wilson DC. 2007. Development drivers for waste management. *Waste Manag. Res.* 25(3):198–207
37. Bras A, Berdier C, Emmanuel E, Zimmerman M. 2009. Problems and current practices of solid waste management in Port-au-Prince (Haiti). *Waste Manag.* 29(11):2907–9
38. Chen X, Geng Y, Fujita T. 2010. An overview of municipal solid waste management in China. *Waste Manag.* 30(4):716–24
39. Strasser S. 1999. *Waste and Want: A Social History of Trash*. New York City: Metropolitan Books. 355 pp.
40. Kaika M, Swyngedouw E. 2000. Fetishizing the modern city: the phantasmagoria of urban technological networks. *Int. J. Urban Reg. Res.* 24(1):120–38
41. Thieme T. 2010. Youth, waste and work in Mathare: Whose business and whose politics? *Environ. Urbanization* 22(2):333–52
42. Moore SA. 2009. The excess of modernity: garbage politics in Oaxaca, Mexico. *Prof. Geogr.* 61(4):426–37
43. Vergara S. 2011. *Transforming trash: reuse as a waste management and climate change mitigation strategy*. PhD dissertation, Univ. Calif., Berkeley. Berkeley: ProQuest/UMI
44. Louis GE. 2004. A historical context of municipal solid waste management in the United States. *Waste Manag. Res.* 22(4):306–22
45. Kollikkathara N, Feng H, Stern E. 2009. A purview of waste management evolution: special emphasis on USA. *Waste Manag.* 29(2):974–85
46. Ziblatt D. 2008. Why some cities provide more public goods than others: a subnational comparison of the provision of public goods in German cities in 1912. *Comp. Stud. Int. Dev.* 43(3–4):273–89
47. Tsai L. 2007. Solidary groups, informal accountability, and local public goods provision in China. *Am. Polit. Sci. Rev.* 101(2):355–72
48. Ostrom E. 2000. Collective action and the evolution of social norms. *J. Econ. Perspect.* 14(3):137–58
49. Chibber P, Nooruddin I. 2004. Do party systems count? *Comp. Pol. Stud.* 37(2):152–87
50. Savedoff W, Spiller P. 1999. *Spilled Water: Institutional Commitment in the Provision of Water Services*. Washington, DC: Inter-Am. Dev. Bank
51. Tripp AM. 1997. *Changing the Rules: The Politics of Liberalization and the Urban Informal Economy in Tanzania*. Berkeley: Univ. Calif. Press
52. Delgado A. 2008. *Informal economy thrives in cities*. Washington, DC: Worldwatch Inst. **http://www.worldwatch.org/node/5480**
53. Medina M. 2007. *The World's Scavengers: Salvaging for Sustainable Consumption and Production*. Lanham, MD: Alta Mira
54. Wilson DC, Velis C, Cheeseman C. 2006. Role of informal sector recycling in waste management in developing countries. *Habitat Int.* 30(4):797–808
55. Mitchell CL. 2008. Altered landscapes, altered livelihoods: the shifting experience of informal waste collecting during Hanoi's urban transition. *Geoforum* 39(6):2019–29
56. Claudel N. 2010. Solid waste workers and livelihood strategies in Greater Port-au-Prince, Haiti. *Waste Manag.* 30(6):1138–48

57. Martin M. 2000. Scavenger cooperatives in Asia and Latin America. *Resour. Conserv. Recycl.* 31(1):51–69
58. Gutberlet J. 2008. *Recovering Resources—Recycling Citizenship: Urban Poverty Reduction in Latin America*. Aldershot, UK: Ashgate
59. Turan N, Gamze SC, Akdemir A, Ergun ON. 2009. Municipal solid waste management strategies in Turkey. *Waste Manag.* 29(1):465–69
60. Fahmi WS. 2005. The impact of privatization of solid waste management on the *Zabaleen* garbage collectors of Cairo. *Environ. Urban.* 17(2):155–70
61. Fahmi WS, Sutton K. 2006. Cairo's *Zabaleen* garbage recyclers: multi-nationals' takeover and state relocation plans. *Habitat Int.* 30(4):809–37
62. Fahmi WS, Sutton K. 2010. Cairo's contested garbage: sustainable solid waste management and the *Zabaleen's* right to the city. *Sustainability* 2:1765–83
63. Christensen T. 2011. *Solid Waste Technology and Management*. West Sussex, UK: Wiley
64. Rhyner CR. 1995. *Waste Management and Resource Recovery*. Boca Raton, Fla: Lewis
65. Gajalakshmi S, Abbasi SA. 2008. Solid waste management by composting: state of the art. *Crit. Rev. Environ. Sci. Technol.* 38(5):311–400
66. De Baere L. 2006. Will anaerobic digestion of solid waste survive in the future? *Water Sci. Technol.* 53(8):187–94
67. Verstraete W, Morgan-Sagastume F, Aiyuk S, Waweru M, Rabaey K, Lissens G. 2005. Anaerobic digestion as a core technology in sustainable management of organic matter. *Water Sci. Technol.* 52(1-2):59–66
68. Edelmann W, Engeli H, Gradenecker M. 2000. Co-digestion of organic solid waste and sludge from sewage treatment. *Water Sci. Technol.* 41(3):213–21
69. Li Q, Zheng L, Cai H, Garza E, Yu Z, Zhou S. 2011. From organic waste to biodiesel: black soldier fly, *Hermetia illucens*, makes it feasible. *Fuel* 90(4):1545–48
70. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, et al. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867):1238–40
71. Gaunt JL, Lehmann J. 2008. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environ. Sci. Technol.* 42(11):4152–58
72. Reijnders L. 2009. Are forestation, bio-char and landfilled biomass adequate offsets for the climate effects of burning fossil fuels? *Energy Policy* 37(8):2839–41
73. Lehmann J. 2007. A handful of carbon. *Nature* 447(7141):143–44
74. Fowles M. 2007. Black carbon sequestration as an alternative to bioenergy. *Biomass Bioenergy* 31(6):426–32
75. Agunwamba JC. 2003. Analysis of scavengers? Activities and recycling in some cities of Nigeria. *Environ. Manag.* 32(1):116–27
76. Henry RK, Zhao Y, Dong J. 2006. Municipal solid waste management challenges in developing countries—Kenyan case study. *Waste Manag.* 26(1):92–100
77. Erkman S. 1997. Industrial ecology: an historical view. *J. Clean. Prod.* 5(1–2):1–10
78. Vergara SE, Damgaard A, Horvath A. 2011. Boundaries matter: greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. *Resour. Conserv. Recycl.* 57:87–97
79. Lovins AB. 1996. Negawatts: twelve transitions, eight improvements and one distraction. *Energy Policy* 24(4):331–43
80. Rogers EM. 1995. *Diffusion of Innovations*. New York: Free. 4th ed.
81. Schor JB. 1991. *The Overworked American: The Unexpected Decline of Leisure*. New York: Basic Books. pp. 247.
82. De Jaeger S, Eyckmans J, Rogge N, Van Puyenbroeck T. 2011. Wasteful waste-reducing policies? The impact of waste reduction policy instruments on collection and processing costs of municipal solid waste. *Waste Manag.* 31(7):1429–40
83. Sakai S, Ikematsu T, Hirai Y, Yoshida H. 2008. Unit-charging programs for municipal solid waste in Japan. *Waste Manag.* 28(12):2815–25
84. Skumatz LA. 2008. Pay as you throw in the US: implementation, impacts, and experience. *Waste Manag.* 28(12):2778–85

85. Christensen TH, Gentil E, Boldrin A, Larsen A, Weidema BP, Hauschild M. 2009. C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. *Waste Manag. Res.* 27(8):707–15
86. Eur. Parliam. Counc. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. **http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0098:EN:NOT**
87. Graedel TE. 1998. *Streamlined Life-Cycle Assessment*. Upper Saddle River, NJ: Prentice Hall
88. ISO. 2006. *Environmental Management—Life Cycle Assessment—Principles and Framework*, *14040 Series*. Geneva, Switz.: Int. Organ. Stand.
89. ISO. 2006. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines. European Standard. EN ISO 14040.* Geneva, Switz.: Int. Organ. Stand
90. Finnveden G. 1999. Methodological aspects of life cycle assessment of integrated solid waste management systems. *Resour. Conserv. Recycl.* 26(3–4):173–87
91. Gentil EC, Clavreul J, Christensen TH. 2009. Global warming factor of MSW management in Europe. *Waste Manag. Res.* 27(9):850–60
92. Ekvall T, Assefa G, Bjorklund A, Eriksson O, Finnveden G. 2007. What life-cycle assessment does and does not do in assessments of waste management. *Waste Manag.* 27(8):989–96
93. Barton JR, Issaias I, Stentiford EI. 2008. Carbon—making the right choice for waste management in developing countries. *Waste Manag.* 28(4):690–98
94. Gentil EC, Aoustin E, Christensen TH. 2009. Greenhouse gas accounting and waste management. *Waste Manag. Res.* 27:696–706
95. Rabl A, Benoist A, Dron D, Peuportier B, Spadaro J, Zoughaib A. 2007. How to account for CO_2 emissions from biomass in an LCA. *Int. J. LCA* 12(5):281
96. Gentil E, Damgaard A, Bhander GS, Hauschild M, Finnveden G, et al. 2010. Models for waste life cycle assessment: review of technical assumptions. *Waste Manag.* 30(12):2636–48
97. Hunt C. 1996. Child waste pickers in India: the occupation and its health risks. *Environ. Urban.* 8(2):111–18
98. Viel J-F, Arveux P, Baverel J, Cahn JY. 2000. Soft-tissue sarcoma and non-Hodgkin's lymphoma clusters around a municipal solid waste incinerator with high dioxin emission levels. *Am. J. Epidemiol.* 152(1):13–19
99. Williams E, Kahhat R, Allenby B, Kavazanjian E, Kim J, Xu M. 2008. Environmental, social and economic implications of global reuse and recycling of personal computers. *Environ. Sci. Technol.* 42(17):6446–54
100. Chi X, Streicher-Porteet M, Wang MYL, Reuter MA. 2011. Informal electronic waste recycling: a sector review with special focus on China. *Waste Manag.* 31:731–42
101. Sepúlveda A, Schluep M, Renaud FG, Streicher M, Kuehr R, et al. 2011. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. *Environ. Impact Assess. Rev.* 30(1):28–41
102. Giusti L. 2009. A review of waste management practices and their impact on human health. *Waste Manag.* 29(8):2227–39
103. Gregory MR. 2009. Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philos. Trans. R. Soc. B* 364(1526):2013–25
104. Moore CJ, Moore SL, Leecaster MK, Weisberg SB. 2001. A comparison of plastic and plankton in the North Pacific central gyre. *Mar. Pollut. Bull.* 42(12):1297–300
105. Derraik JGB. 2002. The pollution of the marine environment by plastic debris: a review. *Mar. Pollut. Bull.* 44(9):842–52
106. Hohn D. 2008. Sea of trash. *New York Times*, June 22, Mag. **http://www.nytimes.com/2008/06/22/magazine/22Plastics-t.html**
107. Law KL, Morét-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, et al. 2010. Plastic accumulation in the North Atlantic subtropical gyre. *Science* 329(5996):1185–88
108. Frosch RA. 1992. Industrial ecology: a philosophical introduction. *Proc. Natl. Acad. Sci. USA* 89(3):800–3
109. Chertow MR. 2000. Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25:313–37

110. Mulvihill MJ, Beach ES, Zimmerman JB, Anastas PT. 2011. Green chemistry and green engineering: a framework for sustainable technology development. *Annu. Rev. Environ. Resour.* 36(1):271–93
111. Shaw D, Newholm T. 2002. Voluntary simplicity and the ethics of consumption. *Psychol. Mark.* 19(2):167–85
112. McDonald S, Oates CJ, Young CW, Hwang K. 2006. Toward sustainable consumption: researching voluntary simplifiers. *Psychol. Mark.* 23(6):515–34
113. Peattie K. 2010. Green consumption: behavior and norms. *Annu. Rev. Environ. Resour.* 35(1):195–228
114. Ekere W, Mugisha J, Drake L. 2009. Factors influencing waste separation and utilization among households in the Lake Victoria crescent, Uganda. *Waste Manag.* 29(12):3047–51
115. Levis JW, Barlaz MA. 2011. Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. *Environ. Sci. Technol.* 45(13):5470–76
116. Joseph K. 2006. Stakeholder participation for sustainable waste management. *Habitat Int.* 30(4):863–71
117. Agarwal R, Gupta SK. 2003. Rethinking urban waste in India: creating a community paradigm. *Soc. Change* 33(2–3):51–68
118. Sharholy M, Ahmad K, Mahmood G, Trivedi RC. 2008. Municipal solid waste management in Indian cities—a review. *Waste Manag.* 28(2):459–67
119. Martínez Ariza N. 2012. Bogotá, sin vehículos de tracción animal. *Elespectador* (online), Apr. 20. **http://www.elespectador.com/impreso/articuloimpreso-240683-bogota-sin-vehiculos-de-traccion-animal**

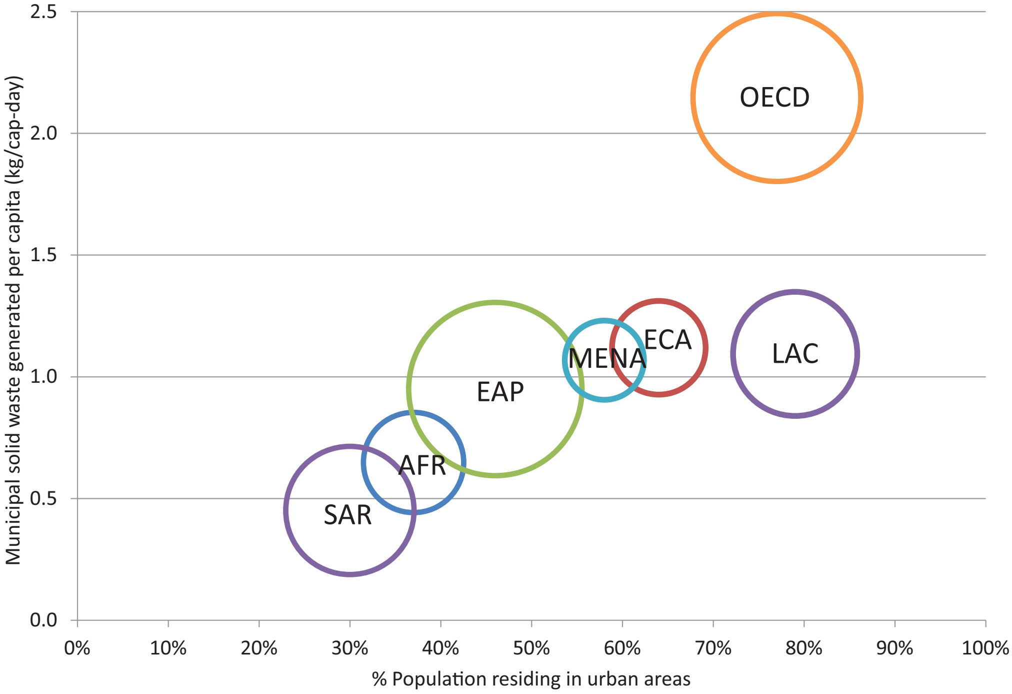

Figure 3

Current (2010) solid waste generation per capita by regions of the world. The Organisation for Economic Co-operation and Development (OECD) countries produce about 50% of the world's waste, and each of their citizens produces at least twice as much waste as does a citizen from any other region of the world. The bubble size is proportional to total urban population. Data are from Reference 18. Abbreviations: SAR, south Asia region; AFR, Africa; MENA, Middle East and North Africa; ECA, Europe and central Asia; LAC, Latin America and Caribbean.

Annual Review of
Environment
and Resources

Volume 37, 2012

Contents

I. Earth's Life Support Systems

II. Human Use of Environment and Resources

III. Management, Guidance, and Governance of Resources and Environment

IV. Integrative Themes

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://environ.annualreviews.org