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POINT-COUNTERPOINT

THE ECONOMICS OF MUNICIPAL SOLID WASTE

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This article examines the generation and management of municipal solid waste through the lens of economics. The authors estimate that the global burden of municipal solid waste amounted to 1.3 billion metric tons in 1990, or two-thirds of a kilogram of waste per person per day. Industrial countries account for a disproportionately high share of the world's waste relative to their share of world population, while developing countries account for a disproportionately high share of the world's waste relative to their share of world income. Analyses across countries and over time reveal that the generation of municipal solid waste is positively related to variations in per capita income and that the generation of municipal solid waste per capita does not vary with population size among countries with comparable per capita income.

Practices for collecting, processing, and disposing of municipal solid waste vary widely across countries, generally in accord with the nature of the waste stream and key environmental and economic features. The least efficient practices tend to be found in developing countries, creating serious threats to local environmental quality and public health. Although considerable evidence indicates that the generation and management of waste is sensitive to income and price variables, natural incentives to overuse common property and the presence of intergenerational externalities both suggest that private economic behavior will not yield socially optimal outcomes in this area. Community intervention may be needed to promote the social good, with evidence accumulating in support of arrangements involving the participation of private firms. The authors' calculations also suggest that improvements made now in the handling of hazardous waste will be far less expensive in discounted terms than undoing in the future the damage being caused by current practices. Addressing these issues from a rational societal perspective will become increasingly urgent in the future, especially in the developing countries, where the authors project that municipal solid waste will increase at an annual rate of 2.7 percent through the year 2010.

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The United Nations Conference on Environment and Development held in Rio de Janeiro in June 1992 focused world attention on the undesirable environmental side effects of population growth and economic advancement. The two problems that garnered the most attention were climate change, caused by the accumulation of greenhouse gases, and depletion of the ozone layer, caused by the emission of chlorofluorocarbons. Yet, to the extent that these problems are understood in scientific terms, both appear to be developing slowly and are not expected to unfold significantly until well into the future.

By contrast, increased levels of municipal solid waste (MSW) may not have the catastrophic potential of either global warming or stratospheric ozone depletion, but they have long posed threats to environmental quality and human health that are reasonably well understood and typically of great local and immediate concern. This article therefore explores through the lens of economics the implications for the future of current trends, practices, and policies in the generation and management of municipal solid waste. Although our analysis focuses mainly on developing countries, we also devote attention to the example of the United States, for which relevant data are more readily available.

Using economic reasoning, data analysis, and a review of the literature, we endeavor to make three main sets of points.

First, huge quantities of municipal solid waste are being generated around the world. Although much of it is collected and disposed of through controlled incineration or burial in sanitary landfills, a good deal of the rest continues to be burned in the open or dumped haphazardly, especially in developing countries. Such practices are putting increasing pressure on land, air, and water quality, and posing threats to human health that will be exacerbated by projected increases in total waste generation. Our calculations suggest that some improvements in the handling of hazardous wastes now would be less expensive (in discounted terms) than undoing in the future the damage to the environment and to human health caused by current handling practices.

Second, solid waste has resource value. Some of it is captured through the scavenging and recycling practiced in the informal sector throughout the developing world, and some through community-sponsored recycling systems and the conversion of waste into energy, compost, or both. Many studies are under way throughout the world to determine whether further value can be economically captured from solid waste.

Third, because the benefits of solid waste disposal extend beyond the households and firms that incur the costs, community intervention may promote the social good.

Patterns and Trends in MSW Generation

The focus of this article is on municipal solid waste generated by communities. Municipal solid waste can be divided into recycled and nonrecycled materials (see the glossary in box 1 for definitions of MSW, recycling, and other technical

Box 1. *Glossary*

Aerobic composting. A method of composting organic wastes using bacteria and other organisms that need oxygen. Requires that oxygen be diffused throughout the organic material, either by mixing the material to expose it to air or by forcing air through perforated pipes that pass through the material.

Anaerobic composting. A relatively slow method of composting organic wastes using bacteria that cannot function in the presence of oxygen.

Collection. Gathering MSW from where it is generated and transporting it to a transfer station, processing facility, or landfill to safeguard public health, limit congestion, and preclude unpleasant odors and offensive sights.

Compost. A soil amendment derived from decomposed organic wastes. Valuable in agriculture, horticulture, and land reclamation because it improves the ability of soil to retain moisture and chemical fertilizers and to resist erosion. Can also be used as a feedstock in aquaculture and as intermediate cover in MSW landfills to reduce the volume of waste and prevent waste from attracting pests or blowing away into residential neighborhoods.

Disability-adjusted life-year. A measure of the burden of disease representing the present value of future years of disability-free life that are lost because of premature deaths or cases of disability that occur in a particular year (World Bank 1993).

Disposal. Isolation and containment of the residual waste left after processing.

Landfilling. Disposal of MSW by burying it.

Leachate. Liquid that has seeped through MSW in a landfill and has accumulated possibly harmful dissolved or suspended materials.

Materials-balance analysis. A method for estimating MSW generation based on the weight of the domestic output of nondurable goods minus net exports and of discards of durable goods (based on past domestic production minus net exports and on estimated product lifetimes) adjusted for an estimate of permanent diversions from the waste stream. Examples of permanent diversions: paperboard used in construction, and sanitary papers disposed of in sewage systems.

Methane. By-product of anaerobic composting; can be used as a fuel.

Municipal solid waste (MSW). All solid wastes generated in a community except for industrial and agricultural wastes. Generally includes discarded durable and nondurable goods, containers and packaging, food scraps, yard trimmings, and miscellaneous inorganic debris, including household hazardous wastes and often construction and demolition debris and sludges and ashes generated by sewage treatment plants and MSW incinerators. Sources of MSW include households, commercial enterprises such as food markets and offices, and institutions such as schools, transportation terminals, and hospitals.

Processing facility. Facility that transforms the physical characteristics of MSW by recycling, composting, burning, or compacting to reduce the threat it poses to human health and ecosystems, improve its disposability, and possibly capture value from the waste.

Recycling. The act of gathering and refining the by-products of production or consumption activities for use as inputs for production activities.

Recycling facility: high-tech capital-intensive. Facility that uses automated processes to separate recyclable materials from commingled recyclable materials or raw MSW.

Recycling facility: low-tech capital-intensive. Facility at which workers hand sort commingled recyclable material as it passes by on a conveyor belt.

Residual waste. Incinerator ash, materials that are not recyclable or not worth recycling, residues from recycling and composting processes, and unprocessed MSW; generally disposed of in landfills.

(Box continues on following page.)

Box 1. *(Continued)*

Sanitary landfill. Method of disposing of MSW to minimize effects on human health and the environment. Generally consists of a pit lined with clay and plastic to prevent leachate from seeping into groundwater, drainage pipes to draw off leachate for treatment, deposits of MSW in thin layers that are frequently covered with soil or other materials to keep out water and prevent waste from blowing away or attracting pests, and a system to collect methane to prevent explosions (the methane is either flared or used as fuel).

Transfer station. A facility where MSW from collection vehicles is consolidated into larger loads that are transported by tractor trailors, railroad, barges, or other means to processing facilities or landfills.

Windrows. Piles of aerobically composting materials that are formed into rows and turned periodically to expose the materials to oxygen and to control the temperature to promote biodegradation.

Note: This glossary relies heavily on the more comprehensive glossary that appears in Kreith (1994a). Another excellent glossary appears in Tchobanoglus, Theisen, and Vigil (1993).

terms). Examples of recycled materials are discarded aluminum soft-drink cans melted down to create new cans, food and yard wastes composted and used to enhance soil fertility, and old newspapers and plastic bottles burned to produce electricity. The nonrecycled portion of MSW consists of by-products that must generally be removed from the site lest they interfere with production and consumption by attracting vermin and flies, obstructing passage, clogging drains, emitting unpleasant odors, and so on. Whether or not materials are recycled depends on the nature and cost of available production, consumption, recycling, and disposal technologies, as well as on government regulations. These can vary widely across economic settings. In developing countries, municipal solid waste is often disposed of with ash, human waste—where sewage systems do not reach substantial portions of the population (Mensah and Whitney 1991)—medical waste (Bartone, Bernstein, and Wright 1990), and industrial waste (Benavides 1992). For this reason, MSW in developing countries is sometimes more harmful to human and ecological health than it is in industrial countries.

Economic research on MSW is impeded by a lack of data and by imperfections in what data we have. Time-series data on MSW generation, recovery, and disposal rates are available for only a few countries. Like most variables used in cross-national empirical research, few country estimates of MSW are derived using common definitions, data sources, or estimation techniques. Most country estimates of MSW generation (and its composition) are based on either the sampling method or materials-balance analysis. The sampling method involves sorting and weighing samples of the MSW of individual households (see, for example, the description of the Garbage Project at the University of Arizona in Rathje and Murphy 1993) and using the results to infer MSW generation rates for a larger group of households. This method is labor intensive, and therefore prohibitively expensive in some contexts (U.S. Environmental Protection Agency 1992). By contrast, materials-balance analysis estimates MSW generation by weight as the tonnage of nondurable-goods consumption plus estimated discards of durable goods. Generation rates estimated by the Environmental Protection Agency using materials-balance analysis appear to be broadly consistent with estimates obtained using the sampling method (U.S. Environmental Protection Agency, 1992).

Putting aside questions of data quality and comparability, note that published data on the generation of MSW vary with key economic variables. Data for thirty-six countries compiled by the World Resources Institute (1993) show that daily per capita rates of MSW generation range from 0.5 kilograms for Mozambique (with a per capita gross domestic product, or GDP, of $620 in 1990) to 1.9 kilograms for Australia ($17,000 per capita GDP in 1990). On the basis of other data sources, researchers have found that the generation of per capita MSW appears to be at least 0.3 or 0.4 kilograms per day for even the poorest people.

The first column of table 1 estimates the responsiveness of MSW generation to changes in income and population. The findings show that a 1 percent increase in per capita income is associated with a 0.34 percent increase in total MSW generation, and a 1 percent increase in population is associated with a 1.04 percent increase in MSW.[1]

One might expect the generation of MSW to be relatively insensitive to variations in per capita income. Even if MSW generation were roughly proportional to consumption, empirical studies have found that consumption does not vary in equal proportion with income. Moreover, the share of services in consumption expenditure appears to rise with income, which also suggests that the generation of waste is relatively insensitive to income, because the MSW that accompanies the consumption of goods is likely to be greater than that produced by the consumption of services.

Along with the World Resources Institute data, we use the estimated measures of the responsiveness of MSW to variations in income and population, and data on per capita GDP and population in 1990 for 149 countries and territories not included in the analysis summarized in the first column of table 1, to construct an estimate of global MSW generation (see table 2). This exercise suggests that approximately 1.3 billion metric tons of MSW were generated in 1990, an average of two-thirds of a kilogram per person per day, or more than the combined global output of wheat and rice in that year (*The World Almanac 1993*).[2]

The last column of table 2 indicates that daily per capita generation of MSW in low-income countries is well below that in higher-income countries and that the latter account for a disproportionate share of MSW on a *population* basis (these countries account for less than one-sixth of the world's population but generate more than one-fourth of global MSW), while developing countries account for a disproportionate share of MSW on an *income* basis (with less than half of global GDP but nearly three-fourths of global MSW).

Assuming that national GDP growth rates for the 1980s hold steady, that population growth proceeds according to World Bank (1992) projections,[3] and that the statistical relationship reported in the first column of table 1 remains stable,

Table 1. *Cross-Sectional Patterns in MSW Generation Rates*

	Country cross-section		*Forty-five cities in China, 1990*		*Thirty-three states in the United States, 1992*	
Independent variable	*Unrestricted*	*Restricted*[a]	*Unrestricted*	*Restricted*[a]	*Unrestricted*	*Restricted*[a]
GDP per capita	0.34 (0.06)	0.34 (0.06)	0.26 (0.13)	0.29 (0.12)	0.62	0.60
Population	1.04 (0.04)	1.00 (—)	0.95 (0.06)	1.00 (—)	0.96 (0.04)	1.00 (—)
R^2	0.96	0.96	0.87	0.87	0.94	0.94
Number of observations	36	36	45	45	33	33

— Not applicable.

a. Restricted refers to regression estimation that imposed the assumption that MSW generation per capita does not vary with population.

Note: Ordinary least squares (OLS) estimates of the covariates of MSW generation rates. Dependent variable: natural logarithm of annual MSW generation by weight. Standard errors in parentheses. Though not reported, each regression model was specified with a constant term. Chinese city regressions are based on per capita GDP for each city. U.S. state regressions are based on average personal income in each state. Eighteen states whose waste included construction and demolition debris, sewage sludge, and industrial wastes were dropped from the analysis.

Source: For MSW generation rates: World Resources Institute 1993; for GDP per capita and population estimates: World Bank 1992; for data on Chinese cities: State Statistical Bureau of the People's Republic of China 1991; for data on U.S. states: Steuteville and Goldstein 1993, U.S. Bureau of the Census 1993, and U.S. Bureau of Economic Analysis 1994.

global MSW generation is projected to double between 1990 and 2019 (that is, an average annual growth rate of about 2.4 percent). The per capita MSW generation rate will not double until 2049, however. In all likelihood these doubling times will be even longer because of substitution (using aluminum and plastic instead of steel and glass in containers and packaging, for example) and because of technological innovations, such as new containers that use less material (Rathje and Murphy 1993; Alexander 1993).

The same trends and patterns that are evident across countries exist across jurisdictions in China and the United States (see table 1). That is, per capita MSW does not vary with population (holding per capita income constant), and total MSW is positively related but relatively insensitive to variations in per capita income.

Trends and patterns can also be explored using available time-series data for Taiwan (China) and the United States (table 3). For Taiwan (China) the estimated sensitivity of MSW generation to variation in income is 0.59, and its sensitivity to variations in population is 1.63. If one assumes that MSW generation per capita does not vary with population among countries with comparable per

Table 2. *Estimated World MSW Generation and Selected Characteristics by Income Classification of Economies, 1990*

	Total MSW generation[b]		*Population size*			
Income classification[a]	*Billions of metric tons a year*	*Percentage of world total*	*Millions of people*	*Percentage of world total*	*Percentage of world total GDP*[c]	*Kilograms of MSW per capita per day*
Low	0.598	46.3	3,091	58.5	18.7	0.53
Lower-middle	0.145	11.2	629	11.9	9.9	0.63
Upper-middle	0.193	14.9	748	14.2	16.5	0.71
High	0.357	27.6	816	15.4	54.9	1.20
All economies	1.293	100.0	5,284	100.0	100.0	0.67

a. Classification is based on estimates of GNP per capita: low-income economies, $600 or less in 1990; lower-middle-income economies, $630 to $2,490; upper-middle-income economies, $2,490 to $7,050; high-income economies, $9,550 and above.

b. Regression coefficient estimates were used to calculate fitted values for MSW generation for countries with no published MSW data. Fitted values (and the published MSW data if available) were then summed across the countries to arrive at global estimate of MSW generation.

c. International Comparison Project of the United Nations (ICP) estimates of GDP. ICP GDP is adjusted for purchasing power differences. GNP per capita estimates for countries with populations of less than 1 million if these were available. For countries for which data on GDP or GNP per capita were not available, averages (weighted by population) of the ICP estimates of GDP per capita for countries within the income classifications used in World Bank 1992 were computed. Cuba and the People's Democratic Republic of Korea were classified as low-income countries. Per capita income in the former U.S.S.R. was estimated by computing the average (weighted by population) 1991 estimated GDP per capita of the countries that constituted the former U.S.S.R., using estimates from World Bank 1993.

Source: For population, GDP per capita, and income classifications: World Bank 1992; for GDP per capita for former Soviet republics, World Bank 1993.

Table 3. *Time-Series Patterns in MSW Generation Rates*

	Taiwan (China) 1980–91[a]		*United States 1970–88*[b]	
Independent variable	*Unrestricted*	*Restricted*	*Unrestricted*	*Restricted*
GDP per capita	0.59	0.72	0.86	0.63
	(0.21)	(0.04)	(0.16)	(0.05)
Population	1.63	1.00	0.63	1.00
	(1.02)	(—)	(0.25)	(—)
R^2	0.98	0.97	0.98	0.92
Durbin-Watson statistic	1.73	1.90	1.61	1.69
Number of observations	12	12	19	19

— Not applicable.

Note: Standard errors in parentheses. Ordinary least squares(OLS) estimates of the covariates of MSW generation rates. Dependent variable: natural logarithm of annual MSW generation by weight. Though not reported, each regression model was specified with a constant term. Taiwan exchange rate based on 1986 average of 39.88 Taiwan dollars to the U.S. dollar.

Source: For Taiwan (China): (Taiwan) (China) 1992 and authors' calculations; for the United States: Council of Economic Advisers 1993; U.S. Bureau of Census 1978, 1983, 1990; and U.S. Environmental Protection Agency 1990, 1992.

capita income, the estimated income sensitivity of MSW generation rises to 0.72 but remains significantly less than 1.0. For the United States the estimated income sensitivity of total MSW generation is 0.86, and the population sensitivity is 0.63. If one assumes that per capita MSW generation does not vary with population (holding income per capita constant), the sensitivity of total MSW to income falls to 0.63 and is significantly less than 1.0 and very close to the cross-state income responsiveness shown in table 1. These estimates suggest that MSW is more responsive to income per capita than the cross-country estimates noted earlier. Nevertheless, MSW generation appears to be positively related but relatively insensitive to variations in per capita income, and per capita amounts do not vary with respect to population among countries with comparable income per capita.[4]

Cost-Benefit Considerations in Managing MSW

Most systems for managing MSW have three basic components: collection and transport, processing, and disposal. The purpose of collection and transport is to gather and remove MSW from its point of generation to safeguard public health, limit congestion, and preclude unpleasant odors and aesthetically offensive sights. The purpose of processing is to transform the physical characteristics of MSW by recycling, composting, burning, or compacting in order to reduce the threat it poses to human health and ecosystems, improve its disposability, and possibly capture value from the waste. The purpose of disposal is to isolate and contain the residual waste that is left after processing. Some MSW management systems ignore or incompletely implement one or more of these key components. For example, typically only 50 to 70 percent of MSW is collected in the cities of developing countries (Cointreau-Levine 1994).

Ideally, cost-benefit comparisons will guide choices among the range of options available for each component of MSW management. Such comparisons will reflect a variety of technical parameters that define the physical characteristics of specific waste streams and local geography, such as climate, suburbanization, and transportation infrastructure. They will also reflect key economic parameters, such as the relative prices of labor, plant and equipment, materials, energy, and land, which can vary considerably both within and between countries.

The valuation is relatively clear cut for some costs and benefits of management options, such as out-of-pocket collection and transport expenses and revenues from the sale of recyclable materials, compost, and energy. Other, less obvious, costs and benefits must also be accounted for, however, such as the opportunity costs of land (for transfer stations, processing facilities, or landfills) and household labor (especially if households are expected to sort their waste or transport it to a central collection point) and savings from disposal costs avoided by new technologies. Further complexities arise in valuing outcomes that are not easily expressed in pecuniary terms, such as changes in public health or in the aesthetic quality of air, water, or land. Cost-benefit comparisons must reflect complementarities among options for MSW management; for example, the cost of producing agricultural-quality compost may fall sharply if households separate their compostable and noncompostable waste. The comparisons must also account for the time value of resources, which requires choosing a discount rate, often a controversial issue.

Although estimating reliable monetary values for all costs and benefits is often not feasible, the framework of cost-benefit analysis can nonetheless provide guidance for decisionmaking and evaluation. Four factors generally weigh heavily in cost-benefit comparisons of alternative options for MSW management: the relative costs of labor and other production factors, the physical characteristics of the waste, efficient scales of operation, and nonpecuniary costs and benefits.

Relative Costs of Labor and Other Production Factors

Compared with industrial countries, in developing countries unskilled labor is abundant, skilled labor and physical capital are scarce, and infrastructure is often limited. As a consequence, the cost of unskilled labor relative to skilled labor, land, and capital is generally lower. Although capital-intensive waste-management techniques, which are typically intensive in human capital and infrastructure as well, may be economically efficient in industrial countries, they are not likely to be so in developing countries.

Labor-intensive collection and processing of recyclable materials are found throughout the developing world. Households bring their recyclables to redemption centers (Cointreau and others 1984). Small-scale entrepreneurs go door to door to purchase recyclables. (The Zabbaleen in Cairo, for example, provide collection services in exchange for the opportunity to extract recyclable materials and food waste for resale.) Collection workers and scavengers rummage through household waste put out for collection. The proportion of official work time that collection workers take to sort recyclables ranges from 10 percent in Mexico City to 40 percent in Bangkok. In Manila collection workers routinely take with them on their routes scavengers who pick out and sell recyclable materials and share the proceeds with the collection workers. Scavengers sift through waste at transfer stations and final dumpsites. It is estimated that about 7,000 scavengers are working at the MSW dumps in Manila, 8,000 in Jakarta, and 10,000 in Mexico City (Cointreau-Levine 1994).

Often the privately run businesses that purchase, clean, sort, and sell recyclables in bulk to other middlemen or directly to factories are also highly labor intensive. (See Bennett and others 1993 and Sicular 1992 for descriptions of the recycling industry in Jakarta.) The practice of scavenging may also have implications for the adoption of other waste-management techniques, as in Jakarta, where scavengers were observed regularly tearing apart waste that had been machine-compacted and baled by the city government's MSW sanitation agency (Bartone, Bernstein, and Wright 1990).

By contrast, the collection and processing of recyclable materials in industrial countries are considerably more capital-intensive. Nevertheless, there is a broad range of capital intensities of recycling activities within the United States and presumably within other industrial countries.[5] The most capital-intensive method is mixed MSW collection, in which MSW is collected and delivered to a facility using complex equipment to extract recyclable materials, the remainder often being used to make fuels for electricity-generating incinerators.

A somewhat less capital-intensive system for recycling is the collection of old newspapers and commingled glass, metal, and plastic materials. Generally, this method requires special trucks that have two compartments, one for newspapers and the other for the rest of the recyclable materials. Households and firms perform the initial separation of recyclable materials, and the process is refined at materials-recovery facilities.

Here again the range of capital intensities is broad. Some recovery facilities use highly automated systems with magnets to extract ferrous metals, air classifiers with blowers to separate light materials, such as plastics, by weight, and eddy-current separators with magnets above a conveyor belt that induce an opposing magnetic field in aluminum on the belt and push it off into a separate bin. Others use a "low-tech" conveyor belt that transports recyclable materials past workers who pick and sort the materials.

Among the least capital-intensive, and hence most labor-intensive, recycling systems in use in industrial countries is one in which either households sort and separate each type of recyclable material (paper, aluminum, steel cans, different types of plastic, glass by color, lawn and compostable food wastes) or workers sort commingled recyclable materials as they collect them and place each type of waste in its own compartment in the collection truck. Sometimes households must transport separated recyclable materials to drop-off centers—containers scattered throughout a community or staffed facilities—or to bottle buy-back centers, in the case of beverage-container deposit systems. To reduce transport costs, all capital-intensive recycling systems require that materials be shredded, baled, or pulverized.

Labor-intensive aerobic composting facilities may be more appropriate in developing countries than the highly automated aerobic or anaerobic facilities typical of industrial countries. In the most extreme cases, workers may use only simple hand tools to handsort nonrecyclable biodegradable materials from noncompostable materials, build and turn windrows, and screen and bag finished compost. (See Bennett and others 1993 for details of a project in Jakarta that developed a highly labor-intensive composting technique. To avoid the labor-intensive process of turning windrows, researchers experimented with a more capital-intensive forced-aeration static-pile technique but quickly rejected it as economically inefficient.) Capital-intensive composting projects in developing countries often fail, as in Lagos (Cointreau-Levine 1994: 29), or they may be converted to relatively more labor-intensive facilities, as in Jakarta and a number of cities in India.

Substituting labor for capital in the management of MSW has its limits, however. Singapore's Environment Ministry claims that recycling materials other than paper and metal cans is impractical and that capital-intensive incineration to produce energy, conserve landfill space, and recover some metals is more cost-effective (*The Straits Times* 1994). Landfill disposal in developing countries usually involves discarding the waste in open dumps (Bartone and Bernstein 1993). This practice is insufficiently capital-intensive, because siting landfills in areas with a high water table or constructing them without clay liners may lead to the formation of leachate that can seep out of the landfill and pollute groundwater and surface water. To the extent that hazardous waste is present in the MSW stream, leachate could seriously contaminate the water supply, which could adversely affect agriculture, with costly health implications for current and future generations.

Public cleansing of streets and open areas is critically important in areas where waste is indiscriminately dumped alongside roads. Inefficient collection techniques exacerbate this problem. In the old quarters of Moroccan cities, for example, residents discard food waste in the streets, and the following morning, when crews sweep it up into wicker baskets, some of it spills back onto the streets (Ohnesorgen 1993). In Shanghai, uncovered collection trucks also spill some of their loads back onto the streets (Ward and Li 1993). In developing countries, the cost per metric ton of cleaning waste off the streets is estimated to be between two and three times the cost of collection (Cointreau-Levine 1994), so covered trucks or other more costly collection equipment that reduces spillage would probably be more efficient.

Composition and Physical Characteristics of MSW

The composition and physical characteristics of MSW affect the economics of collecting, processing, and residual disposal.

Table 4 reports data on the average composition by weight of MSW for several cities in developing countries and for the United States. Food waste is the largest component in the cities of developing countries but is a relatively small component in the United States. This difference reflects relatively high consumption of unprocessed vegetables, fruits, and meats in the developing countries, which leads to more discarding of peel, bones, and other food wastes. A comparative study of MSW in Mexico City and the United States, for example, found that Mexican households consumed less processed and packaged foods and discarded higher amounts of food waste. An estimated $1.4 million worth of food (in 1980 dollars) was discarded each day in Mexico City in 1980. The high figure is attributable to poor refrigeration and storage facilities in low-income Mexican households and to the low cost of food staples because of heavy government subsidies (Rathje, Reilly, and Hughes 1985). In the United States, factories that

Table 4. *Composition and Physical Characteristics of Municipal Solid Waste, Selected Locations and Years*

Category	*Bangkok*[a] *1989*	*Dar es Salaam 1988*	*Jakarta 1989*	*Mexico City 1980*	*United States 1990*
Composition of MSW (percentage by weight)					
Food waste	39.2	62.5	60	43.1	8.1
Glass	3.2	0.3	2	8.4	6.5
Paper	12.4	6.2	2	19.2	32.3
Plastic	9.4	0.3	2	5.0	9.8
Leather, rubber	1.9	n.a.	n.a.	n.a.	2.7
Metals	1.7	1.2	2	3.7	7.7
Textiles	3.2	1.8	n.a.	5.7	3.3
Miscellaneous	29.0[b]	27.7	32	14.9[c]	29.6[c]
Characteristic					
Discard rate (kilograms per capita per day)[d]	0.9	0.7–0.9	0.5[e]	1.0	1.6
Landfill density (kilograms per cubic meter)[f]	615	980	1,000	640	460
Potential landfill utilization rate (cubic meters per capita per year)[g]	0.5	0.3	0.2	0.6	1.3
Percentage biodegradable (by weight)[h]	67	69	62	66	67
Moisture content of biodegradable portion of MSW (percent)	31	44	42	34	20
C/N ratio of biodegradable portion of MSW	88:1	32:1	24:1	49:1	90:1
Energy content of MSW (kilojoules per kilogram)	11,300	6,300	6,000	8,900	12,900

n.a. Not available.

Note: C/N is carbon to nitrogen. 1 kilojoule = 0.948 British thermal unit (BTU).

a. Estimates are for residential MSW from low-income-housing areas.

b. Wood and grass constitute 15.2 percent of total MSW discards and are included under "Miscellaneous" in the table but counted separately as yard wastes to compute average physical characteristics of MSW.

c. Yard wastes (grass and shrub trimmings) constitute 4.1 percent of total MSW discards for Mexico City and 26.3 percent for the United States. They are included under "Miscellaneous" in the table but counted separately to compute average physical characteristics of MSW.

d. For the United States, discards equal MSW net of materials recovered for recycling or composting. For other countries, discards by households and firms are MSW net of materials recovered by them, by scavengers, or by collection workers.

e. Based on estimated total daily MSW generation rate of 5,000 metric tons per day and estimated population of 9,882,000 in 1991.

f. The landfill density estimates for each material were based on experimental compaction of each material to simulate landfill conditions in the United States (U.S. Environmental Protection Agency 1992). These densities were used to estimate landfill density of MSW in the cities of developing countries.

g. Based on the landfill densities of MSW components, these are upper-bound estimates, because when the materials in MSW are intermingled, there tends to be less void space than if only one material were deposited in the landfill.

h. The sum of shares of paper, wood, yard wastes, and food wastes.

Source: For Bangkok: Muttamara, Visvanathan, and Alwis 1992/93; for Dar es Salaam: Yhdego 1991; for Jakarta: Bennett and others 1993, *The World Almanac 1993*, and Yhdego 1991; for Mexico City: Rathje, Reilly, and Hughes 1985; for the United States: U.S. Environmental Protection Agency 1992. For data on characteristics: Tchobanoglous, Theisen, and Vigil 1993.

produce packaged foods generally recycle food preparation wastes into animal feed or incinerate them to produce energy.

By contrast, paper accounts for a much smaller share of MSW in the cities of developing countries than in the United States, reflecting lower per capita consumption of packaged goods, office paper, newspapers, and magazines. A study using data from twenty-seven countries found a negative and statistically significant correlation between packaging waste and food waste: an additional kilogram of plastic packaging was associated with 1.1 fewer kilograms of food waste, and an additional kilogram of paper packaging with 0.7 fewer kilograms of food waste (Alter 1989). The higher food-waste content of MSW in cities of the developing countries is more or less offset by the lower paper content, resulting in comparable biodegradable content.

Key characteristics of MSW affecting collection, composting, and disposal include density, biodegradable content, moisture content of the biodegradable portion, the carbon-to-nitrogen (C/N) ratio of the biodegradable portion, and energy content.

Density affects landfill capacity and equipment requirements for collection and transport. Biodegradable content is important because biodegradable materials can be converted through microbial activity either into compost or into methane, which can be captured and used as a fuel. Such conversion may be economical in the northeast United States, where landfill tipping fees run as high as $110 a metric ton. Worldwide, the only commercial venture that converts waste into transport fuels is operating in Italy. The process is likely to yield less fuel in developing countries, where MSW contains less paper and wood and more moisture than in industrial countries. Tipping fees are likely to be lower as well, making these processes less economically efficient (Chen 1995).

The moisture content of biodegradable MSW affects collection, composting, and incineration. Compacting trucks designed in the United States often perform poorly when loaded with the high-moisture waste typically found in many developing countries (Bartone, Bernstein, and Wright 1990). High-moisture waste also tends to clog windrow aeration machines, reducing the efficiency of the equipment.

With respect to composting, the moisture content needed to achieve the most rapid conversion into compost is 50 to 60 percent (Tchobanoglous, Theisen, and Vigil 1993). This exceeds the moisture content of biodegradable MSW for every location reported in table 4 (although moisture content can vary considerably by season). Maintaining moisture content at a level that reduces composting time may keep average production costs down, but it may make composting prohibitively costly in arid regions and in areas with water contaminated by salt, heavy metals, or other nonbiodegradable pollutants. Arid regions can conserve water by using compost in agriculture; thus there is a tradeoff in deciding how best to use scarce water resources in these regions.

With respect to incineration, the energy content of MSW in developing countries is generally much lower than in the United States, as table 4 indicates, mainly because of high moisture content. Incineration to reduce volume (which lowers landfill costs) and perhaps to generate energy is impeded by moisture. This problem is generally dealt with by adding fuel, which increases the capital intensity of incineration and reduces its cost-effectiveness (Elkington and Shopley 1989).

The C/N ratio of the biodegradable portion of MSW is another important determinant of the speed (and therefore the cost) of composting. The optimal C/N ratio of 25:1 is substantially exceeded for all the locations reported in table 4 except Jakarta and Dar es Salaam. Lower C/N ratios can be achieved, although at a cost, by blending waste with sewage sludge or certain animal manures, such as chicken or cow, that have relatively low C/N ratios (Tchobanoglous, Theisen, and Vigil 1993). But if the primary goal is to recover energy by anaerobic digestion of organic materials, too low a C/N ratio can lead to excessive generation of ammonia. A C/N ratio of less than 10:1 kills the anaerobic bacteria that generate methane (Tchobanoglous, Theisen, and Vigil 1993).

Efficient Scale of Operations

Because the average cost per ton of collecting, processing, or disposing of MSW generally varies with the amount of waste being handled, the scale of operations may be crucial to the selection of cost-effective management options. Average management costs per ton of MSW may decline as the scale of operations increases, for several reasons. First, MSW management facilities have certain costs that are relatively invariant to the amount of waste dealt with at the facility, within a specified range. These fixed costs include (a) compensation for workers in such overhead occupations as administrator, engineer, technician, mechanic, and salesperson, and (b) the cost of plant and equipment, access roads to facilities, water and electricity hookups, and siting and licensing. For example, a study of 340 MSW collection operations in the United States found that average collection costs per ton declined as the scale of operations increased to service for 50,000 persons and remained unchanged when the service population exceeded 50,000 (Stevens 1977). Management alternatives that are intensive in unskilled labor will tend to achieve their minimum average costs per ton at lower levels of capacity than alternatives that are intensive in physical and human capital.

Second, average costs of MSW management may decline as the amount of waste handled rises and more specialized workers or machines are used. For example, a relatively small but capital-intensive composting facility may use a single bulldozer or bucket loader for forming and turning windrows and for consolidating and moving composted material from the windrow area of the facility to the curing area. These are not the most efficient machines for turning windrows, however, because they compact the material and do not accomplish much mixing or aeration. Specialized windrow-turning equipment may be more cost-effective at large-capacity (more than a few metric tons per day), capital-intensive facilities (Diaz, Savage, and Golueke 1994).

The geographical characteristics of metropolitan areas may affect the degree to which there are economies of scale in waste management. Households in rural areas are typically able to dispose of MSW in ways that do not adversely affect their neighbors. For example, rural households may dump their MSW in nearby fields or wooded areas; they may burn their MSW; or they may compost organic substances. Urban households that cannot exercise these options require frequent and reliable MSW collection.

Although urbanization raises the concentration per square meter of MSW, which may lower the average cost of collection, urbanization may also increase the cost of MSW management because low-income urban areas often have narrow or congested streets that cannot support large collection trucks (Cointreau-Levine 1994). Given such infrastructure, it may be cost-effective to use communal containers to which residents bring their MSW. Waste-management systems in Egypt, India, Indonesia, and the Philippines use handcarts for door-to-door MSW collection in low-income neighborhoods. The MSW is often delivered to neighborhood bins or mini-transfer stations (Bartone, Bernstein, and Wright 1990); the waste is collected by larger trucks for transport to processing or disposal facilities. Because handcart collection requires relatively little capital investment compared with motorized vehicle collection, the minimum efficient scale of handcart collection is relatively small. If urbanization outpaces the development of transportation infrastructure, the average cost of MSW management will tend to rise.

Suburbanization can raise the costs per ton of collection and transport.[6] First, insofar as it is associated with rising land costs at the fringes of metropolitan areas, suburbanization may raise the cost of establishing new MSW management facilities. Taiwan (China), for example, is increasingly turning to incineration, presumably because of prohibitively high land-acquisition costs for landfills. Second, suburbanization may increase the average distance that collection vehicles must travel from one collection site to the next. Greater travel distances increase the likelihood that a system of transfer stations would be cost-beneficial. If hauling distances to MSW processing or disposal facilities are greater than fifteen to twenty kilometers or travel time exceeds thirty minutes, delivering collected MSW to transfer stations where it can be consolidated into large loads that can be transported by tractor-trailer trucks, rail cars, or barges to large-scale management facilities is generally less expensive than transporting the same amount of MSW in smaller vehicles (Bartone and Bernstein 1993).

These efficiencies occur because vehicle operators, fuel, and container requirements are relatively unresponsive to increases in truck capacity. Cointreau-Levine (1994) suggests that there may be considerable economies of scale in transfer stations, especially if compaction devices are used to fill tractor-trailer trucks, as in Bogotá, Colombia (Tchobanoglous, Theisen, and Vigil 1993). Building enough capacity to cut down the time that collection vehicles must wait to unload can reduce transportation costs. Locating transfer stations near MSW generators and near major transportation routes also helps